Flight Readiness Report

Macstronauts
Macalester College

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Summary of Design

Before we began to design the rocket, we first did research into the different systems we could incorporate into a high-powered rocket to control the roll. This research led us to three main options:

- Adjustable canards/fin set
- Flywheel
- Jets of compressed gas

We quickly rejected compressed gas out of concerns of storage and reliable implementation at the scale of a 2.6-4” diameter rocket. We then debated the merits of a flywheel versus canards before eventually settling on a flywheel system. We did this primarily for two reasons. As a team, we are concerned with the safety of a our rocket and the people around it. A canard set could be improperly implemented to induce pitch and yaw as well as roll, turning the rocket into a missile-like object. A flywheel that is nearly the diameter of the airframe is unable to affect motion outside of the roll of the rocket. Additionally, a canard set, as per competition guidelines, is required to be below the center of mass. Most designs we looked at for inspiration had the canard set above the center of mass or involved a complex mechanical system to adjust the rocket’s main fins. While there are creative ways around these potential roadblocks (ie, adding mass to the nose cone of the rocket in order to shift the center of mass up), we preferred the flywheel system for simplest implementation of the physical system.

For the design of this rocket, named Quantum Heavy in homage to our Faculty Advisor’s area of research, we modified a fiberglass Arcas HV kit from MadCow Rocketry. We chose this kit to minimize the moment of inertia of our rocket by using 2.6” diameter tubing instead of a larger diameter and also for the durability of fiberglass components. For additional convenience, it was a kit we already had on hand. We made three major modifications to the kit in the areas of the ***avionics bay***, ***flywheel cage***, and ***airframe modification***.

Avionics Bay

We started the avionics bay design by deciding on a list of chips we wanted as per the requirements of the competition. We knew we would need a gyroscope, a flight computer, an altimeter, a motor control chip, an ejection charge chip, and potentially a magnetometer and radio. For simplicity in interfacing and programming, we decided to use a Raspberry Pi Zero (W) as our flight computer. The motor driver chip was chosen as a direct result of the stepper motor we decided to use, which is discussed more in ***Flywheel Cage***. For ejection charges, we used a Raven3 Altimeter. Our gyroscope and altimeter were chosen for sensitivity, ability to be mounted on our sleds, and ease of interfacing via the Pi and are the L3GD20 gyroscope and the MPL3115A2 altimeter. This is a different gyroscope than the one mentioned in our PDR as that gyroscope was difficult to mount securely to the sled and was proving difficult to interface with as well. We also included the HMC5983 magnetometer in our design.

In order to power all of these electronics and the flywheel, our avionics bay includes 3 separate 3.7v, 3000mAh LiPo batteries. One battery powers the motor driver chip and thus the flywheel, one powers the Raven3 via a screw switch, and one powers the main flight computer which then powers the other chips. The flight computer receives power through a mounted LiPo SHIM.

To be able to use our space as efficiently as possible, we deviated from the normal single-sled avionics bay design. Figure 1 below shows a near final design of our avionics bay from both the front and the back. We broke the avionics bay into an "upper" avionics bay and a "lower" avionics bay.

The upper section was designed in much the same way as a normal avionics bay would be. It has a single sled of plywood (3.725" x 2.225" x 0.25") with a terminal block, electronics (flight computer and motor driver chip), a battery, and a screw switch (not shown in the below rendering). Initially this was designed to be connected via epoxy to two copper tubes through which would run steel threaded rods to secure the upper avionics bay. This would prove to be unnecessary, and so was removed from the final design.

The lower avionics bay was comprised of two battery cases (2.975" x 0.825" x 0.75") epoxied to the middle bulkplate. Epoxied to the flat edges of the battery cases were two lower sleds (2.65" x 1.75" x 0.25") which would, respectively, house the Raven3 and the gyroscope, altimeter, and magnetometer. In the center of the lower avionics bay is an aluminum threaded standoff secured via an aluminum screw with a custom washer through the middle bulkplate. This is then secured via a forged eyebolt through the lower bulkplate. That eyebolt is then sticking out from the lower avionics bay into the lower airframe and is where the shock cord is attached. Also on the side of the lower bulkplate that faces the lower airframe, a ceramic ejection charge canister is affixed using epoxy. Figure 2 shows a cardboard model of the lower avionics bay assembled without one sled to better illustrate the physical connections taking place.

