NUSTARS

NORTHWESTERN UNIVERSITY SPACE TECHNOLOGY AND ROCKETRY SOCIETY

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Rocket Design

<u>Design and Dimensions</u>

Figure 1: OpenRocket representation of competition rocket.

Dimensions of the rocket

The rocket is 4 inches in diameter with a total length of 58 inches. The rocket is 58 inches long because the length should be 10-20 times the diameter. Our diameter to length ratio is 1:14.5, 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 boat-tail 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 34.813 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 326.00 mm (12.83 inches) long, 54.00 mm (2.13 inches) in diameter, and weighs 40.00 oz. The thrust duration is 1.8s and has a total impulse 1229.1 Ns (average thrust 696.5 N). The motor is reloadable and will be used for both launches. The thrust curve is located in the Appendix.

Materials

The nose cone, AV bay, upper body tube, fins, and lower body tube are all made out of fiberglass. The bulkheads are made out of aluminum. West Point epoxy was used during rocket construction.

Construction 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 and is quicklinked to the drogue's parachute cord. The motor retainer was epoxied with West System 105 Epoxy (which was used throughout the construction of the rocket) onto the bottom of the motor tube (Figure 3). The boattail was then screwed onto the motor retainer.

Figure 2: Loop Figure 3: Epoxied motor tube

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: Filleted fins

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. The parachute is then quicklinked to a shock cord that connects to the top bulkhead's U-bolt—linking the whole system together.

Figure 5: Nose cone and metal tip

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 into one bulkhead, and subsequently thread-locked, connecting the two holes placed 1 inch from the outer edge of the bulkhead. An eyebolt was screwed into the center other bulkhead and treadlocked in place. 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: Bulkhead with U-bolt

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: Avionics bay

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 (Figure 8). 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: Coupled nose cone and avionics bay

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 2.37 cal. After burnout, the rocket has a stability of 3.21 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.

Constructed for Safe Flight and Recovery

The rocket is designed for safe flight. Our stability of 2.37 cal, calculated with OpenRocket, is above 2.00 cal. The stability after motor burnout is 3.21 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 tested on the ground to ensure the charges can blow the nose cone and booster. This lets the parachutes deploy correctly, 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. 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. This corresponds with the average descent rate from the test launch.

AV-Bay Design

The avionics bay has two main sections: the sled and the flywheel. The top of the AV bay (section closest to the nose cone) holds the electronics, flight computers, and batteries inside of the sled. The sled was made so only one side of the AV-Bay needs to be opened for reassembly. The bottom of the AV bay holds the flywheel. The flywheel and the sled are separated by an aluminum bulkhead which holds the motor for the flywheel.

The sled holds the electronics that control the flywheel as well as the flight computers and the batteries (Figure 9). The electronics are attached to the middle board and protrude outward to the right (Figure 10). The flight computer is attached to the rightmost tall board and protrudes to the right (Figure 10). The flight computers and electronics were attached to the sled by screwing the corners into holes in the sled (Figure 11). The three batteries are held in cup holders and taped down with duct tape (Figure 12). Duct tape was used because the alternative, zipties, create a single point of pressure on the batteries may cause explosion. There are two nuts that will prevent the sled from moving too far down the threaded rods and hitting the motor.

Sled model and final product

Figure 9 Figure 10 Figure 11 Figure 12

The flywheel is used to rotate the rocket during flight. The flywheel has four main components made out of aluminum: a motor housing, a radial thrust bearing housing, a shaft, and the actual flywheel (Figure 13). Each component will be described starting from the top (component closest to the nose cone) to the bottom (component closest to the booster). The flywheel will be secured inside the Avionics Bay by drilling holes through the side of the AV bay. Screws will be inserted into the sides of the housing to ensure the motor housing doesn't move up and down. Additionally, there are two holes in the two housings for the threaded rods to pass through. The radial thrust bearing housing also has two nuts on the threaded rods to hold it down.

Figure 13: Assembled flywheel

To ensure that the entire AV bay was made robustly and can withstand a launch, we also let the AV bay, electronics, and flywheel fall off the side of a three story building with a small parachute. Not only did the flywheel and AV bay survive the trip, the electronics did as well.

