# NUSTARS

NORTHWESTERN UNIVERSITY SPACE TECHNOLOGY AND ROCKETRY SOCIETY

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## Executive Summary


Competition guidelines

The guidelines for the competition were to design a rocket that used automatically minimized rotation after apogee on the first flight and rotates following a set of instructions given by judges after apogee on the second flight. The rocket must log its orientation angle and record with a camera the roll orientation for later comparison.

Basic requirements

The rocket must land safely and must be in good enough condition for a second launch. The rocket's apogee should be at least 3000 feet. The same I or J motor must be used on both launches.

Developing the design

To develop the final rocket design, the iterative design process was used in conjunction with conferring with more experienced members of NUSTARS. In addition, the Team Advisor was consulted throughout the brainstorming and design process to ensure the rocket would successfully, and safely, launch.

Design

The final rocket design has two main body tube sections. The nose cone is hollow and holds the main parachute, its shock cord, and the top part of the coupler. The coupler has a 5 inch long upper bay on the outside and contains the flywheel and electronics system. The lower bay holds the second half of the coupler, the drogue parachute, motor, video camera, and fins and is 34 inches long. The flywheel smoothly controls the amount of rocket rotation. The electronics system communicates with the ground station, controls the video camera, and alters the flywheel's rotational speed.

Meeting the competition guidelines

This design for NUSTARS' rocket satisfies the competition guidelines through several different components.

- Rotation: The flywheel allows the rocket to rotate on both the first and second launches by using torque and angular momentum.
- First launch: The electronics system has code that constantly checks the gyroscope and alters the speed and direction of the flywheel's rotation accordingly to prevent rotation of the rocket.
- Second Launch: The XBees in the electronics system communicate with the ground station to alter the flywheel's speed and direction so the rocket's orientation corresponds with the judge's' instructions.
- Documented orientation: The video camera provides the video confirmation of the rocket's orientation. The electronics system sends the orientation angle from the gyroscope to the ground station through the XBees. The ground station's program calculates the orientation angle.

Basic requirements

- Landing safely: The rocket has a stability above 2.0 and a 48 inch diameter main parachute.
- 3000 feet: The rocket's apogee, after launching a test flight and using a simulation, is above 3000 feet because of the J motor and weight of 292 ounces.
- I and J motor: An Aerotech J800T-10 motor, which is a J motor, was used.

**Diagram of Rocket**

Airframe and propulsion system specifications

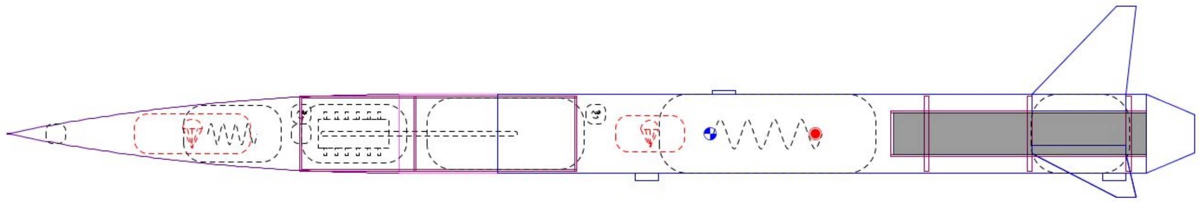

Figure 1

*Dimensions of the rocket*

The rocket is 4 inches in diameter with a total length of 60.5 inches. The rocket is 60.5 inches long because the length should be 10-20 times the diameter. Our diameter to length ratio is 1:15.125, which is in the middle of the required diameter to length ratio. The body of the rocket is made up of one nose cone, one coupler, and two body tubes. The nose cone is a 4 inch diameter fiberglass filament wound 5 to 1 Von Karman Nose cone with a metal tip. The coupler connects the nose cone with the lower body tube. The coupler is 14 inches long with an outer diameter of 3.84 and inner diameter of 3.682 inches. The upper body tube is bolted to the outside of the coupler about 5 inches from the nose cone. The upper body tube is 5 inches long with an outer diameter of 4 inches and an inner diameter of 3.84 inches. The lower body tube is 33 inches long with an outer diameter of 4 inches and an inner diameter of 3.84 inches.

There are three beveled fins at the end of the rocket and one boattail instead of a motor retainer. The three beveled fins have the following dimensions: root chord of 4.8 inches, tip chord of 1 inch, height of 4.5 inches, and sweep length of 4.3 inches. The thickness of the fins is 0.125 inches. The boattail is a 54 millimeters to 3.9 inch motor retainer. It is 2.5 inches long.

*Center of gravity*

The center of gravity of our rocket is located at 35.758 inches from the top of the rocket.

*Center of pressure*

The center of pressure of our rocket is located at 44.29 inches from the top of the rocket.

*Motor specifications*

Our rocket will be using a J800T AeroTech motor. The J800T is 326.00mm (12.83 inches) long, 54.00mm (2.13 inches) in diameter, and weighs 40.00oz. The thrust duration is 1.8s and has a total impulse 1229.1Ns (average thrust 696.5N). The motor is reloadable and will be used for both launches.

Planned construction solutions and techniques

First, the motor tube was attached to the centering rings. The motor tube and centering rings were sanded, and the bottom two were epoxied onto the motor tube at the correct lengths. The third centering ring was sanded so that the kevlar shock cord could slip in-between the centering ring and the motor tube, forming a loop (Figure

2). The kevlar shock cord and the centering ring were epoxied to the motor tube. The kevlar shock cord serves as the kevlar harness. The motor retainer was epoxied onto the bottom of the motor tube (Figure 3). The boattail was then screwed onto the motor retainer.


Figure 2

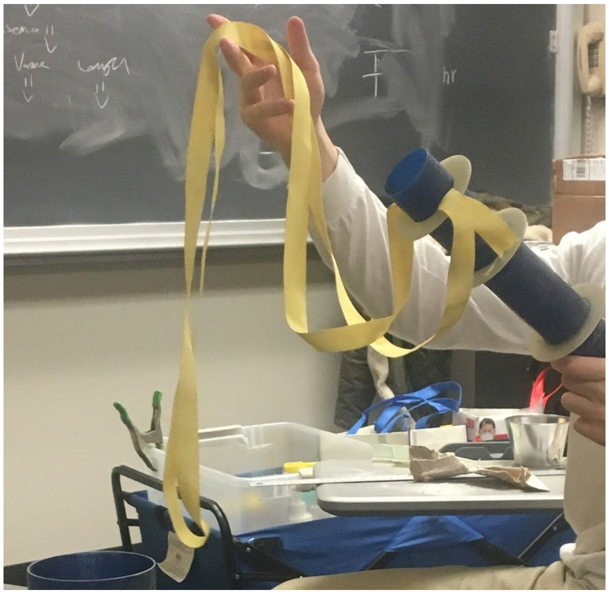
Figure 3

To attach the fins to the rocket, four holes were drilled around the slots for each fin on the lower body tube. The fins were inserted into the slots and tacked with five minute epoxy. After the five minute epoxy dried, a 20 minute epoxy and carbon fiber mix was injected into the slots via the four holes on each fin slot. After the 20 minute epoxy dried, the fins were filleted with rocket epoxy (Figure 4). This ensures that the fins are held securely in place and that they don't break off during flight or during landing.