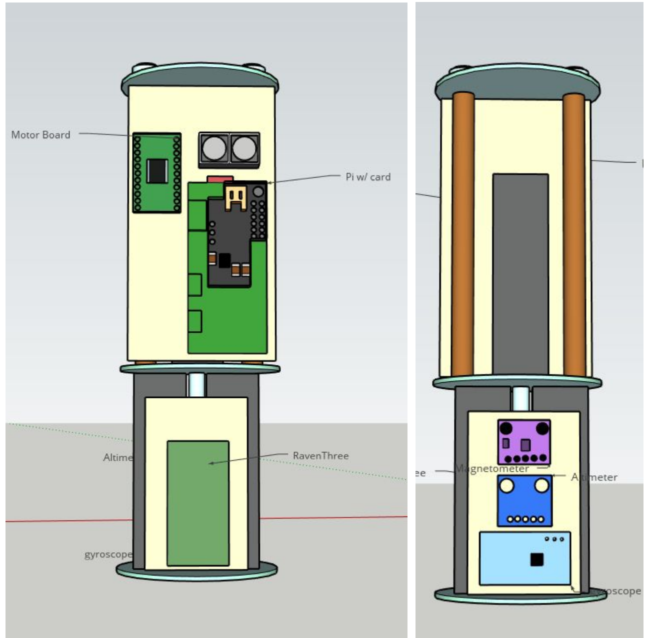

Figure 1. — 3D model of the avionics bay.

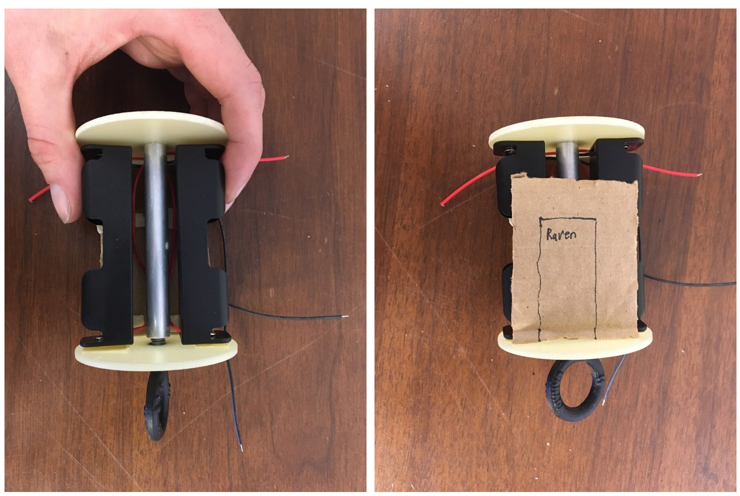

Figure 2. — An early physical model of the lower AV bay using cardboard and tape in addition to fiberglass bulkplates, an aluminum threaded standoff, and a forged eyebolt as in the final model.

The avionics bay is placed inside of a coupler tube with two centering rings situated to sit just above the lower bulkplate and just below the middle bulkplate respectively. Thus, forces applied to the eyebolt are carried through the threaded standoff to the middle bulkplate to the upper centering ring to the coupler tube to the upper airframe as the coupler tube is secured in the upper airframe with a series of 4 plastic rivets. With that in mind, no significant forces are applied to the upper sled and so the standard copper tubes with threaded rods are useless and were eliminated from the design allowing use to more fully utilize the space.

In order to pass wires from one section of the avionics bay to another, various holes were designed to be drilled through bulkplates as well as the upper sled. In the lower bulkplate, one hole was planned to allow wires from the Raven3 to pass through the bulkplate to the ejection charges sitting on the exterior face of that bulkplate. In the middle bulkplate, two holes, slightly larger than the lower ones were designed 180° apart from each other centered on the lower sleds. These holes allow wires to pass from the batteries to the upper sled, wires from the flight computer to the sensors on the lower sleds, and wires from the screw switch and terminal block from the upper sled to the lower sleds. The upper sled also was designed with a 1.1” x 0.5” square hole to allow wires to pass from one side of the upper avionics bay to the lower and also to allow the aluminum screw and custom washer to rest on the middle bulkplate. The upper bulkplate was designed with one hole to allow wires passing from the motor control chip to the flywheel system.