<u>Changes Since PDR</u>

The main change since the PDR is that the LED lights for the active roll system will be secured to the AV bay and connected to the electronics during rocket assembly instead of trying to poke the LED lights through the holes in the AV bay. This makes assembly significantly easier. In addition, one of the bulkheads in the AV bay uses an eye bolt to attach the drogue parachute to the coupler. Finally, the upper body tube was lengthened which made the rocket longer and raised the stability as well as increasing the distance between the center of gravity and the center of pressure.

Rocket Operation Assessment

Launch and Boost Phase Analysis

The rocket had a great launch phase. It came off the launch pad relatively straight and the motor functioned well. The motor stayed in the motor tube and the LED lights and camera stayed on the rocket during the launch phase.

Coast Phase Analysis

The rocket will have 15.1 seconds to apogee, which means 12.1 seconds of coasting according to the simulation when there are 15 mph winds. This means that the rocket will have 12.1 seconds to roll during the competition.

During the test launch, burnout took around 2.5 seconds. The flight time until apogee was 18.45 seconds. The rocket had 15.95 seconds to rotate before drogue deployed. The OpenRocket Simulation for the K500 motor predicted that the rocket would have 18.2 seconds until apogee with a motor burn out of 2.5 seconds. The simulation was under the actual time by 1.37%. Therefore, it is reasonable to assume that during the competition, the rocket will have 15.3 seconds to apogee with a coast time of 12.3 seconds. 15.3 seconds was found by multiplying 15.1 by 1.0137 (the scaling factor corresponding to the ratio between the simulation and the results of the test launch).

The rocket did not move off its flight path too much. It wasn't until after the rocket was recovered that it was discovered that the SD card was completely broken which caused the code that would rotate the flywheel to malfunction. Given that it worked during the tests before the flight, it was determined that the SD card must have broken during transit in the two-hour drive to the test launch site in Michigan.

Recovery System and Descent Phase Analysis

The recovery system deployed correctly during the test launch. Drogue deployed at apogee, and the main deployed 700 feet from the ground. The descent rate after the main parachute deployed was measured by two different flight computers to be 25 and 23 ft/s. This produces an average descent speed of 24 ft/s, which is within the safety limit of 24 ft/s. The drogue descent rate was between 51 and 54 ft/s. This averages to a descent rate when the drogue parachute was deployed of 52.5 ft/s. The result was a very successful recovery of all of the pieces of the rocket and a safe descent.

Pre- and Post-Launch Procedure Assessment

The pre-launch procedures worked pretty well. The assembly time of the rocket was cut in half from the first test launch. However, it still took about 45 minutes over the one hour limit. This is due to difficulty threading wires through the avionics bay, so we can easily cut down on this time by "preloading" parts of the bay like the flight computer and electronics before arriving to the launch site. With this change and more practice with other parts of assembly, we will be well within the one hour time limit.

Active Roll System

Our active roll system, a flywheel, works by utilizing the conservation of angular momentum. The conservation of angular momentum states that if the flywheel rotates in one direction, the rocket must rotate in the opposite direction with the same amount of momentum so angular momentum is conserved. We can use this principle to induce a rotation in one direction to counteract a rotation in the other and, by "balancing" the natural roll of the rocket and the counter-rotation created by the spinning flywheel, we should be able to reach a point where our rocket does not roll.

The active roll system was implemented using a PID controller. The PID system was given a desired orientation and recorded the error between that orientation and the current one. The PID control corrected for the error by applying a control signal to the flywheel motor. This was calculated by summing terms that were proportional to the error, the derivative of the error, and the integral of the error. The orientation of the rocket is monitored by a BNO055 gyroscopic sensor which allows us to obtain the orientation changes of the rocket by monitoring how the Arduino/sensor rotates. Additionally, we are able to transmit this data via XBee 802.15.4 to a "ground station" interpreter to monitor the orientation data remotely during testing.

The active roll monitoring system performed pretty well during the end of ground testing. However, tuning the PID constants took a while. To tune the PID constants, we hung the AV bay from the ceiling and tested different values. We also attached the booster of the rocket with some extra weight to the AV bay so we could calibrate the PID values with the weight of the actual rocket. It took a lot of time and a lot of different values, but in the end, it was able to oscillate to approximately zero. The rotation angle became zero once we took the batteries out of the AV bay. Making the AV bay rotate a certain amount became easier once the PID system was tuned. The main thing that we needed to test once the PID system was tuned was when the flywheel needed to start accelerating in the opposite direction. Another problem that we faced was getting the flywheel to make the AV bay rotate a certain amount, but this problem was again solved by experimental testing and fine tuning of the program.