Figure 4

The nose cone of the rocket came with a metal tip (Figure 5). The metal tip was secured by screwing an eye-bolt into the tip. This eye-bolt allows the parachute to easily quicklink into the nose-cone.

Figure 5

To construct the avionics (AV) bay, eight holes were drilled into the two bulkheads. The first five were drilled colinearly on a diameter of the bulkhead: two 10/24 inch diameter holes placed 0.15 inches from the outer edge, two ¼ inch diameter holes placed 1 inch from the outer edge, and one ¼ inch hole in the center (Figure 6). A U-bolt was screwed in using washers and nuts, and subsequently thread-locked, connecting the two holes placed 1 inch from the outer edge of the bulkhead. A ¼ inch diameter threaded rod was placed in the center hole, which we employed to secure the masses used to simulate our flywheel during test launch. The two 10/24 inch holes were used to hold the 10/24 inch threaded rods that secure the top and bottom bulkheads together. The threaded rods were secured using washers and nuts on the top and bottom of the bulkhead closest to the nose cone. On the other bulkhead, the rods were secured with washers and nuts on the outer side of the bulkhead only. Another ¼ inch hole was drilled 0.25 inches from the edge and 0.25 inches from the line of holes, in which we placed the terminal blocks. This is responsible for holding the cables that connect the flight computers to the ejection charges. The terminal blocks were further secured by drilling two more holes into the bulkhead and screwing in two screws that attached to nuts.

Figure 6

The outer body tube was epoxied onto the avionics bay (Figure 7). Note that the top of the avionics bay is the side that goes into the nose-cone, depicted in Fig. 6. The top of the outer body tube is 3 inches from the top of the avionics bay. This is so the top of the outer body tube lines up with the bottom of the nose-cone.

Figure 7

Next, we drilled 3 static ports 120 degrees apart (equidistant from one another on the perimeter of the avionics bay), that were placed 1.5 inches from the top of the outer body-tube on the avionics bay (Figure 7). We also drilled two holes in the outer body tube so that the cables for the flight computer can exit the rocket.

The rocket was dry-fit and taped together. Three shear pin holes 120 degrees apart were drilled through the nose cone and into the avionics bay. We similarly placed shear pin holes through the lower body tube and into the avionics bay. These holes were then tapped to allow the shear pins a strong hold. This was done so the rocket will stay together during flight but come apart when the ejection charges explode.

Figure 8

Structural analysis of scratch-built parts

To ensure that our rocket's flywheel would function safely and correctly, several stress tests were performed on its components at the weakest and most critical points to simulate how it will perform in-flight. The stress tests were done using Solidworks' Simulation feature on the individual CAD designs of each component in question. The flywheel's motor will operate with an angular velocity of 4300 rpm and a torque of 25.6 mNm (millinewton-meters). We purposefully overestimated these values in our stress test, specifically choosing a running angular velocity and torque of 5500 rpm and 40mNm respectively, to ensure that our parts would perform safely in a wide margin of circumstances. The yield strength of the 1080 aluminum alloy used to model and make the reaction wheel is $2.757 \times 10^{7}$ N/m$^2$. It is not necessary that we test the operational capacity of our reaction wheel motor under thrust because rolling only occurs after burnout.

*Shaft Part 1*

On this portion of the flywheel, two tests were performed. In the first one, a 40 mNm torque was applied to the upper curved surface of the shaft where the shaft of the flywheel couples to the shaft of the motor. The maximum von Mises stress from this torque is $4.908 \times 10^{5}$ N/m$^2$ and occurs at the tip of the shaft where it couples to the motor. This value is approximately 56 times smaller than the yield strength of the component. Additionally, any deformation in the component is negligible (Figure 9).

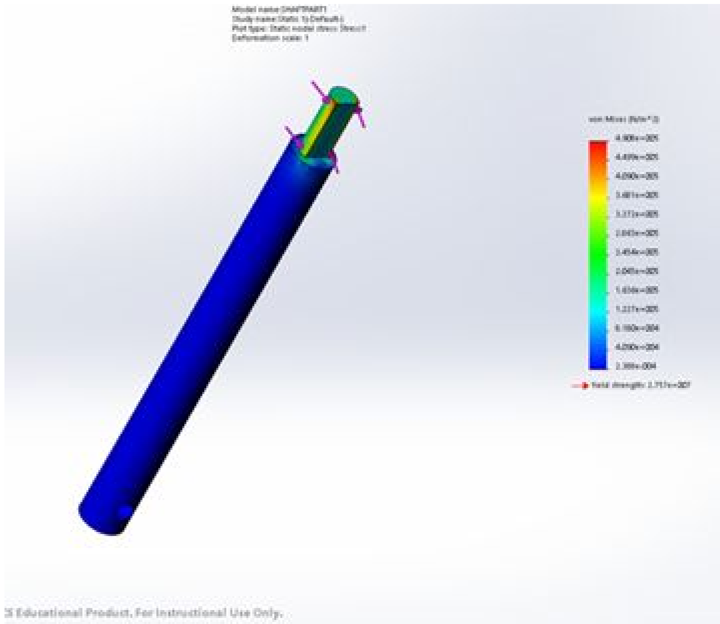

Figure 9: Shaft Part 1 Torque at Couple

In the second test, the same 40mNm torque was applied to the curved faced inlet at the bottom of the shaft where a set screw couples the piece to the next part of the shaft. Von Mises stress from this torque is $1.847 \times 10^{6}$ N/m$^2$ and occurs at the bottom of the portion of the shaft that couples to the motor. This value is approximately 14 times smaller than the yield strength. Additionally, as can be seen, any deformation in the piece is negligible (Figure 10).

