inVenTs High-Power Rocketry

Virginia Polytechnic Institute
and State University

Student Team Lead	Andrew Farley, afarley0@vt.edu, (540) 588-8473
Faculty Advisor	Kevin Shinpaugh, kashin@vt.edu, (540) 231-1246
Team Mentors	Wade Foster, John Gilleran, Genevieve Gural, Ziomara Madero-Vargas, Aaron Morris, Francisco Ramos Mora, Caitlyn Stone, Andrew Touzinsky
Team Members	Bruce Barbour, Payleigh Behan, Aaron Brown, Nicolas Bulzoni Jonathan Dronfield, Meghan Eck, Nicole Gouhin, Jeremy Gross Aayush Jain, Deep Jain, Vamsi Manne, Justin Metzger Kyle Sakmyster, Sara Schlemmer, Guanang Su

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Table of Contents

Executive Summary………… 3
Budget………… 4
Rocket Design………… 5
    Overall Design………… 5
    Recovery System………… 6
    Motors………… 6
Analysis of Anticipated Performance………… 6
    Environmental Conditions………… 6
    Launch………… 7
    Flight………… 7
    Recovery………… 7
Drag System………… 8
    Drag System Mechanics………… 8
    Drag System Prototype………… 9
    Actuating the Drag System………… 10
    Construction………… 10
Avionics System………… 11
    Data Logging Code………… 11
    Data Acquisition Code………… 12
    Hardware………… 12
Model Rocket Flight………… 13
    Construction Description………… 13
    Launch Description………… 13
    Launch Results………… 14
Safety………… 14
    Material Handling Procedures………… 14
    Assembly Procedures………… 15
    Pre-Launch Procedure………… 15
    Post-launch Procedure………… 16
Appendix………… 17

Executive Summary

The 2016-2017 Space Grant Midwest High-Power Rocketry Competition is an academic rocketry design challenge hosted by the Minnesota Space Grant Consortium. The competition guidelines require teams to design, construct, and launch a single-stage high-power rocket with the intention of reaching the same apogee with two different motors. The teams must predict the anticipated performance, and log the actual flight performance with a non-commercial data acquisition system. This system must detect airframe separation, chute deployment, and record video footage of the outside of the airframe.

The team has developed a rocket using OpenRocket and Autodesk Inventor. Propulsion for the rocket is provided by Aerotech J800T-P and K400S-14 rocket motors. The rocket is 77" long, weighs an estimated 156 ounces with the J motor, and weighs 169 ounces with the K motor. This rocket will meet the competition apogee requirements by having an on-board drag system with retractable horizontal flaps. The drag system is powered by a motor controlled by an Arduino Mega 2560 inside an avionics bay. This Arduino-based avionics bay has an altimeter, accelerometer, and GPS to actuate the drag system and log critical flight data.

The inVenTs High-Power Rocketry team is a technical design team based in the inVenTs living learning Community. This living learning community is devoted to improving STEM education by mentoring first-year students and providing them with resources to ensure success. InVenTs is composed of four integral communities: Galileo and Hypatia, which caters to students in Engineering, and Curie and DaVinci, which supports students in the Life, Physical and Quantitative Sciences. InVenTs provides tutoring, academic mentoring, professional development assistance, community service outreach opportunities, social activities, and technical skills training. For the competition, the team will be working out of Studio 1, an in-dorm workshop, where members have access to a variety of handheld power tools, 3D printers, laser cutters, CNC routers, and soldering stations.

This 24-member multidisciplinary team is comprised of primarily first-year students who are representative of each of the communities present within inVenTs. Dr. Kevin Shinpaugh, an Aerospace Engineering professor and avid rocketry enthusiast, is our team's faculty sponsor and advisor. Although the team is relatively new in the field of high-power rocketry, subteam leads are working closely with the Virginia Tech Rocketry Club and the New River Valley Rocketry Association, our local Tripoli prefecture, for assistance in the construction of the rocket and to ensure the safety of the design.

Budget

The 2016-17 budget was calculated using the estimated cost of rocket construction, materials, and launch related cost (**Figs. 1 and 2**). This leads to a total budget of $7,500. The Virginia Space Grant Consortium has granted the team with $4,500 and the rest of the project will be funded with the help of corporate sponsorship.

Estimated Expenses

Item	Costs ($)
Test Launch Costs	
Model Rocket Components	$150
4X K-Class Motors	$720
Motor Casings	$250
Electronics	
Arduino	$60
Sensors	$300
Camera	$100
Structure and Payload (Other)	$1,500
Travel(to cover at least half of the team)	
Rental Car(s)	$800
Gas	$450
Tolls	$120
Hotels	$2,150
Food	$500
Registration	$400
Total	**$7,500**

Figure 1: Estimated Expenses

Spendings

Date	Purchase	Category	Amount
11/25/16	Sub team Rockets	Aero	$56.89
1/23/2017	Registration	Registration	$400
2/3/17	Arduino Supplies	Electronics	$25.61
2/4/17	F30-6JF Motors	Model Rocket Test Launch	$37.98
2/20/17	Female and Male headers, 9V Battery Box Case, Key Lock Switch	Electronics	$36.71
2/22/17	Gear and G10	Mechanical	$270.91
2/24/17	Ultra-Low-Friction Oil-Embedded Thrust Bearing with PTFE, for 1/4" Shaft Diameter Alloy Steel Shoulder Screw 1/4" Diameter x 1-3/4" Long Shoulder, 10-24 Thread Size Nylon Shoulder Screw 1/4" Diameter x 1-3/4" Long Shoulder, 10-24 Thread Size, Black, Packs of 25	Mechanical	$33.21
2/24/17	54mm Motor Mount Tube	Aero	$15.04
2/24/17	E-Flite EFC-721 720p HD Video Camera	Electronics	$46.94
2/24/17	Chutes	Aero	$117.15
3/6/17	Nose Cone	Aero	$32.65
3/6/17	Airframe, Coupler	Aero	$96.85
		Total	$1,169.94

Figure 2: Up to date expenses

Rocket Design

Overall Design

The rocket design is composed of four major sections. The first section is the 12” Poly-propylene nose cone with a diameter of 4.014” and wall thickness 0.079”. This section separates from the second section using an explosive charge which deploys the drogue chute. The second, third, and fourth sections are constructed out of a 65” BlueTube airframe. The second section of the rocket is 13” long, and the third section is 21” long. The fourth section is 31” long, and is coupled using the bottom electronics bay to control the main parachute and drag system deployment. This allows for ease of maintenance.