In order to monitor our orientation during the flight, there are three LED lights in a row on the outside of the AV bay (Figure 14). When the left LED light is on, it indicates that the rocket is trying to rotate to the left. When the center LED light is on, it indicates that the rocket is not trying to rotate. When the right LED light is on, it indicates that the rocket is trying to rotate to the right. The camera is attached to the AV bay above the LED lights to provide a video confirmation of how the rocket is rotating.

Figure 14: LED system to display rotation

Photographs of Completed Rocket and Test Flights

Test Flight Report

Flight Performance

The second test flight was semi-successful. The rocket was assembled faster than the first test flight. However, the rocket assembly still took about one hour and forty-five minutes. The rocket launched successfully and didn't move too far off its flight path. However, the SD card was broken so the code to rotate the flywheel didn't actually run. This means the flywheel wasn't rotating during the launch. The SD card breaking also meant the code to run the camera didn't work either. All of the electronics and the flywheel still worked after the flight when the SD card was replaced. This means the electronics can survive a rocket launch and still work. The main parachute deployed at 700 feet and the drogue parachute deployed at apogee. The parachute system worked perfectly and resulted in a safe average landing speed of 24 ft/s according to the data collected from the flight computers (Appendix).

Recovery System Performance

Our recovery system functioned as expected. The drogue parachute deployed at apogee and slowed the rocket down to either 51 or 54 ft/s (the two flight computers had different data). This produces an average descent rate of 52.5 ft/s when the drogue was deployed. The main parachute deployed correctly around 700 feet. One flight computer gave a descent speed of 23 ft/s; the other gave a descent speed of 25 ft/s. These values average to 24 ft/s, which is on the boundary of the safe descent speed criteria. To ensure that the descent speed is below 24 ft/s during the competition, the main will deploy around 800 feet instead of 700 feet. Finally, trackers were used to help find the rocket more easily after the rocket landed. These worked relatively well and reduced our recovery time significantly.

Table of Flight Characteristics

Mass

The mass of the rocket is 200 ounces.

Motor

The motor being used for the competition is J800T. However, there were no J800T motors in stock during the entire month before the test launch due to a country-wide motor shortage. Thus, the motor used during the test launch was a K500 which had an impulse close to the J800T. For the Test flight results, OpenRocket simulations compared with the actual test flight data were used to give a better estimate for the rocket's behavior during the competition.

Maximum Altitude

The maximum altitude from the test flight was 6131 feet.

Maximum Velocity

The maximum velocity from the test flight was 747 ft/s.

Ascent Time

The ascent time of the rocket was 18.45 seconds.

Presentation

Roll angle vs. time

Figures 15, 16, and 17 show three different trials of ground testing for the flywheel's active roll system. While the active roll system failed due to a faulty SD card during the test launch, we were able to test the flywheel by hanging it from the ceiling. Figure 15 shows the angle of rocket rotation vs. time during one of the failed tests (before the PID was configured correctly). It barely approached a stable 0 radian of rotation value. The plateau of 0 radians is because we turned the rotation system off. The negative angles are caused by the flywheel rotating in different directions.

Figure 16 shows a more accurate PID oscillation. To get this data, we physically rotated the AV bay off center to force it to self correct. The roll angle oscillates above and below approximately zero for about 3 seconds before settling around an angle of 0 radians. Like in Figure 15, it plateaus at exactly 0 at the end, which is caused by the battery being removed. The negative angles are caused by the flywheel rotating in different directions.

Figure 17 also is oscillating above and below 0 radians, but it settles around 0 radians much faster than Figure 16. It only took Figure 17 around 2.5 seconds to settle. This is because the PID values were better for the data from Figure 17 than the data in Figure 16. The negative angles are caused by the flywheel rotating in different directions. The angle starts out as negative because the orientation we physically started the rocket at in Figure 17 was in a different direction from Figures 15 and 16.