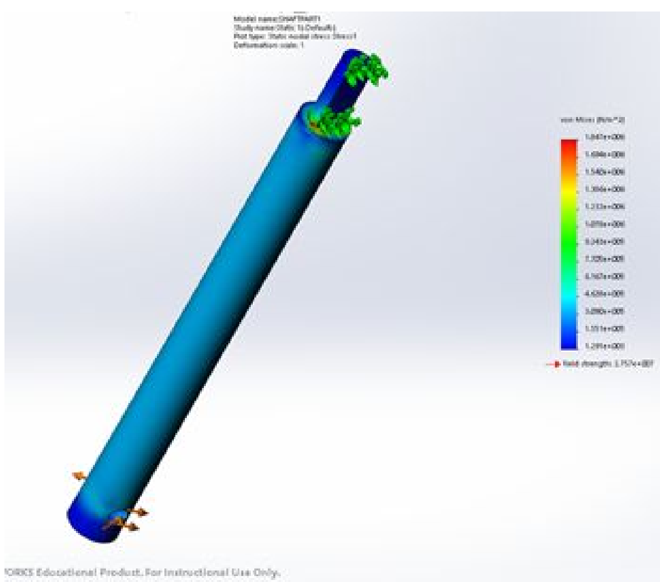

Figure 10: Shaft Part 1 torque at assemble

*Shaft Part 2*

A force was applied on one of the faces of the key slot between the shaft and the flywheel in the flywheel mechanism. This simulates the force that must be delivered by this piece to the key that connects it to the flywheel. This force was calculated by multiplying the 40mNm torque by the distance from the axis of rotation to the key slot. The maximum stress is $4.762 \times 10^{5}$ N/m$^2$. This is approximately 58 times smaller than the yield strength. Additionally, as can be seen, any deformation in the part is negligible (Figure 11).

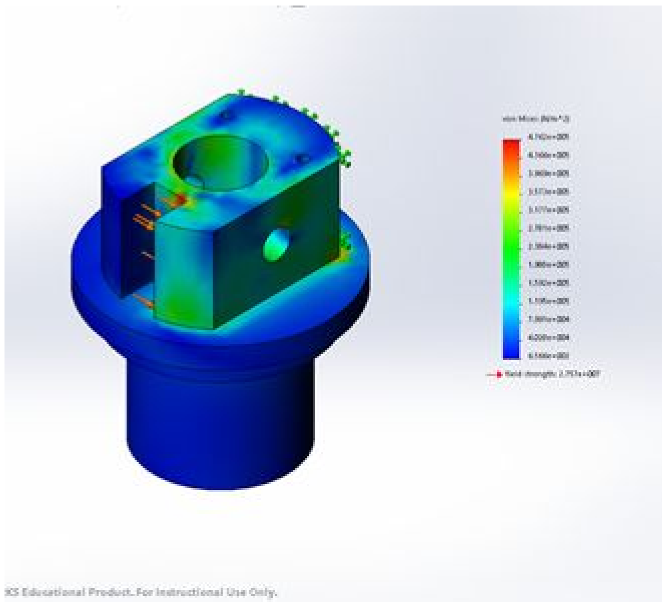

Figure 11: Shaft Part 2 force on Key Slot

*Flywheel*

On this portion of the flywheel, two tests were done. In the first one, a force was applied on one of the faces of the key slot on the flywheel. This simulates the force delivered from the motor spinning the flywheel by way of the key. This force was calculated by multiplying the 40mNm torque by the distance from the axis of rotation to the key slot. The maximum von Mises stress from this force is $1.111 \times 10^{5}$ N/m$^2$ and occurs at the tip of the shaft where it couples to the motor. This value is approximately 248 times smaller than the yield strength of the component. Additionally, as can be seen, any deformation in the component is negligible (Figure 12).

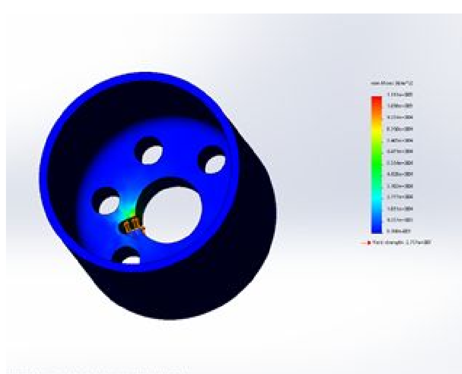

Figure 12: Flywheel force on key slot

In the second test, a centrifugal force was applied to the flywheel. This centrifugal force was simulated with a speed of 5500rpm. The maximum von Mises stress from this force is $1.752 \times 10^{5}$ N/m$^2$ and occurs at the bottom of the portion of the shaft that couples to the motor. This value is approximately 16 times smaller than the yield strength. Additionally, as can be seen, any deformation in the piece is negligible (Figure 13).

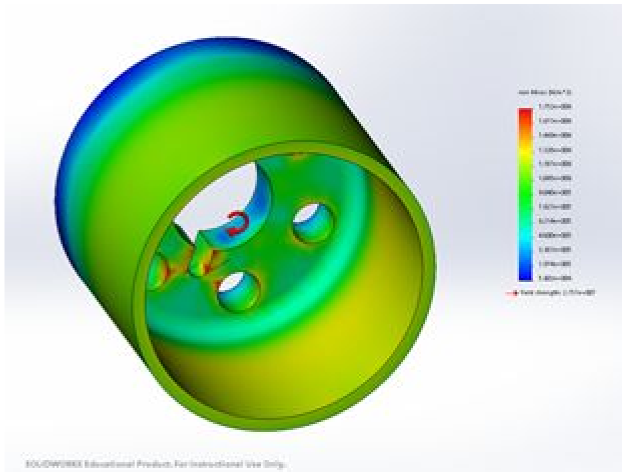

Figure 13: Flywheel centrifugal force from motor

*Motor Housing*

On this piece of the assembly, a force was applied to the bottom of the motor housing where the motor comes in contact with its housing. This force simulates that imparted by the motor on its housing due to the upwards acceleration of the rocket in takeoff. This force was calculated by taking the maximum acceleration from our simulation in OpenRocket multiplied by the mass of our rocket which came to about 116N. The force we used in this simulation was 150N to provide a safe margin of error. The maximum stress from this force is $3.448 \times 10^{6}$ N/m$^2$. This value is approximately 8 times smaller than the yield strength. Additionally, as can be seen, any deformation in this component is negligible (Figure 14).