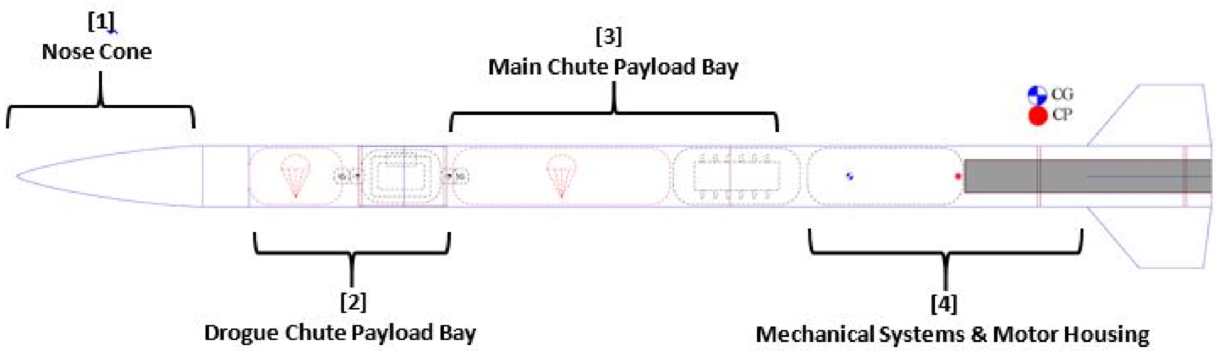

Figure 3: OpenRocket, Rocket Design

The rocket will have two different electronics sections (E-Bay). The first E-bay is located in the coupler between Section [2] and [3] of the rocket in Figure 3. This E-bay is responsible for the deployment of both the drogue and main parachutes. The second E-bay is located within Section [3] and is responsible for deploying and retracting the mechanical system, located below the second E-bay. The mechanical system is described in greater detail in the Mechanical Drag System section.

The rocket will have four trapezoidal shaped fins. The shape and number of fins were determined using the optimization tools in OpenRocket and will be constructed from G10 Fiberglass. The fins have a root chord length of 8” and a tip chord length of 4.125”. The sweep length and angle of the fins are 3.356” and 40 degrees respectively, with an airfoil cross sectional thickness of 0.157”.

Recovery System

The current recovery system design will involve the deployment of two ripstop nylon parachutes. The main parachute has a diameter of 84" with sixteen shroud lines, and the drogue chute has a diameter of 24" with six shroud lines. The drogue chute is located above the recovery E-bay in the second section of the rocket, and the main chute is located below the recovery E-bay in the third section of the rocket. Both parachutes will be deployed using gunpowder charges mounted on either side of the recovery E-bay. These charges are set-off via an electric impulse from the recovery E-bay where the drogue chute is deployed at apogee, and the main chute is deployed at 700 feet above the ground.

Motors

The rocket will be launched with a J-class motor on its first flight followed by a K-class motor on its second. The J-class motor is an Aerotech J800T-P with an average thrust of 845 N, a burn time of 1.49 seconds, and a thrust-to-weight ratio of 19.836. It measures 2.13" in diameter and is 12.8" in length. The K-class that will be used is a Kosdon by Aerotech K400S-P with an average thrust of 392 N, a burn time of 3.51 seconds, and a thrust-to-weight ratio of 9.178. The Kosdon K400S-P measures 2.13" in diameter and is 15.9" in length.

Analysis of Anticipated Performance

All of the anticipated performance data was derived from OpenRocket simulations. Numerical simulation data was then exported for additional analysis. Specific time and data values that were not provided from simulation summaries in OpenRocket were pulled from the exported data. Figures 7 through 11 are additional plots created from the exported data for reference.

Environmental Conditions

Flight performance simulations were conducted assuming nominal launch conditions at the launch site in North Branch, MN. Average environmental conditions for North Branch, as indicated in weather almanac accessed via The Weather Channel's website, on May 21 and May 22 are a high of approximately 70F and a low of approximately 45F with a 3% chance of precipitation. All simulations were run assuming International Standard Atmosphere conditions that were pre-set in OpenRocket, using an average wind velocity of 6.56 ft/s with a standard deviation of 0.656 ft/s. It should be noted that this standard deviation of average wind velocity does have a minor effect on simulated launch results from one iteration to the next.

Launch

Overall launch behavior of the rocket is ultimately dependent on which motor is used. For the J800T-P motor, the rocket has a simulated stability of 1.97 calibers (cal) at ignition, reaching a velocity of 76.4 ft/s off the launch pad. For the K400S-P motor, the rocket has a simulated stability of 1.74 cal at ignition, reaching a velocity of 43.7 ft/s off of the launch pad.

Flight

Flight behavior is heavily dependent on which motor is used. For the J800T-P, burnout is simulated to be 1.6286 seconds into flight and apogee 16 seconds into flight, reaching a simulated altitude of 5,171 ft. Maximum simulated velocity achieved with the J800T-P motor is 858 ft/s with a nominal velocity of 856 ft.s, and maximum simulated acceleration achieved is 27.5 G with a nominal maximum acceleration of 27.0 G. For the K400S-P, burnout is simulated to be 3.8913 seconds into flight and apogee 17.6 seconds into flight, reaching a simulated altitude of 5,538 ft (nominally 5,474 ft). Maximum simulated velocity achieved with the K400S-P motor is 761 ft/s with a nominal velocity of 758 ft/s, and maximum simulated acceleration is 8.92 G with a nominal maximum acceleration of 8.89 G.

Figures 7 through 11 in the appendix are graphs detailing simulated flight characteristics for altitude, velocity, acceleration, thrust, and stability during the course of the rocket's flight.

Recovery

The drogue chute deployment for both motors occurs at flight apogee and main parachute deployment occurs at 700 ft above ground level. Under the J800T-P motor configuration, the main parachute deploys 97 seconds into flight at a descent velocity of 54.4 ft/s and slows the rocket to 15.3 ft/s before landing a simulated 126 seconds after apogee. Under the K400S-P configuration, the main parachute deploys 102 seconds into flight at a descent velocity of 56.2 ft/s and slows the rocket to 15.6 ft/s before landing a simulated 128.4 seconds after apogee.

Drag System

Drag System Mechanics

In order to achieve identical apogees, a mechanical system will deploy flaps that will increase the cross-sectional area of the rocket. This will cause an increase in drag, which will decrease the rocket's kinetic energy. This mechanical system consists of one driving motor, one driving gear, four smaller gears, and four drag flaps. This design is an improvement from previous designs due to the decreased vertical space, and light weight system.

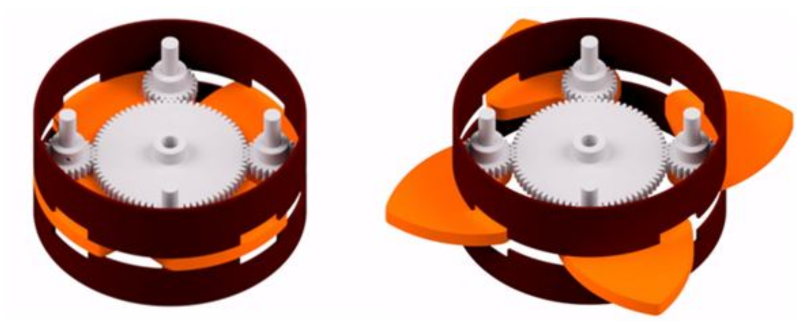

Figure 4: Drag System Modeled in Inventor

The gear system operates around a central 2.25" gear that is rotated by a 12V DC motor. This gear turns the four smaller 0.75" gears on the flaps, allowing the drag system to deploy. Both gears have a 20 degree angle of pressure. The 0.75" gear has a shaft diameter of 0.25", a width of 0.25" and 24 teeth. The shaft is made of stainless steel, finished with a press fit. The 2.25" gear will have a shaft diameter of 0.25", a width of 0.25", and 72 teeth. This shaft is also made of stainless steel, and finished with a press fit. The flaps are constructed from G-10 fiberglass because of its high strength and dimensional stability at high pressures. This material is a fiberglass epoxy laminate sheet high in strength and rigidity, and easy to work with.