Flywheel Cage

The flywheel cage was designed as a removable housing for the flywheel, allowing alterations and enabling an iterative style of design. We are using a Nema 17 Hybrid Stepper Motor with a rated maximum torque of 83.6 oz-inches. The Nema 17 was chosen to maximize torque while fitting within our rocket’s airframe. Figure 3 shows a white-board mockup of the design.

The stepper motor is attached via 4 mounting screws to a fiberglass bulkplate that is epoxied into the surrounding coupler tube. The axle from the motor extends through a hole in that bulkplate to the flywheel mass itself. The flywheel mass is secured to the motor axle via a hex screw tightened with an Allen wrench. Unlike the system shown in Figure 3, this is not a solid axle through the flywheel. A second axle extends from the top of the flywheel to the flange mounted bearing attached to a bulkplate. This axle is also secured inside the flywheel via hex screw. The upper bulkplate is secured down against an internal centering ring with a shaft collar, also tightened with a hex screw.

A hole is placed in the coupler tube at the height of the lower hex screw in the flywheel mass to allow the mass to be placed into the coupler tube and then secured to the motor’s axle. The upper axle is assumed to be secured before loading the mass in. After the mass has been loaded in, the upper bulkplate and bearing are put in place to ensure the axle and flywheel stay exactly aligned along the vertical axis of the rocket. Below the centering ring but above the flywheel mass, four plastic rivets secure the flywheel cage to the upper airframe.

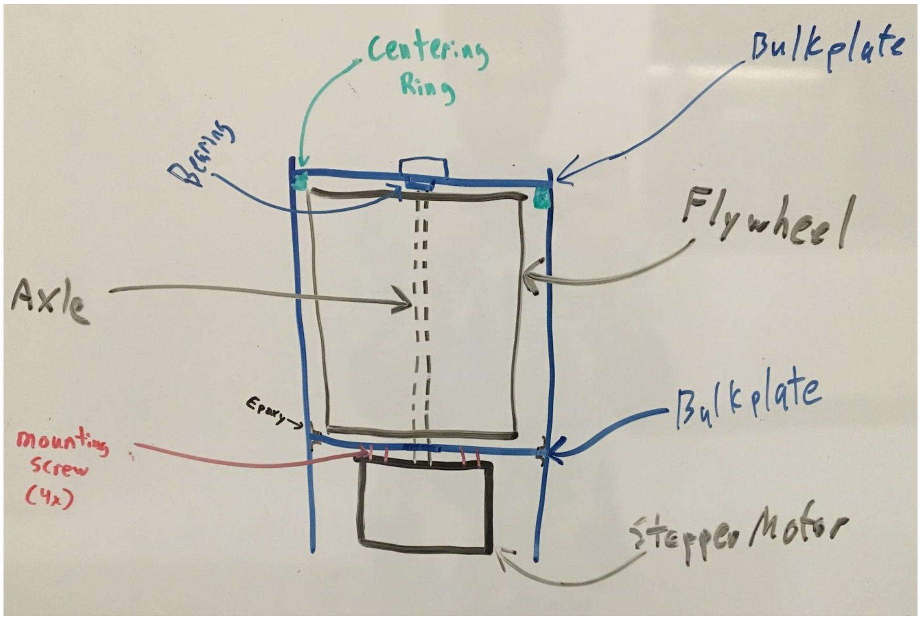

Figure 3. — A whiteboard sketch of the flywheel cage

Airframe Modification

We cut four inches off the lower airframe to achieve a higher factor of stability. Modeling our rocket using OpenRocket using the standard kit gave us a stability factor of 4.19 calibers. This is within competition guidelines, however, our experience led us to strive for between 1.25 and 3 calibers. To hedge toward a better stability, we looked at a lot of factors including fin shape and weighing down the aft end of the rocket to move our center of mass. At the end of it all, the easiest change to implement was to cut the lower airframe by four inches, increasing our stability to 3.45 cal.