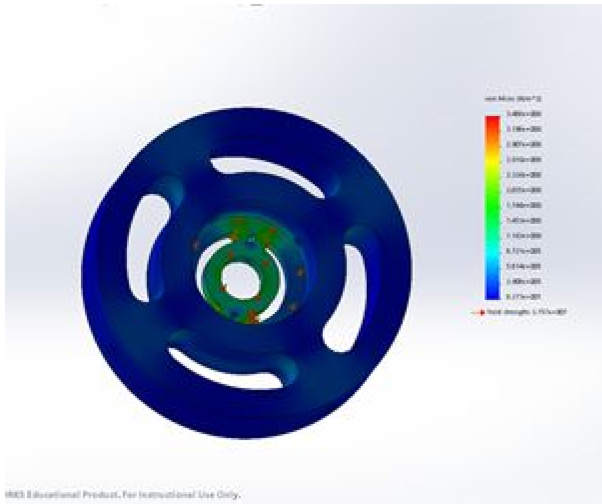

Figure 14: Motor Housing force of flight

In conclusion, all of the most concerning parts of the flywheel can operate in flight without bending, breaking, or deforming within an appropriately large safety margin. No additional changes to the design will be needed to ensure proper functionality and safety.

<u>Risk mitigation analysis</u>

To ensure a safe flight and reduce the amount of risk associated with launching our rocket, the following measures were taken.

| Risk | Mitigated Risk |
|---|---|
| Unstable rocket | • Center of Gravity before center of pressure<br>• Stability above 2.0 cal<br>• Length of the rocket to diameter of the rocket ratio is in between 10:1 and 20:1<br>• Thrust to weight ratio was above 5:1<br>• Flywheel was constructed symmetrically so it would not cause the rocket to wobble |
| Poorly attached fins | • The inserts of the fins were filled with epoxy, and the drying was watched to ensure the fins were safely and straightly attached |
| Parachutes gets burned | • Fireproof material was put in between the parachute and ejection charges so the parachute doesn’t get burned<br>• Parachute was wrapped in Nomex so the parachute doesn’t get burned |

| | |
|---|---|
| Rocket goes ballistic | ● Quick links were used to attach the parachute to the shock cord to make sure the parachutes will remain attached to the rocket<br>● A drogue parachute was used to reduce the descent speed to less than 73 ft/s so that the main parachute doesn’t rip when it is deployed<br>● Two flight computers were used to reduce the possibility of ejection charges not being deployed<br>● Eye-bolts were epoxied and screwed into the metal tip at the nose cone to make sure the nose cone is attached to the shock cord<br>● U-bolts are screwed into the fiberglass bulkheads onto the AV Bay. The nuts are epoxied to the U-Bolt so it doesn’t come off |

**Design Features of Rocket Airframe**

Active roll and angle sensing design

Our rocket utilizes a flywheel to control its roll orientation. The system will be housed in the avionics bay under the flight computer and sensing hardware (described below) and consists of a motor and a feedback system that uses a proportional–integral–derivative (PID) control loop. The PID controller will control the PWM signal sent to the motor controller. Due to the capacitive nature of the motor, the PWM signal will be converted into a analog signal for the voltage across the terminals of the motor, allowing variable speeds and directions to be commanded. This will allow fast, stable control of the flywheel. The feedback uses a BNO055 sensor from Bosch to determine the orientation of the rocket, which will be fed into the PID controller for the next iteration. Since the BNO055 already performs sensor integration from the gyroscopic and accelerometer sensors, it directly gives orientation information.

LED System

The LED is attached to the camera to indicate the orientation of the rocket as it is rising. The LED is red to make it more visible on the camera display. The LED will be mounted on the outside of the camera in view of the downward looking video.

Mounting down-looking video

Adafruit’s Mini Spy Camera was chosen for the rocket because it is light, inexpensive, and simple. Due to the lightweight and durable nature of the camera, we will attach it to the outside of the rocket via tape. It is connected to the rocket’s LED system. The camera will record the orientation of the rocket to compare to the data collected by the feedback system (described below) by filming the LED.

Recovery system specifications

Our recovery system employs the dual deploy ejection of a 24 inch drogue and 48 inch main parachute. These sizes were chosen to allow an adequate descent rate while minimizing drift. We used a Fruity Chutes calculator to obtain these values (given below).

**Design Features of Electronics/Payload**

Avionics design specifications

*Ease of assembly*

To ensure that the AV bay is easily assembled, it can only be accessed via the top bulkhead. This is the bulkhead closest to the electronics. The flight computer and electronics system are encased in an ABS plastic container so that they can easily slide in and out of the AV bay. The flywheel is mounted on a central axle so that it doesn't interfere with the AV bay's supporting rods. The flywheel is closest to the bottom bulkhead which will always remain closed. The nuts on the bulkhead that remains closed are epoxied onto the threaded rods. Finally, a U bolt is attached to the bulkheads so that no extra strain is applied to the supporting rods. This ensures that the AV bay won't come apart mid-flight.

*Flywheel Design*

The flywheel is used to rotate the rocket during flight. The flywheel has four main components: two bulkheads, a shaft, and the actual flywheel (Figure 15). Each component will be described starting from the top (component closest to the nosecone) to the bottom (component closest to the booster). The flywheel will be secured inside the Avionics Bay.

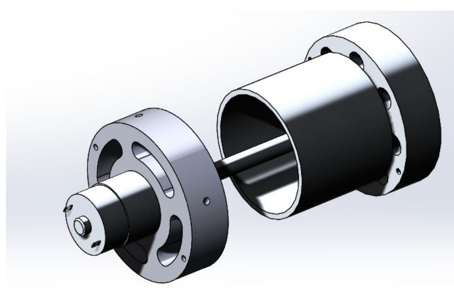

Figure 15

The first component, the top bulkhead for the flywheel, is 6.5 inches away from the bottom bulkhead of the avionics bay and 7.5 inches away from the top bulkhead of the avionics bay. It is going to be bolted through the avionics bay and into the upper body tube. This bulkhead has a cylindrical depression in the center with screws to hold the motor for the flywheel in place (Figure 16). There are four pieces machined out of the bulkhead to reduce its mass. There are two antipodal holes on the bulkhead through which the threaded rods are secured.

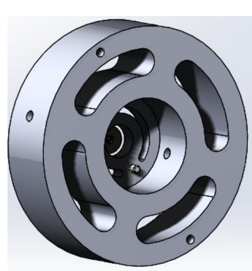

Figure 16: Top bulkhead

The second component is the shaft. The shaft connects the driveshaft of the motor to the center of the flywheel. A coupler clamped around the motor's shaft and the larger shaft connects the two (Figure 17). The larger shaft has a key at the bottom so it can attach to the flywheel.