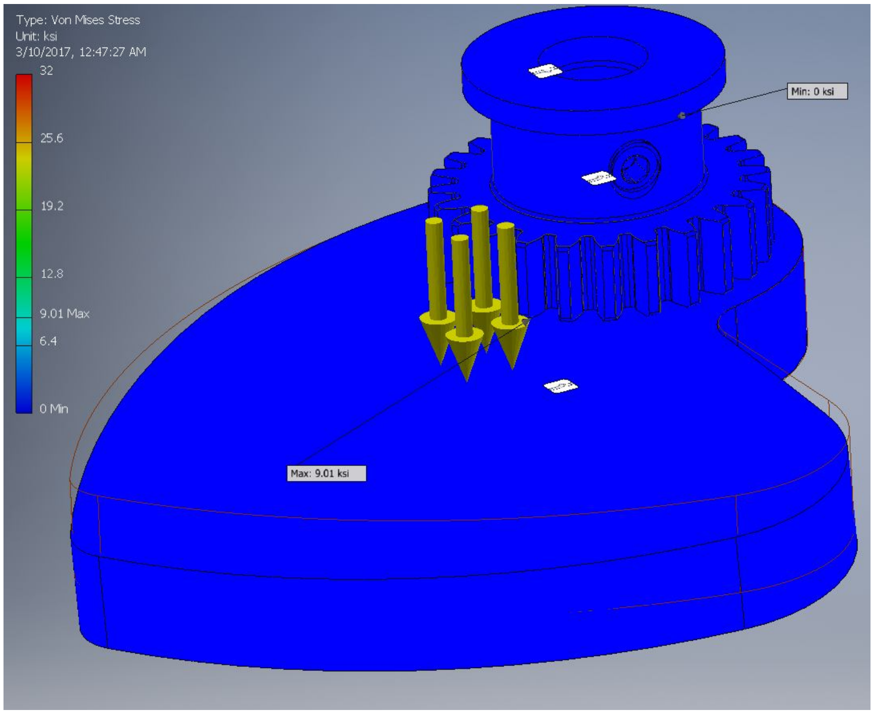

Figure 5: Analysis of Flaps: Max. Von Mises Stress of 9.01 ksi

A safety factor of 4.02 for the flaps was determined using Finite Element Analysis. This safety factor was determined through OpenRocket by finding what the maximum deceleration of the rocket would be upon deployment. Then it was assumed that this force acted only on the flaps, ensuring a very conservative stress estimate. This force was converted to a pressure applied equally across the leading face of the flap.

Drag System Prototype

The drag system was modeled in Inventor, and a prototype was laser cut and assembled based on the design. After turning the gears in the prototype, it became apparent that the high levels of friction between the separate layers of the drag system could pose a higher risk than originally thought. To reduce the friction, it was decided to include thrust bearings made of bronze with embedded plastic and oil where applicable.

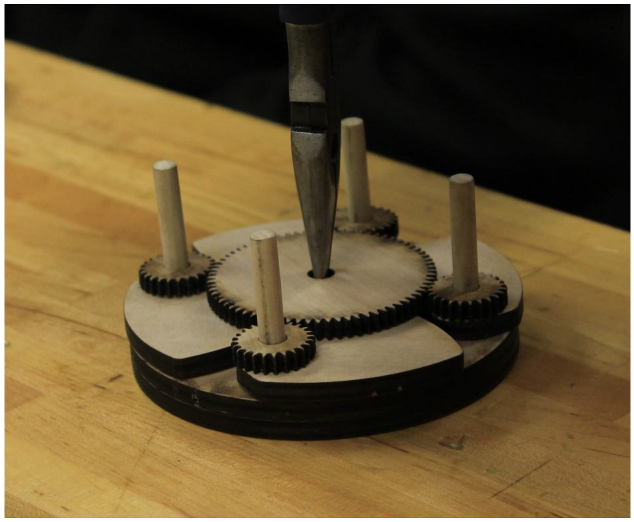

Figure 6: Wooden Drag System Prototype

Actuating the Drag System

To actuate the system and deploy the drag flaps, the drag system will use a 9V, (2.91" x 1.46" x 1.08") Lithium Polymer battery with an XT60 connector to power the DC motor. The DC motor will turn the central gear until the external drag flaps meet the Plastic Micro Mini contact switches, signaling the DC motor to turn off in order to keep the flaps fully extended. These contact switches have Simulated Roller SPTD Lever Actuators. They are rated for AC 125V/250V 5A, weighing 0.3 ounces (6.7 x 5.7 x 0.4 inches) each. An Adafruit DRV8871 motor driver breakout board with 6.5V to 45V motor power voltage controls the motor. The board has a 3.6A peak current and 565mΩ typical RDS(on).

Construction

After deciding on the proper design and components for the drag system, our team began construction. The bottom bulkhead is made from 0.5" thick wood using a laser cutter, bandsaw, and drill press. The outline of the bulkhead is rastered using the laser cutter, then cut out on the bandsaw. The holes for the bolts that attach the bulkhead to the gears are made with the drill press. The bottom bulkhead, which all of the fins are attached to, is sanded down to ensure a tight fit in the body tube. The contact switch and DC motor mount rings are made in a similar fashion, and are constructed out of 0.25" thick stock wood. Similar to the bulkhead, G10 fiberglass drag flaps are constructed by rastering an outline with the laser cutter, then cut using the bandsaw. When handling fiberglass, all team members will be wearing the appropriate PPE, including safety glasses, dust masks, and at times gloves. Our team will buy the gears, thrust bearings, washers, nuts and bolts from McMaster-Carr. The DC Motor was donated to the team by a team member.

To assemble the flaps, the surface of the flap and the surface of the gear will be scored and roughened over where they contact to create a strong surface for the epoxy to bond to. The shoulder bolts will be put through the bottom bulkhead. After the flap and gear are joined, they will be mounted on the shoulder bolts above the bulkhead with washers and thrust bearings placed as needed. Following this the sun gear will be mounted to the DC motor, which will be held in place by centering rings in the body tube. The electronics required to actuate the drag system will be mounted above the DC motor.

Avionics System

Data Logging Code

The data logging section of code enables the Arduino microcontroller to acquire data from the barometer, altimeter and GPS simultaneously. This program uses many prebuilt libraries and hard coded methods to record the data to a SD card that is provided from the sensors.