Figure 18 shows one ground test for the flywheel rotating to a specific angle (0.5 radians in this case). This was done after most of the PID tuning occurred, which made it easier to control. The data started out at 0 degrees and then accelerated until it reached around 0.25 radians. The flywheel then began to de-accelerate until the rocket reached an angle around 0.5 radians. The flywheel de-accelerated so the rocket would de-accelerate and not pass the 0.5 radian angle.

Figure 15: Large oscillations until manually killing the battery at ~2.6 seconds

Figure 16: Response to manual offset of +0.7 radians

Figure 17: Response to manual offset of -0.7 radians

Figure 18: Attempt to rotate rocket 0.5 radians

Roll angle vs. What Rocket should be doing

The roll angle of the rocket after the PID system was tuned matched up with what the rocket should have been doing for those tests. The data for Figure 15 was from before the PID system was tuned and very clearly did not do what it was supposed to do. Figure 15 was supposed to do what Figures 16 and 17 did: oscillate from a positive to a negative angle until the rocket reached around zero. Figure 15 went from rotating to 0.9 radians back down to approximately -0.9 radians. The negative and positives in the data indicate rotation direction.

The roll angle of Figure 16 did what it was supposed to do. The flywheel turned so the rocket rotated to around 0.8 and then damped until it reached approximately 0. This is consistent with what the rocket was programmed to do: the rocket had to self correct until it reached its starting point. The negative angle corresponds with the rocket rotating in a specific direction.

The roll angle of Figure 17 did what it was supposed to do. The flywheel turned so the rocket rotated to around 0.6 and then damped faster than Figure 16 until it reached approximately 0. This is consistent with what the rocket was programmed to do: the rocket had to self correct until it reached its starting point. The negative angle corresponds with the rocket rotating in a specific direction. Figure 17 started off in a different direction than Figures 15 and 16, which is why it starts oscillating in the negative direction. This corresponds to what the rocket did in real life.

The roll angle of Figure 18 did what it was supposed to do. Figure 18 shows the roll angle of the rocket when the rocket was supposed to rotate 0.5 radians. This data shows the rocket starting at an orientation of 0 degrees and accelerating until about 0.25 degrees and starting to de-accelerate until the rocket has rotated approximately 0.5 radians. The rocket itself rotated a specific amount and then stopped (with a few small oscillations).

Discussion of Test Flight Results

Predicted vs. Actual Apogees

The predicted apogee for our rocket with the K500 motor (which was used during the test launch) was 6442 feet. The actual apogee was 6131 feet. The ratio of the actual apogee to predicted apogee was 0.95 (or 95%). This makes sense because the simulation doesn't account for a lot of wind, or the rocket launching at a non-vertical angle. The discrepancy between the simulated and the actual apogee was because the 6442 feet was simulated with 2 mph winds. The wind can make the rocket travel at an angle and reduce the apogee of the rocket. This would explain why the actual apogee and the predicted apogees were different.

The predicted apogee for our rocket with the J800T motor is 4021 feet with 2 mph winds, and 3828 feet with 15 mph winds. Because the OpenRocket simulation was off for the K-motor by about 5%, 4021 and 3828 feet were multiplied by 0.95 to get a better prediction for the height of the actual rocket during competition. This produces 3820 feet with 2 mph winds and 3637 feet with 15 mph winds, respectively.

During the competition, it is likely that the wind speed will be between 2 mph and 15 mph, which is why we simulated the rocket launch in those conditions. The angle of the launch pad was simulated to be 85 degrees because the launch pad probably will not be perpendicular to the ground. It is unlikely that the launch pad will be at an 85 degree angle instead of a 90 degree angle, but we wanted to simulate it assuming worse conditions than are likely to be found at the actual competition to get the 'worst case' scenario of our rocket launch.

<u>Predicted vs. Actual Peak Velocities</u>

With the K500 motor used during the test launch, Rasero predicted the maximum speed would be 730.7 ft/s. The maximum velocity recorded by the flight computer during flight was 750 ft/s. The maximum velocity seen at the test launch was 2.6% larger than the simulated maximum velocity. The discrepancy between the simulated peak velocity and the measured peak velocity likely comes from wind conditions. Our simulation accounted for 2 mph winds which would reduce the overall velocity due to the increased surface area and drag as the rocket travels at an angle.