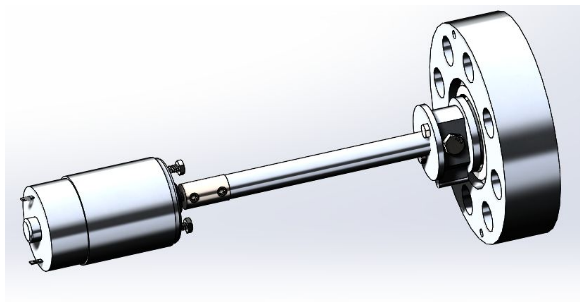

Figure 17: Flywheel Shaft

The third component is the flywheel itself. The flywheel is a hollow cylinder with a disk in the center connecting the cylinder to the shaft (Figures 18 and 19). The disk is located at the very bottom of the flywheel, and has evenly spaced circles around the disk so that weight of the flywheel is reduced. There is a key slot in the center of the disk that fits around the shaft. Most of the weight is distributed around the edge of the flywheel to maximize the moment of inertia to mass ratio.

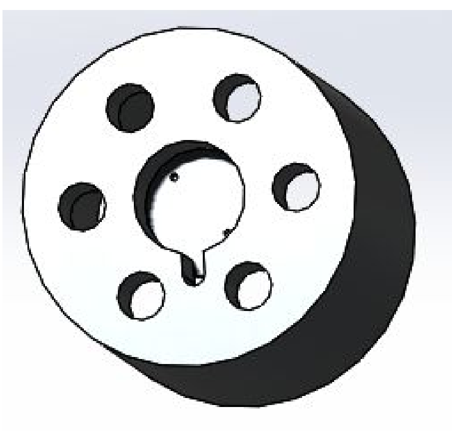

Figure 18: Bottom view of flywheel

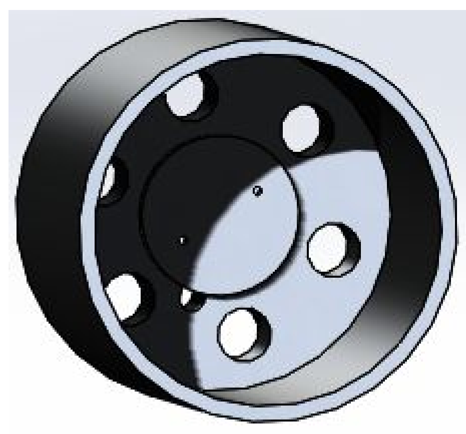

Figure 19: Top view of flywheel

The last component is the bottom bulkhead. The bottom bulkhead has a radial thrust bearing which allows the shaft to rotate in the bulkhead without static or sliding friction. This also stabilizes the shaft from two ends so that the flywheel remains in the center of the rocket. It is crucial that this be the case, so that the flywheel's angular momentum does not influence the rocket to pitch or yaw during use. This bottom bulkhead is also bolted to the bottom avionics bay bulkhead (Figure 20).

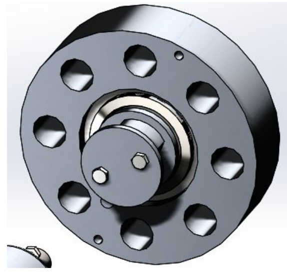

Figure 20: Bottom bulkhead for the flywheel

*Sled layout*
The sled holds the electronics that control the flywheel, as well as the flight computers and the batteries (Figure 24). The electronics that control the flywheel are attached to the middle board, and protrudes outward to the right (Figure 21). The flight computer is attached to the rightmost tall board and protrudes to the right (Figure 21). The flight computers and electronics were attached to the sled by screwing the corners into holes in the sled (Figure 22). The three batteries are held in cup holders and taped down with duct tape (Figure 23). Duct tape was used because we didn't want to have a single point of pressure on the batteries so they don't explode.

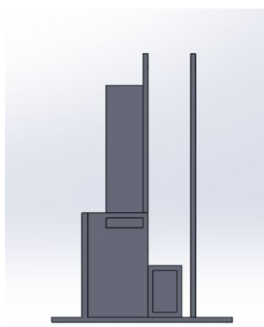

Figure 21

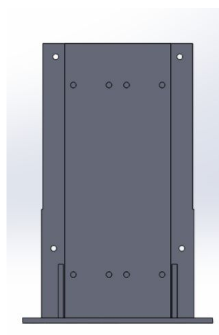

Figure 22

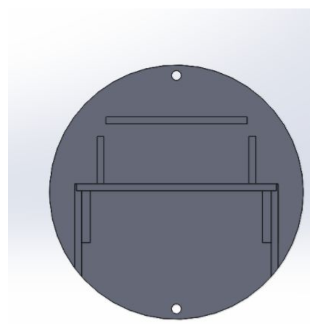

Figure 23

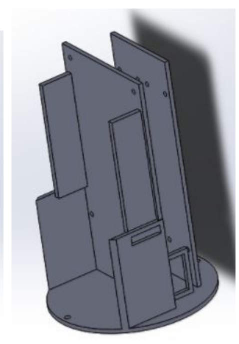

Figure 24

*Power layout*
Two sources of power are provided for the electronics and the roll motor to prevent any noise on the power line for the electronics. A 6 volt, 4 AA power bank is supplied to the board, and this voltage is stepped down to 5V for the electronics board. A 11.8V battery and the motor are connected to the motor controller. Common ground was used for the full design.

*Wiring layout*
The wiring for the flight computer is done on a dedicated printed circuit board (PCB). The BNO055 and BMP280 are connected on a single I2C line to reduce the number of traces that have to be made on the PCB. The GPS is connected to the Teensy over UART1, and the XBee is connected to UART2. UART0 is used for the Serial monitor in Arduino.

*Switch position*
The switch is connected in line with the power to the board. The motor cannot be powered without the board being powered first and the code must be running for any voltage to be supplied. This prevents a

need to source for a high current switch as well as reduces the amount of manual switches that have to be turned on for the electronics to work.

## Payload system specifications

### *Main microcontroller*

We used a Teensy 3.5 because it operates at 150Mhz. It is integrated into Arduino, which allows for easy programming over USB. It also has 48 pins broken out so multiple sensors can be attached to it. The Teensy is also very well supported in terms of libraries and software support. The Teensy 3.5 was chosen over the Teensy 3.6 because it is 5V tolerant. Even though it is slightly slower, the risk of shorting is lower because some sensors that we are using have a 5V logic level.