The program automatically starts when the microcontroller turns on. The program writes the data into a notepad format that is easily readable. The initial 'if' statements are used to check if the sensors are correctly initialized, and ready to record. If one of the sensors' begin() method does not return true, then the program will stop and print an error message informing us that the sensor is not correctly set up. The 'setup' method is seen in Figure 12 in the appendix.

The code uses the 'print' function to write the sensor data to a text file stored on the SD card. This data is written in orderly lines so it may read legibly after recovery. An example of how this section of code prints can be found in the appendix. Figure 13 is an example of a piece of code would be used to print data from the altimeter.

The main purpose of the drag system code is for the slowing down of the rocket. The drag system will use the onboard altimeter to know to deploy and retract the drag system. This drag system code is seamlessly integrated within the data logging code. As a result, the flaps on the rocket will toggle at precise moments during flight. This allows the rocket to slow down and reach the correct apogee during the second launch with the higher-class motor.

Data Acquisition Code

The electrical team's subteam rocket contained a prototype of the avionics bay designed to test data acquisition through the sensors. It recorded the Altitude, Roll, Pitch, Heading, Temperature and Current Pressure. An example of what was recorded in 22 seconds when the rocket was on the launch pad can be seen in Figure 14 in the appendix. This prototype had a sampling rate of 1 Hz due to it being an early version of the code. Figures 15 through 17 in the appendix are graphs of the altitude, velocity, and acceleration over time created from the launch data.

In order to utilize the SD card, our team used two libraries: SD, and SPI from the Adafruit website. These libraries contain necessary information about the SD class's methods and attributes. In the initSensors() method, if the SD card is successfully detected, then the program continues to the setup() method. A File object called mySensorData is created to store all of the data recorded throughout the rocket's flight. The open() method for the SD class writes the specified file into the SD card, and ensures that the file is not overwritten in every time interval. Our subteam decided to print the data in a column format to promote legibility. The code prints the title of each type of data being collected in the headings outside the loop at the start.

In the loop, the code calls the methods that command the sensors to record the data. First, the sensor events are set up for the acceleration, pressure, temperature, and orientation, which includes the heading, pitch, and roll. Then the data is read from the sensors and stored into their respective variables. User defined functions, such as TempPressAlt_out() and RollPitch_out(), were created to print out each value one at a time with the correct units. These functions were called in the loop to organize all of the code inside the loop, and divide the rest of the print statements into their corresponding functions. At the end of the loop, the close() method is called to deactivate the SD card, and save the file inside it. Figure 14 in the appendix shows how the text output would appear for logging data.

Hardware

The microcontroller controlling the avionics bay is the Arduino Mega 2560, with dimensions of 4.24" X 2.8" X 0.57", a mass of 34.19g. The Arduino Mega 2560 has 54 digital I/O pins, 16 analog input pins, and takes 7-12V in at 40-50mA. A GPS Data Logger Shield mounted above the Arduino has a built in SD card slot for logging sensor data from the different sensors. In addition to the logging, a transmitter will be attached directly to the GPS shield to assist with recovery of the rocket. The GPS shield is the same size of the

Arduino, and is mounted through a direct pin connection. The extra height of the shield when added onto the Arduino took a small amount of space, but it did not have any great effect on the overall performance on the internals of the rocket. The breadboard is 1.78" X 1.78" X 0.56", has a mass of 49.93g, and will contain the altimeter, accelerometer, gyro, barometer, and GPS. A prototype of our avionics bay is shown in Figure 18 in the appendix.

The Adafruit BMP 180 has a barometer that measures atmospheric pressure in hPa and then uses that measurement to determine the height of the rocket. The Adafruit 9-DOF IMU Breakout board measures the head, pitch and roll in degrees, along with the acceleration of the rocket in m/s^2. A 9 volt battery inside a holder with a toggle switch will be used to power the Arduino and various sensors. Both BMP 180 and 9-DOF IMU Breakout board draw five volts from the Arduino. The size of the battery holder is 2.68" X 1.3" X 0.87" with a 7.56" cord, and the mass of the holder and cord without a battery is 69.5g. The camera that will be used to record the drag system is the E-Flite EFC-721. It weighs 15g, records in 720p full-color, and has an internal 3.7V 150mAh rechargeable Li-Po battery. The storage port accepts a Micro-SD memory card, has a USB charger and includes a mounting bracket.

Model Rocket Flight

Construction Description

Our team chose to construct rockets using left over blue-tube from last year's competition. In order to give new team members competition experience, our team chose to create a challenge from this. Each of our three sub teams were tasked with constructing their own rocket with the goal of reaching the highest apogee. The rockets were constructed in Studio 1 of Lee hall on February 2nd, and February 3rd. Pictures of the construction can be seen in figure 19 and 20 in the appendix.

Launch Description

The launch occurred at Kentland farms, our local designated rocket site. The launch was scheduled for February 4th around 1 o'clock in the afternoon. The weather was partly cloudy with a temperature around 42 degrees fahrenheit. The wind speed was roughly 5 miles per hour, and the barometer reading was approximately 30.12 inches of mercury. The visibility was around 10 miles.

Launch Results

Mechanical subteam was the first to launch their rocket. Their apogee was 481 ft, with a max acceleration 2.5 g's. Due to the fact that the delay on the E9-6 motors were longer than necessary, the rocket went to apogee and began to fall back to earth for about two seconds before deploying its parachute. This delayed deployment caused the parachute to tear, but the rocket managed to land mostly unharmed.

The electrical subteam launched second. Their rocket was heavier due to an electronic logging payload, so their rocket was launched using an F30-6 motor. The apogee was 870 ft, with a max acceleration of 6 g's. Their rocket went straight up with some slight spin, but parachute deployment was normal. Data was successfully collected from the launch.

The aero subteam rocket launched last using an F30-6 motor. Unfortunately, a faulty motor cause the rocket to explode. Our team believes that the motor failure activated the delay charge and ignited the motor simultaneously. Photos from the launch can be found in the appendix.

Safety

Material Handling Procedures

The blue tube and G10 fiberglass materials used in the construction of the rocket will require the use of properly fitted dust masks to ensure particulates are not inhaled when the materials are cut to design specifics. Inhalation of blue tube or G10 fiberglass particles can cause respiratory complications.

The explosive charges used in parachute deployment are to be handled with extreme caution and care despite the relatively small amounts of gunpowder used in creating the separation charges. Mishandling of the separation charges can result in unintentional detonation, which can cause a fire or personal injury. The charges will only be armed when the rocket is set up on the launchpad, to ensure safety of the observing crowd.

All materials are to be transported with caution and care to ensure that no accidental discharge of the separation charges or damage occurs to the rocket in transit. The rocket will be divided into its four sections during transportation . The separation charges will be created prior to launch and transported in a container carried by a designated team member.