OpenRocket predicted that the maximum velocity reached by the rocket would be 566 ft/s with a J800T motor in 2 mph winds and 561 ft/s with 15 mph winds. Our best approximation for the maximum speeds of the rocket in the two conditions with the correct motor are found by multiplying 566 ft/s and 561 ft/s by 1.026 (the proportion of actual K-motor velocity to simulated K-motor velocity). The expected maximum velocity for the rocket with a J800T motor is 580.9 ft/s for 2 mph winds and 575.6 ft/s in 15mph winds.

The same rationale for simulation values (as discussed above) were used.

<u>Predicted vs. Actual Peak Accelerations</u>

The maximum acceleration of the rocket based on the simulation was 382 ft/s^2 with a J800T motor. The flight computers didn't record the maximum acceleration of the rocket. However, because the velocity vs. time relationship was graphed (and was very linear), we could get an approximation for the maximum acceleration of the test flight. On a 2 second interval, the velocity changed from 0 ft/s to 750 ft/s. This corresponds to an acceleration of 375 ft/s^2, which is extremely close to the simulated acceleration. The discrepancy here likely comes from the fact that the our calculation assumed perfect linearity in this interval and this was likely not the case.

<u>Performance of Active Roll System</u>

Our active roll system was relatively effective in controlling the orientation of the rocket. From Figure 16 and Figure 17 we can see how, over a short period of time, the flywheel corrected for the angular offset after only a few oscillations. This was accomplished by creating a "virtual zero-point" at the initialization time and countering any offset by spinning the flywheel in the opposite direction. In Figure 19, we see the method with which we tested the system. Although the flywheel works well, we had a difficult time with the PID controller when we first got the system working. The PID constants are purely experimental and do not correlate to the motor, so we were forced to test random constants, make changes based on the results, and repeat. We found that certain PID constants cause overdamping or underdamping of the oscillatory response, and we had to conduct multiple trials to critically damp the system. Our tests consisted of offsetting the system from the "zero" at known angles and observing the process by which the flywheel returns to this point. Despite our fine-tuning, sensor error in the gyroscope and lag in the Arduino still makes the system slightly imperfect—however, the effect is small enough that we concluded that there is no significant effect on performance of the flywheel or stability of the rocket.

Figure 19: AV Bay rotation testing

Video Results vs. Data Logging of Rocket Orientation Angle

Since the SD card was broken during the test launch, no video results were collected at that time. However, we were able to test the light and video system as well as the data logging of the rocket during rotation ground testing. During testing, video results showed the rocket rotating in the correct direction and reacting to changes in the orientation of the avionics bay. We noticed that the rocket seemed to overcorrect, rotate the other way, overcorrect (but this time a little less), and so on until reaching the zero point. Figure 17's data corresponds closely to what we saw in our video. When we induce an offset, the flywheel rotates the avionics bay but "misses" the zero point. Then, it rotates the other way and misses again (but by a smaller amount). Eventually, the system dampens down to a zero point of no offset or rotation.

Recovery System Performance and Descent Velocity

The recovery system appeared to perform correctly during the test launch: the drogue deployed at apogee and the main deployed around 700 feet. The main parachute appeared to unfurl completely and slow the rocket down to a safe speed. However, the flight computer had a different descent speed. One of the two flight computer's data was corrupted but, using the data from the graph and the corrupted data (which said the main descent rate was -1), the descent rate can be calculated to be approximately 23 ft/s. The other flight computer had a drogue descent rate of 25 ft/s, which was reasonable given the Fruity Chutes descent rate calculator. However, the safe descent rate required for the competition was a maximum of 24 ft/s. This could be due to a heavier rocket or the parachute not unfurling completely. If the parachute didn't unfurl correctly, it wouldn't be as effective at slowing down the rocket. Overall, the recovery system performed very well and the descent rate was averaged to be 24 ft/s.