### *Commercial altimeter*

To measure the altitude of the rocket, we chose the Adafruit BMP280 I2C Barometric Pressure and Altitude Sensor. It has a barometric pressure accuracy of ±1 hPa and temperature accuracy of ±1℃. Combined, the altimeter has an accuracy of ±1 meter. This altimeter was chosen based on the ease of programming and low cost.

### *Motor Control*

The motor for the flywheel is controlled by a PID controller. The proportional (P) aspect of the controller gives an output proportional to the current error by comparing the desired point with the actual/feedback process value. The integral (I) aspect of the controller works to zero the steady-state error - the difference between the process value and the desired value. It does this by integrating the error over time unless the error is zero, effectively driving the steady-state error to zero. The derivative (D) aspect of the controller is proportional to the rate of change of the process value. It causes the control system to speed up its response.

### *Monitor roll angle*

The rotation of the flywheel will be controlled by a 12V electric motor. The motor will be connected to a feedback system. The feedback system will measure the orientation and rotation of the rocket, and use the PID motor to control the rotation of the flywheel. The feedback system will receive information from a 3D orientation system. The Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout (BNO055) was chosen for orientation data collection because it has an onboard MCU that integrates pace orientation data in Euler vectors, angles, and quaternions by combining accelerometer, magnetometer, and gyroscope data. Thus, it greatly simplifies calculations. This offloads processing from the main controller and allows us to obtain a faster control loop.

The orientation of the rocket will be visually confirmed with video recorded by a downward-facing camera flanking the rocket.

### *Radio Power*

The 5V Step-Up/Step-Down Voltage Regulator S7V7F5 from Pololu was used because it was a cheap 5V power supply that accepts a range of input voltages. It is cost effective and has a small footprint.

*Motor Power*
In order to power the motor, we chose the VNH5019 Motor Driver Carrier from Pololu. We chose this driver for a brushed DC motor because the motor was specced at 12V and 2A stall. This driver can draw up to 13A continuously, so it is suitable for our chosen motor, with a factor of safety of 6. This ensures that additional modifications such as overvolting the motor or using a motor with a higher stall current can be performed without having to change the driver.

*GPS*
To record altitude, velocity, and positional data, we chose the Ultimate GPS Breakout V3 from Adafruit. We chose this GPS device because of its tracking and acquisition sensitivities (-165 dBm and -145 dBm, respectively). Additionally, the Ultimate GPS has a better positional accuracy and similar velocity accuracy when compared to other GPS devices like the Sparkfun GP20U7.

**Analysis of the Anticipated Basic Flight Performance**

The analysis of the anticipated flight performance was done in two ways: test launching the rocket and using rocket simulations. The rocket simulation was employed to make sure that the rocket would reach the required apogee while also staying within required rocket safety standards such as having a center of gravity in front of the center of pressure. Our test launch ensured that the physical rocket was built correctly, and that its recovery system performed appropriately.

Simulated flight analysis
Even though our rocket was built on OpenRocket, Rasaero was used to simulate the rocket because it is more conservative on maximum altitude and it let us insert a boattail.

*Estimated maximum altitude*
Rasaero software was used to simulate the maximum altitude of the rocket. Rasaero estimated that the rocket's apogee would be 3,108 feet using a 54mm to 3.9 inch boattail that is 2.5 inches long.

*Estimated peak velocity*
Rasaero software was also used to estimate the peak velocity of the rocket. The peak velocity of the rocket on Rasaero was 449.1 ft/second.

*Estimate peak acceleration*
Rasaero software calculated a maximum acceleration of 300.5 ft/second$^2$.

*Estimated descent speed*
OpenRocket simulated the descent speed for the rocket to be 20.8 ft/second. OpenRocket was used for simulating the descent speed because Rasaero has difficulty importing specific parachutes.

Test launch analysis
The rocket was test launched on February 25 in Richard Bong State Park. The flywheel was not tested during this flight; rather, it was simulated with a 5 pound mass centered about the central axis using a threaded rod.

The conditions were very windy, and a J800T motor was used for the test launch. Despite these conditions, the rocket still had an apogee of over 2700 feet. Even though the rocket needs to go 300 more feet, we are confident that it will achieve that since our flywheel will be lighter than anticipated. In addition, our stability is high enough that losing some weight won't be an issue. The following values were also recorded by our flight computers:

Maximum altitude: 2756 ft.

Peak velocity: 400 ft/s

Peak acceleration: 150 ft/$s^2$

Recovery analysis

The rocket test launch also tested how well the recovery system worked. A dual deploy system was used to ensure that the main parachute was not shredded when it was deployed. The dual deploy method worked: our rocket descended at 22 ft/s, which is within the descent speed limit set by the competition. This showed that the flight computers worked and that the ejection chargers were the correct mass. In addition, this test launch showed that our rocket could be launched safely to almost the required height. For the future, we are working on reducing the weight of the rocket so that it flies over 3000 feet.

Stability analysis

The stability of the rocket was calculated using OpenRocket. To ensure the rocket's stability, the center of gravity lies in front of the center of pressure throughout the entire flight. In addition, the stability is always above 2.00 cal. With the motor, the stability was calculated to be 2.13 cal. Without the motor (after burnout), the rocket has a stability of 2.78 cal. The flywheel was designed to be symmetrical so that its flight path is more likely to stay with the axis of symmetry. The fins are long enough to provide leverage so that the rocket can correct its flight path if it does deviate from the flight path. The rocket also has a thrust to weight ratio of 10:1 to ensure a safe flight.

Environmental conditions analysis

The conditions on the day of the test launch were windy. The winds were blowing at 25 mph from the west with 30 mph gusts. This, in addition to our launch rod being angled away from spectators, caused our rocket to fly at a 25 degree angle from the launch pad. In addition, it was sunny and cold on the day of the launch. The sun meant that we had to be more diligent to make sure we could see the rocket as it was descending. The cold meant that we had to keep the batteries for the flight computer warm so that our parachutes would deploy. We kept the batteries in the warm car until they were inserted into the avionics bay.

## Safety

The team safety officer is Judy Lubin, who has a level 3 certification. She will ensure that all launch vehicles and components are properly assembled and used according to protocol. She will also assist in mitigating and identifying potential risks. During launches, the safety officer will provide a list of safety procedures to follow concerning the safe handling of all launch vehicles. If the safety officer is unable to attend an event, another safety officer will be appointed for the event.