Assembly Procedures

The rocket will be assembled from its four completed subsections prior to launch. Each subsection, as identified and numbered in Figure 3, will be joined to the adjacent section number - i.e. Section 1 will be joined to Section 2, Section 3 will be joined to Sections 2 and 4. The nose cone will be secured using shear pins. Sections 2 and 3 will be joined by the dual purpose recovery E-bay coupler component and will also be secured via shear pins to prevent separation from occurring too early in flight. Sections 3 and 4 will be pseudo-permanently joined using screws and will functionally act as one larger section.

Pre-Launch Procedure

1. Pack and secure parachute and drogue chute as according to set parachute packing procedure
2. Ensure the electronics are activated and are secure in the rocket
    a. Turn on and test tracking beacon
    b. Set delay
    c. Turn on and secure both competition altimeters
    d. Turn on and secure camera
    e. Download the flight program to the microcontroller, ensuring everything is connected and working properly
    f. Secure the microcontroller system
3. Test mechanical system for functionality
4. Test security of the motor in the rocket
5. Verify that the correct amount of black powder is in the ejection canisters
6. Verify fin system is functional
7. Place flame resistant wadding separating the ejection charge devices from the payload components in the rocket subsections
8. Inspect fin connections
9. Verify that nose cone is secured to top of rocket
10. Verify that all sections of the rocket are properly connected, aligned and secured
11. Verify correct motor has been installed properly into the rocket
12. Have the Range Safety Officer (RSO), inspect and approve the rocket for flight
13. Mount rocket on launchpad
14. Activate microcontroller
15. Ensure transmitter is activated

16. Arm the recovery devices
17. Insert electronic match for ignition

Post-Launch Procedure

1. Wait for RSO to declare the area clear
2. Recover rocket using tracking beacon if needed
3. Ensure all components were recovered
4. Take photo and video of the landing site
5. Examine the rocket for possible damage
6. Download video from camera
7. Download flight data from microcontroller
8. Deactivate camera, microcontroller, and beacon
9. If rocket is in flyable condition, prepare for next flight

Appendix

Anticipated Flight Performance Graphs

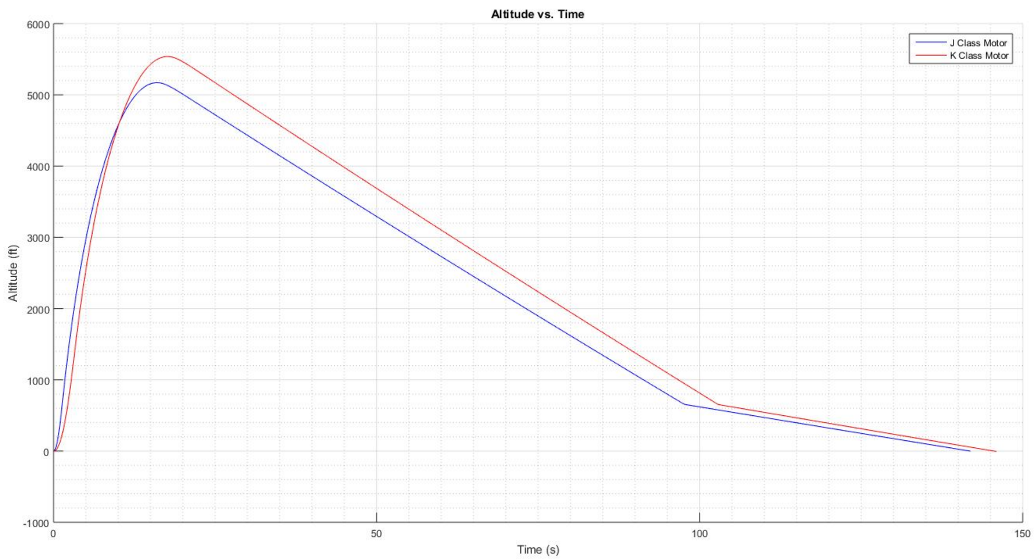

Figure 7: OpenRocket simulation of predicted rocket altitude during flight. Main parachute deployment is indicated by the change in the descent velocity rate that occurs around the 100 second mark for both motor flights.

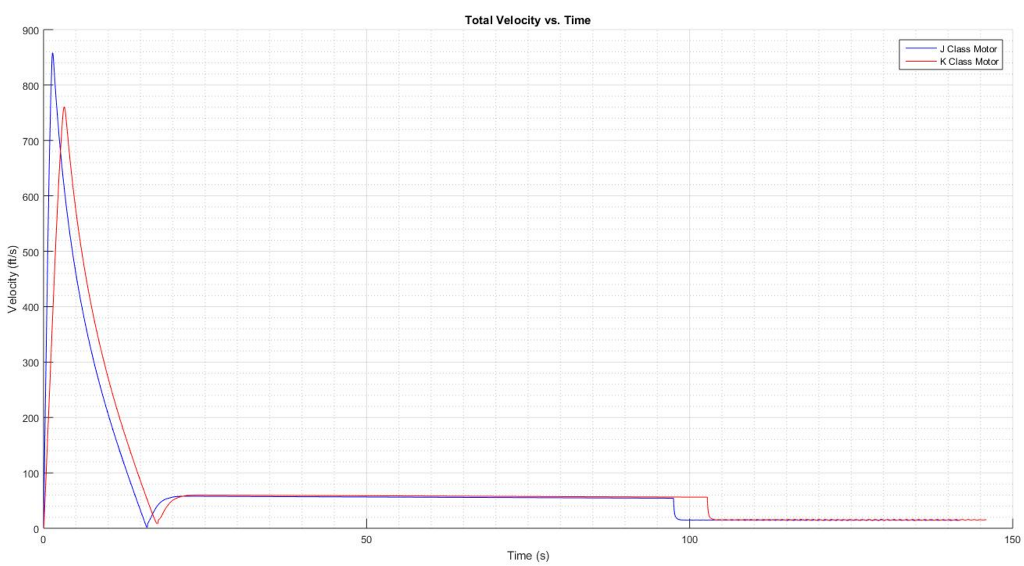

Figure 8: OpenRocket simulation of rocket velocity during flight.