Planned Changes

One change that will be made is securing the LED lights for the active roll system to the avionics bay wall and twisting them together with wires from the electronics. This makes putting the LED lights into the avionics bay significantly easier, since during the test launch, the LED lights had to be stuck through the avionics bay with the sled already in it (which took a long time). In addition, because the SD card had so many issues, a new camera will be used so our active roll system is less dependent on the SD card working. The other change that will be made is securing the wires that connect the drogue parachute to the flight computer to the side of the Avionics bay instead of trying to make them go through a tube. These wires will stay attached to the side of the avionics bay permanently and will be able to come out of the top of the AV bay so they can easily connect to the flight computers. They will be taped to the side of the AV bay so the flywheel doesn't get caught on them. Finally, the main parachute will deploy at 800 feet instead of 700 feet to ensure that the rocket has a descent speed less than or equal to 24 ft/s. We believe that these changes will ensure efficient pre-flight preparation and safe recovery.

Findings and Future Work

Key Findings

Some of the key findings were from the active roll system, the flight computer data, and rocket assembly procedures. The flight computer data indicated that the rocket successfully launched, reached a very high apogee, and landed safely. These are the rocket basics that need to be working before the rocket's rotation can be changed. One of the key findings from the active roll system failing on the day of the test launch was that a broken SD card can prevent the flywheel's code from working. As a result, we have purchased multiple backup SD cards for the competition. Another key finding from the active roll system was tailoring the PID numbers. This allowed the electronics to control the rotation of the flywheel so the rocket can autonomously correct for in-flight rotation. The final key finding involved the rocket assembly procedures. Assembling the flywheel again allowed us to figure out what steps we missed from our written pre-launch procedures. It also revealed that we tended to have to redo assembly steps because we forgot to connect a wire or made other small mistakes. As a result, we have added more checks in rocket pre-launch procedures for maximum efficiency.

Potential Design Improvements

In the future, we would like to increase the amount of space in the avionics bay by increasing the diameter of the rocket. This would allow pre-launch procedures to be carried out more efficiently and create a more cleanly packaged space for the avionics. Additionally, with increased space, we would be able to use a larger battery source and hopefully supply both the motor and the Arduino to save space and provide more concise wiring. These small improvements would allow our prelaunch assembly to be much more efficient than our current method and mitigate the risks of tightly packed electronics.

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	1	34.95

		- BNO055		
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

Electronics Spares

Item	Link	Quantity	Price	Total
XBee Pro 60mW Wire Antenna - Series 1 (802.15.4)	https://www.sparkfun.com/products/8742	2	37.95	75.9
VNH5019 Motor Driver Carrier	https://www.pololu.com/product/1451	1	24.95	24.95
Pololu 5V Step-Up/Step-Down Voltage Regulator S7V7F5	https://www.pololu.com/product/2119	2	4.95	9.9
Adafruit Ultimate GPS Breakout - 66 channel w/10 Hz updates - Version 3	https://www.adafruit.com/product/746	1	39.95	39.95
Adafruit BMP280 I2C or SPI Barometric Pressure & Altitude Sensor	https://www.adafruit.com/product/2651	1	9.95	9.95
Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055	https://www.adafruit.com/product/2472	1	34.95	34.95
Turnigy 1300mAh 3S 30C Lipo Pack	https://hobbyking.com/en_us/turnigy-1300mah-3s-30c-lipo-pack.html	2	12.22	24.44
			Total	220.04

Grand total: 8295.38

Note: the only change in our budget between the FRR and the PDR is the purchase of spares. This is because most items were purchased or we knew we would have to purchase them before we submitted the PDR.

Mentor Report
Mentor Report Form
Mentor Name: Judy Lubin, L3 NAR (88698) and Tripoli (12919), Judy@Lubin.net
Team Name: Northwestern University
Current Phase of Competition: FRR, May 9, 2018
Total interaction hours
More than 10.

List of topics
Attendance at test launch
Parachute fit and folding for tight space
Shock cord attachment to av bay given constraints of fly-wheel mechanism
Reducing rocket weight
Choosing and procuring motor for test launch given lack of availability of contest motor
Prepping for ground testing
Deciphering flight computer data

General Comments about Team Interactions and Mentoring Discussions
The team does a great job of knowing when to ask questions. They are very diligent in their work and are always striving to learn. I am in very close proximity to the school and we frequently meet in person to discuss items big or small. We also email and text. The students are very comfortable contacting me.

General Comments about Difficulties/Obstacles in Mentoring Discussions
None.

Appendix

Flight Computer 1 Data

Flight Computer 2 Data

Motor Thrust Curve

Source: Wildman's Website