Designed for safe flight and recovery

The rocket is designed for safe flight because our stability is above 2.00 cal. The stability with the motor is 2.13 cal. The stability after motor burnout is 2.78 cal. In addition, the rocket was built so that the center of gravity is in front of the center of pressure. The flywheel was designed to be symmetrical and almost on the center of gravity so that the rocket is more likely to stay on the flight path. This means the rocket is more stable and will have a safe flight. The ejection charges used to deploy the drogue and main parachutes were also tested on the ground. This is to make sure the charges can blow the nose cone and booster off so that the parachutes can deploy, ensuring that the rocket won't come down ballistic.

The rocket is also designed for safe recovery. It has two flight computers so that both control the ejection charges just in case one of the flight computers fails during flight. In addition, the drogue and main parachutes were chosen so that the descent speed for the drogue did not exceed apogee rocket's recommended descent speed of 50 mph (73.3 ft/s). The descent speed for the 24 inch diameter classical elliptical parachute is 58.22 ft/s which was found by using Fruity Chutes' online parachute descent rate calculator. This was chosen so the main parachute doesn't shred. The main parachute was chosen so that the descent speed wouldn't exceed 24 ft/s, which is required by the competition. The descent speed with the 48 inch diameter Iris Ultra compact parachute was calculated to be 23 ft/s. However, this descent speed was calculated on Fruity Chutes' parachute descent rate calculator and doesn't take into account the fact that the drogue parachute slows it down. OpenRocket simulated the descent rate to be 21 ft/s. These features will allow us to safely launch and retrieve a high-powered rocket.

Material-handling procedures

To ensure that all materials were handled in a safe manner, all of the fiberglass for the body-tubes, coupler, and nose cone were cut by the manufacturer (Figure 25). NUSTARS members did sand some of the fiberglass parts down. However, they always wore face masks and gloves so they didn't get fiberglass in their lungs or fiberglass splinters. When epoxying the parts together, the fiberglass was sanded and then cleaned with rubbing alcohol to ensure the best epoxy connection. In addition, all parts were epoxied in a well-ventilated room with all parties wearing face masks and protective eyewear. All of the materials when not being used or built are stored in a secure room that requires key-card access. The motors are ordered from Wildman, who brings them to our launch site so we don't need to store any of the motors on campus or assemble any motors which could be potentially hazardous. Any black powder used in the ejection charges was handled by our mentor, who has a Tripoli Level 3 certification to ensure that dangerous explosives were handled safely.

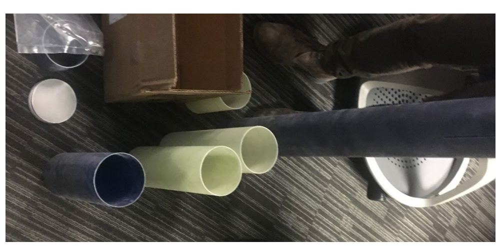

Figure 25

Planned pre-launch procedures

Inspection

- Check shock cords for rips and black powder burns
- Ensure all wires are securely connected to terminal blocks.

- Check the fins for damage
- Check the body tube for damage
- Make sure the quicklink is attached to the eyebolt

Pre-launch prep

- Wiring Flight Computers
    - Color scheme
        - Red: Power
        - Orange: Drogue (body tube, down)
        - Green: Main (nosecone, up)

- Main wires
    - Cut wire for the main (long enough to come out)
    - Make the ends of the wire into loops
    - Insert one loop into the main spot on the flight computer
    - Screw it down
    - Pull on it to make sure it is really tight
    - Repeat three times until all of the ones are in the main spot
    - Wrap the two main wires on each side together

- Drogue wires
    - Cut wire for the drogue (long enough to come out)
    - Make the ends of the wire into loops
    - Insert one loop into the drogue spot on the flight computer
    - Screw it down
    - Pull on it to make sure it is really tight
    - Repeat three times until all of the ones are in the drogue spot
    - Wrap the two drogue wires on each side together

- Switch wires
    - Cut wire for the switch (long enough to come out)
    - Make the ends of the wire into loops
    - Insert one loop into the power spot on the flight computer
    - Screw it down
    - Pull on it to make sure it is really tight
    - Repeat three times until all of the ones are in the drogue spot
    - Wrap the two switch wires on each side together

- Prepping motor (if applicable)
    - Change delay to 10-12 seconds

- Parachutes
    - Fold parachutes

    - Bundle the shock cord for the drogue

- Testing the Flight computers
    - Connect the flight computer's batteries to the flight computers
    - Touch the two main wires together for the primary flight computer
    - Touch the two drogue wires together for the primary flight computer
    - Touch the two switch wires together for the primary flight computer
    - Listen for three beeps (takes some time)
    - Repeat for the secondary flight computer

<u>Planned assembly procedures</u>

At the launch:

- Prepping motor (if applicable)
    - Change delay to 10-12 seconds
    - Assemble motor
    - Put motor into the rocket
    - Screw on the boattail
- Avionics bay
    - Test the voltage of the 9 Volt batteries
    - Attach the batteries to the sled flight computers
    - Secure the batteries onto the sled
    - Stick main and drogue wires out of the bulkhead and into the terminal block
    - Seal up the wire hole (because don't want gas going into the AV bay)
    - Put switch wires out of the holes (wires not touching each other)
    - Screw the threaded rods together

- Nosecone and AV bay assembly
    - Prep two 3 gram ejection charges
    - Hook ejection charges up to the terminal block
    - Quicklink the main parachute to the shock cord
    - Quick link the main shock cord to the eye bolt in the nose cone
    - Quick link the main shock cord to the U-bolt on the top of the AV bay
    - Put the shock cord into the nose cone
    - Main parachute
        - Put the tracker on the shock cord
        - Quick link the nomex and the shock cord to the main parachute
        - Remove the tap from the nomex
        - Put the shock cord into the nose cone
        - Put the parachute in (cords pointing out)
    - Shear pin the nose cone and the AV bay

- Lower body tube and AV bay assembly
    - Prep two 4 gram ejection charges

- Hook ejection charges up to the terminal block
- Quick link the shock cord to the Kevlar harness
- Quick link the shock cord to the bottom of the AV bay
- Drogue parachute
    - Quick link the nomex and the shock cord to the drogue parachute
    - Remove the tap from the nomex
    - Put the shock cord into the nose cone
- Put the parachute in (cords pointing out)
- Put the shock cord into the booster
- Add 4 large handfuls of dog-barf
- Shear pin the lower body tube and the AV bay

On launch pad:

- Slide the rocket onto the launch rail
- Flight computers
    - Twist the main power wires together
    - Listen for the 3 beeps (one long beep, three short beeps)
- Set the igniter

Post-launch procedures

- Once the rocket has safely landed, use a GPS tracker gun to locate and retrieve the rocket.
- Carefully return the rocket back to "home base" and start the disassembly process. Be cautious about any residual black powder. Make sure to pop out shear pins.
- Detach all wires and record altitude from altimeters.
- Rub down the entire rocket with denatured alcohol. Dispose of the black powder charges in a safe manner.
- Dispose of any trash and clean up the assembly/disassembly area.