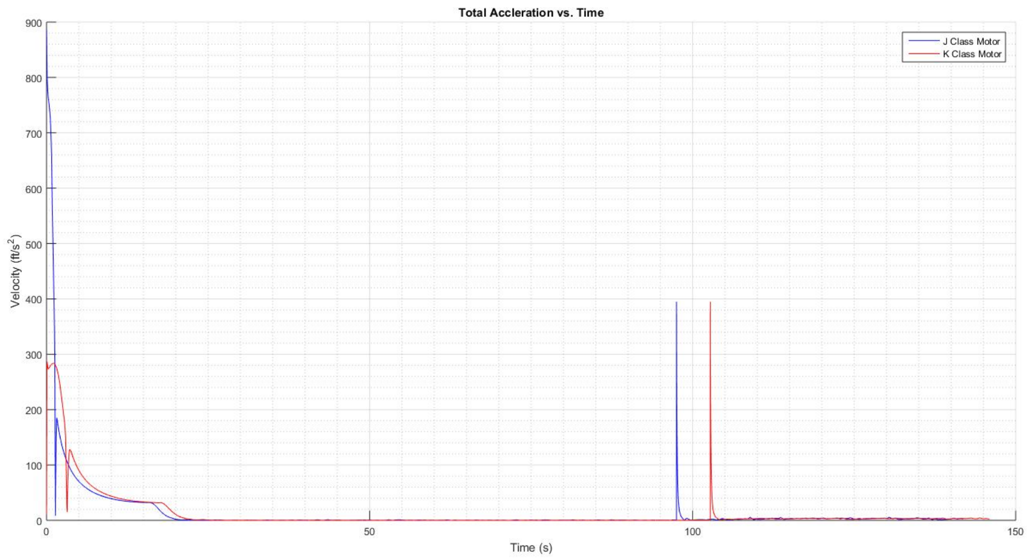

Figure 9: OpenRocket simulation of total rocket acceleration during flight. The sudden spike in acceleration around 100 seconds is main parachute deployment.

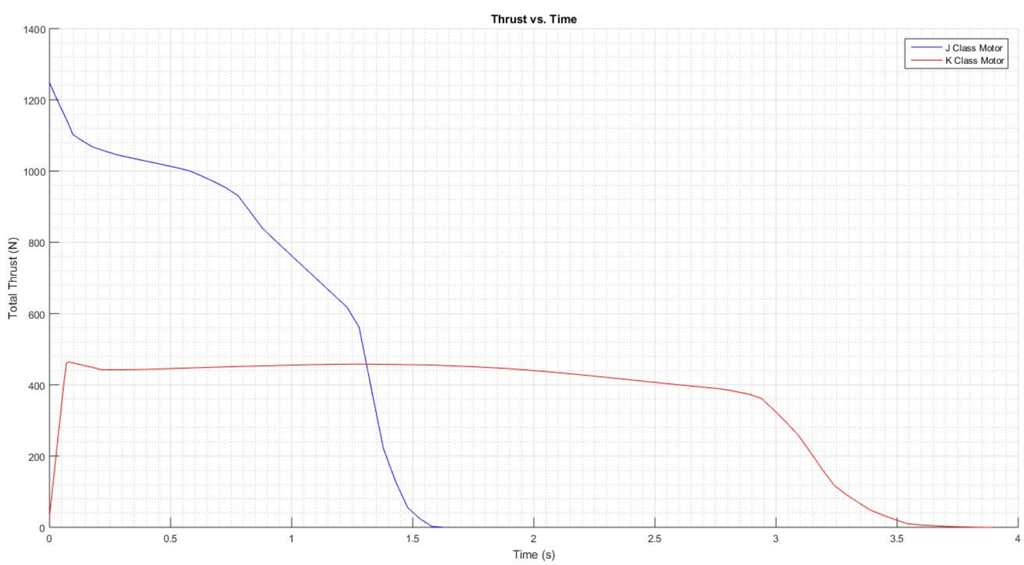

Figure 10: OpenRocket simulation of rocket motor thrust from ignition to motor burnout.

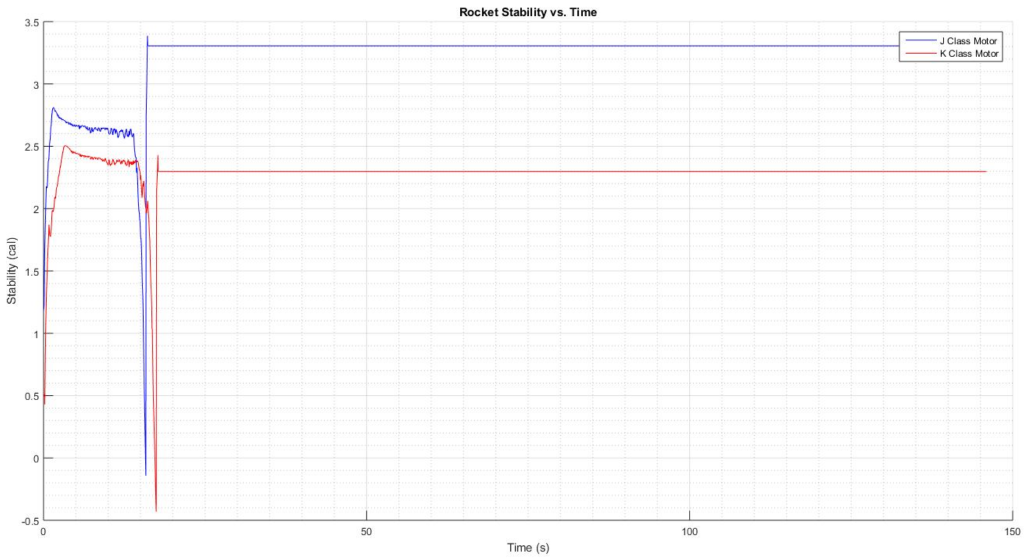

Figure 11: OpenRocket simulation of how rocket stability changes during flight.

Avionics Code and Hardware

```
void setup()
{
  Serial.begin(9600);      // Optimal BAUD rates
  gyro.enableAutoRange(true); // Enable auto-ranging
  initSensors();           // Initialise the sensors
  char filename[15];
  strcpy(filename, "GPSLOG00.TXT");
  for (uint8_t i = 0; i < 100; i++)
  {
    filename[6] = '0' + i/10;
    filename[7] = '0' + i%10;
    // create if does not exist, do not open existing, write, sync after write
    if (! SD.exists(filename))
    {
      break;
    }
  }

  mySensorData = SD.open(filename, FILE_WRITE);
  if (!mySensorData){
    Serial.print("File couldn't be created");
  }
  delay(100);
}
```

Figure 12: Setup code for logging data in the avionics bay.

```
  if (Pressure)
  {
    mySensorData.print("Temperature: ");
    mySensorData.print(Temp);
    mySensorData.print(" degrees F");
    mySensorData.print(", ");
    mySensorData.print("Pressure: ");
    mySensorData.println(Pressure);
    mySensorData.print(" hPa");
    mySensorData.print(", ");
    mySensorData.print("Sea Level Pressure: ");
    mySensorData.print(Slp);
    mySensorData.print(" hPa");
    mySensorData.print(", ");
    mySensorData.print("Altitude: ");
    mySensorData.print(Alt);
    mySensorData.print(" m");
    mySensorData.print(", ");
  }
}
```

Figure 13: An example of how the arduino prints data to a text file.

```
// snippet from TF1 log file
Temperature: 10.10, Pressure: 967.60, Altitude: 387.20, Roll: 160.68, Pitch: 51.20, Heading: -100.72
Temperature: 10.00, Pressure: 967.41, Altitude: 388.84, Roll: -152.26, Pitch: -11.75, Heading: -20.03
Temperature: 9.70, Pressure: 967.04, Altitude: 392.04, Roll: 78.31, Pitch: 77.85, Heading: -110.64
Temperature: 9.70, Pressure: 967.33, Altitude: 389.53, Roll: 150.21, Pitch: 40.95, Heading: 11.83
Temperature: 9.50, Pressure: 967.43, Altitude: 388.67, Roll: -135.00, Pitch: 21.42, Heading: 28.92
Temperature: 8.70, Pressure: 966.92, Altitude: 393.08, Roll: 86.10, Pitch: -66.62, Heading: -33.87
Temperature: 9.30, Pressure: 967.49, Altitude: 388.15, Roll: 164.91, Pitch: 65.15, Heading: -90.26
Temperature: 9.30, Pressure: 967.44, Altitude: 388.58, Roll: 155.16, Pitch: 77.11, Heading: -69.22
Temperature: 7.60, Pressure: 965.87, Altitude: 402.16, Roll: -21.12, Pitch: 80.13, Heading: 76.23
```

Figure 14: Sensor Data from Feb. 11th 2017 Test Flight.

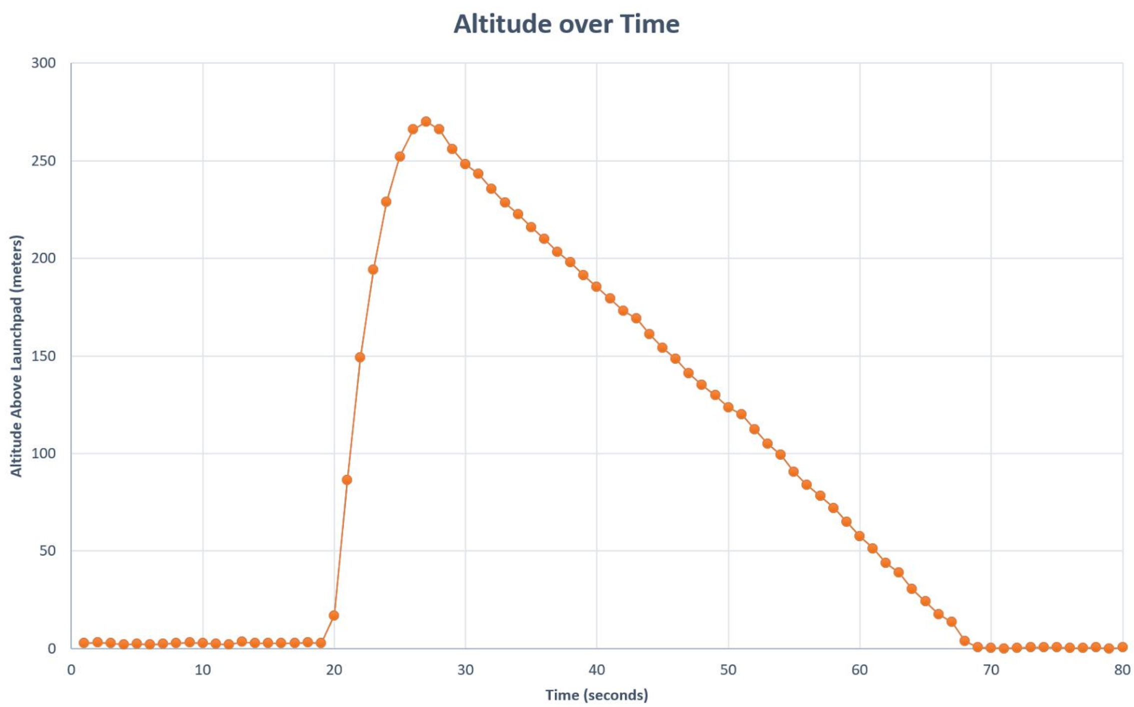

Figure 15: Altitude over time graph from Feb. 11th 2017 Test Flight.

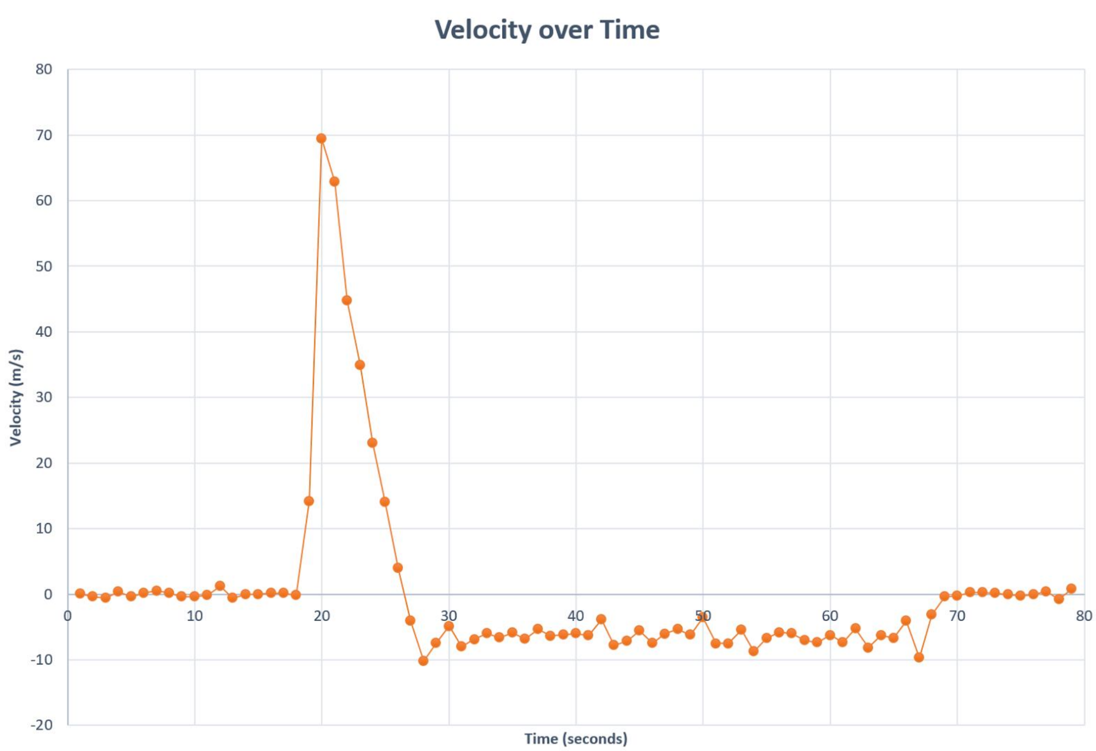

Figure 16: Velocity over time graph from Feb. 11th 2017 Test Flight.