## Budget

Rocket-related

| Item | Material | Dimensions (inches) | Quantity | Cost ($) |
|---|---|---|---|---|
| Nose Cone | Fiberglass | Length: 16.5 ID: 3.90. OD: 4.00 | 1 | 69 |
| Upper Bay | Fiberglass | Length: 3. OD: 4. ID: 3.843 | 1 | 0 |
| Coupler | Fiberglass | Length: 14. OD: 3.843. ID: 3.685: 4 inch coupler | 1 | 36.4 |
| Lower Bay | Fiberglass | Length: 32.75. OD: 4. ID: 3.843 | 1 | 93.4 |
| Motor Tube | Fiberglass | length: 13. ID: 2.142. OD: 2.3 | 1 | 170 |
| Fins | Fiberglass | | 3 | |
| Bulkheads | Fiberglass | Diameter: 3.685. Thickness: 0.079 | 3 | 6 |
| Centering Ring | Fiberglass | Thickness: 0.15. OD: 4.843. ID: 2.3 | 3 | 7 |
| J800T Motor | | | 1 | 94.99 |

| | | | | |
|---|---|---|---|---|
| Main Chute | Nylon | Diameter: 48.0. Packing: 14.6 (inches cubed): 1.8 d by 5.7 l | 1 | 197 |
| Drogue Chute | Nylon | Diameter: 18.0. Packing 6.44 (inches cubed): 1.6 d by 3.2 l | 1 | 60 |
| Motor Retainer | Aluminum, anodized | 54 mm to 3.9 inch | 1 | 37 |
| | | | **Total:** | 796.79 |

Transportation

| **Type** | **Description** | | **Quantity** | **Cost ($)** |
|---|---|---|---|---|
| Van Rental | Bong, WI, test launch | Gas, tolls | 2 | 500 |
| Van Rental | Minnesota, comp launch | Gas, tolls | 1 | 1500 |
| Housing | Hotel for comp. | | 1 | 5000 |
| Food | Groceries | | 1 | |
| | | | **Total:** | 7000 |

*Flywheel materials (ex: aluminum) are offered by Northwestern's on-campus machine shop and were not bought by the team.

Electronics-related

| **Item** | **Type** | **Description** | **Quantity** | **Cost ($)** |
|---|---|---|---|---|
| XBee Radio | Radio | XBee Pro 60mW Wire Antenna - Series 1 (802.15.4) | 2 | 37.95 |
| XBee Board | Radio | SparkFun XBee Explorer Regulated | 2 | 9.95 |
| Motor Driver | Motor | VNH5019 Motor Driver Carrier | 1 | 24.95 |
| Motor | Motor | Mabuchi 555 | 1 | 5.95 |
| Camera | Camera | Adafruit Mini Spy cam | 1 | 12.50 |
| GPS module | GPS | Adafruit Ultimate GPS Breakout - 66 channel w/10 Hz updates - Version 3 | 1 | 39.95 |
| Pressure Sensor | Sensor | Adafruit BMP280 I2C or SPI Barometric Pressure & Altitude Sensor | 1 | 9.95 |
| Orientation Sensor | Sensor | Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055 | 1 | 34.95 |
| MCU | MCU | Teensy 3.5 | 1 | 24.50 |
| Voltage Regulator | Power | Pololu 5V Step-Up/Step-Down Voltage Regulator S7V7F5 | 1 | 4.95 |

| | | | | |
|---|---|---|---|---|
| PCB | PCB | PCB | 1 | 15 |
| | | | Total | 278.55 |

Grand total: 8075.34

**Required Mentor Report Form**

**Northwestern University Mentor report**

**Completed by Judy Lubin, L3 NAR (88698) and Tripoli (12919)**

**Judy@Lubin.net**

**PDR, March 8, 2018**

**1) Briefly describe your interactions with the team to date – how many meetings, in person or remotely, how much time spent, topics discussed**

I have met with the team 4 to 5 times, attended their test launch, and had email discussions with team leaders. I went through several iterations of review of their design file, and I met with them in my shop to go over basic construction techniques. Team members also came to my shop to work on some aspects of the construction and to ask questions throughout the process. I reviewed the construction and prep of the rocket the day before the test launch, and I was with the team at the launch.

The team's project manager and chief engineer both have Level 1 certs. Both are also very open to admitting what they don't know and are willing to ask questions.

**2) How familiar are you with the team's rocket design (which might still be evolving) and what safety concerns do you have about it, if any?**

I will answer question 2 and 3 together.

As noted above, I am familiar with the team's design, construction and launch prep. I have not yet seen the roll control system, as the test launch was done with an equivalent mass. I have also not seen the data logging system, nor any X-Bee communication system (if this will be used).

The only outstanding issues that I have come from the test launch. I have reviewed these with team members, and expect the issues to be fixed by the time of the competition.

The rocket cocked a bit into the wind. It was a windy day and, although other rockets flown that day flew straight, theirs may have caught an exceptionally strong gust of wind. Stability at the test launch was over 2 calibers and thrust to weight ratio was around 10. I have discussed the result with the team engineer, and we agree that the causal factor was the wind. Secondly, main popped at apogee. I discussed potential reasons with the team engineer. Of the possibilities, the two most likely are that a charge may have been wired incorrectly (drogue to main) or that the drogue charge was too forceful. He will review the wiring. If this does not lead to an explanation, he will lower the drogue charge and re-ground test.

**3) How familiar are you with the team's rocket build (THIS MIGHT STILL BE IN THE FUTURE - IF SO, YOU CAN SKIP THIS QUESTION) – in particular, did you see it (or at least photos of it) as it progressed <u>before it was flown for the first time</u> – and what safety concerns do you have about it, if any?**

See Question 2.

**4) Do you have any suggestions about how to improve your interaction with the team going forward? (This feedback will be shared with your team, and possibly with other teams and their mentors too.)**

I really appreciate this questionnaire. By including these questions in the team's required paperwork, you have made it easier for me to involve myself in the process. Thank you!