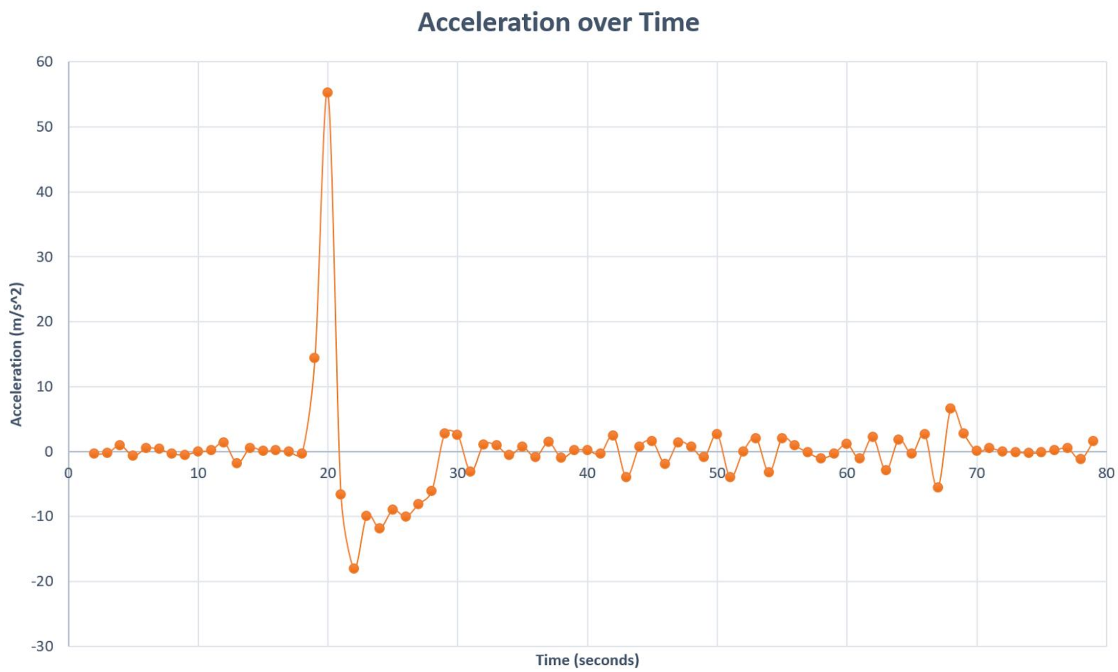

Figure 17: Acceleration over time graph from Feb. 11th 2017 Test Flight.

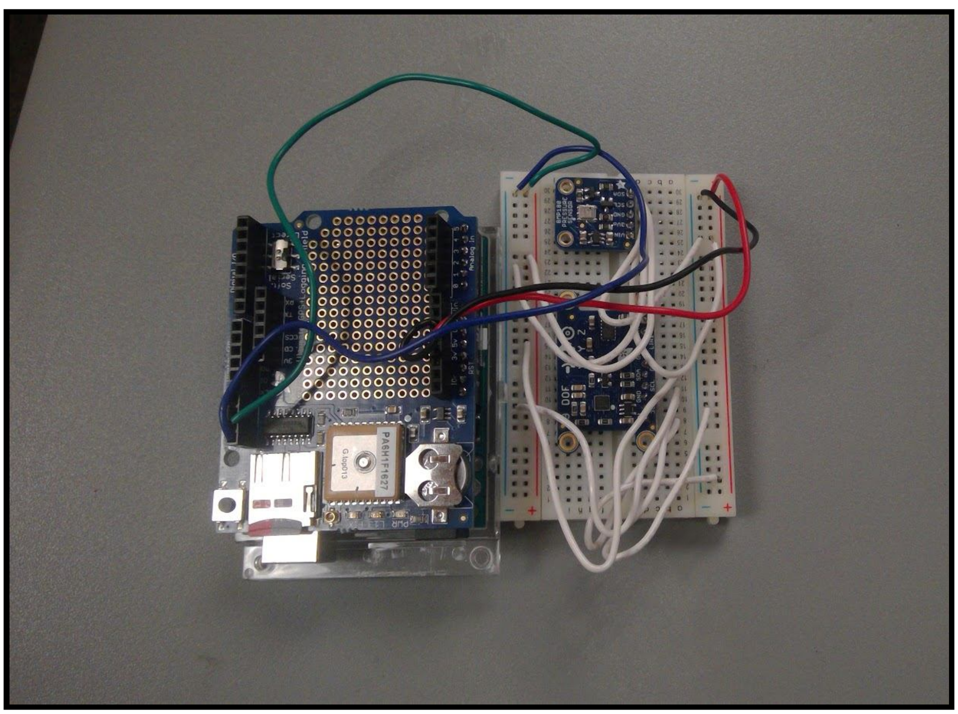

Figure 18: A prototype of the avionics bay with Arduino, GPS logging shield, altimeter, and accelerometer

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Rocket Construction Photos

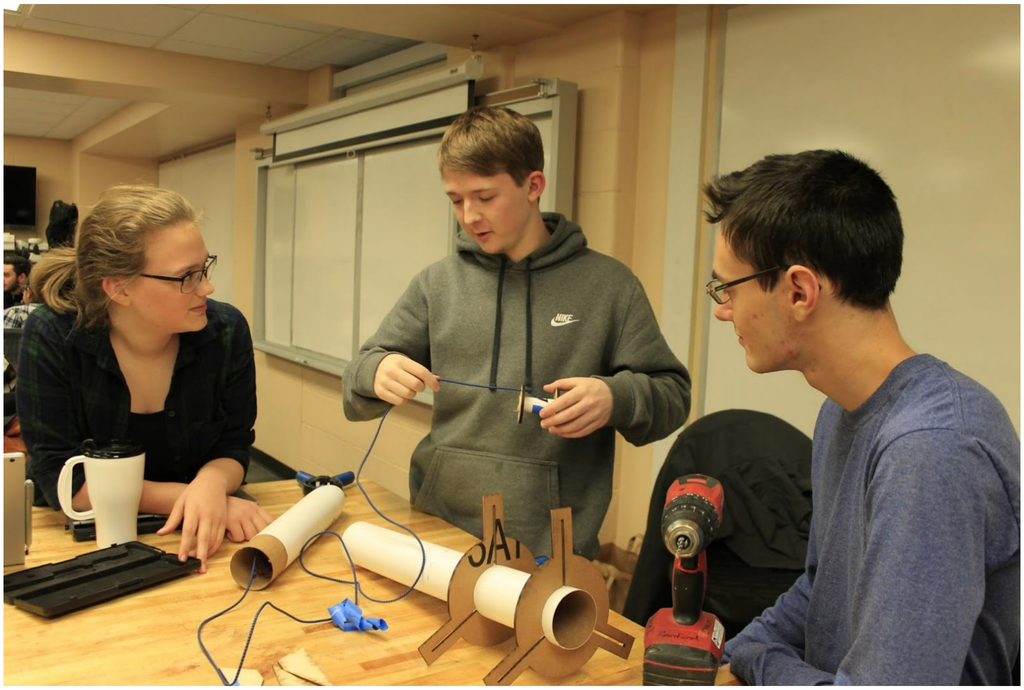

Figure 19: Electrical subteam constructing their rocket's fins.

Figure 20: Mechanical subteam working on their rocket's motor.

Launch Photos

Figure 21: Aero team preparing to launch their rocket .

Figure 22: Our team assembled before launching the three rockets.