Camera Mount

We modified a 3D printable camera mount design given to us by University of Minnesota rocketry team member Ryan Bowers for our Mobius-Mini camera, this is shown in Figure 4. This mount is attached via four screws to the upper airframe.

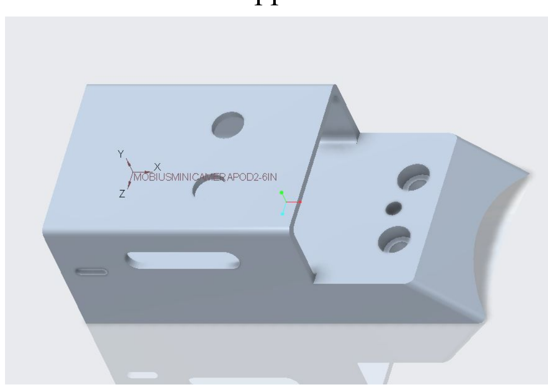

Figure 4. — Mobius-Mini Camera Mount

Budget

In building Quantum Heavy, we have managed to stay under budget so far by about $120, even though we had several unanticipated expenditures. We have made four large purchases since our Preliminary Design Report was submitted: a fourth electronics order, an order of supplies for our educational outreach events, purchasing motors and retention mechanisms, and purchasing parts to repair our rocket after our first test launch.

For brevity's sake, we will not detail the components of the orders made before our PDR was submitted and will only relay the components purchased since then. A summary of our budget is shown in Table 1. In our fourth electronics order, we purchased two Raspberry Pi Zero units, one to replace our original unit that was accidentally damaged, and one to have on hand as a backup unit in case of emergency. We also bought two more LiPo Shims for the same purpose. At the same time, we purchased a new gyroscope that fit more snugly into our avionics bay as well as a 32GB SD card to have on hand. These items were purchased from Micro Center in Saint Louis Park, MN.

For our educational outreach event, we made a purchase from Apogee Components (which included a 12-pack of Apprentice rocket kits, 12 A8-3 motors, 12 Estes motor starters, a launch pad and controller, and six small parachute protectors) as well as a purchase from our local Ace Hardware (for rulers, Elmer's glue, superglue, AA batteries, and masking tape). Our motor-related purchase included one four-foot diameter parachute, ten e-matches, one retention unit, and three motors. These motor-related purchases were all made from Off We Go Rocketry.

We also ordered a few repair parts after our first test flight on May 5. This purchase included a new fiberglass nosecone from MadCow Rocketry, as ours was damaged upon landing, as well as a new parachute and parachute protector from Off We Go Rocketry. We also ordered an Altimeter Three Safety Mount from Jolly Logic, as our altimeter casing was also damaged upon landing.

We would like to use our remaining balance to go towards purchasing backup components for the competition next year (an extra Raven3 altimeter, or potentially another Raspberry Pi) as well as for the team in the shorter term. We plan to build and launch a team rocket in the fall as well as certify two team members, so any extra funds will go towards those endeavors.

Due to not having been billed by OffWeGoRocketry many of our budgetary items are estimates based on their website. However, their website is not up to date, as they do not continue to carry everything listed and so some ambiguity remains in our budget.

Macalester Rocketry Budget — Spring 2018

$114.46	Remaining Balance	NASA Space Grant	$1,900.00
		Registration Fee	-$400.00
		Electronics Order 1	-$87.86
		Electronics Order 2	-$72.29
		Electronics Order 3	-$60.24
		Extra Nose Cone 1	-$31.61
		Residual Order 1	-$219.08
	Pre-PDR	Parts Order 1	-$89.85
	Post-PDR	Electronics Order 4	-$79.44
		Educational Outreach	-$258.89
		Motors and Retention	-$384.97
		Repair Parts	-$101.31

Table 1. — A brief description of our budget for the spring 2018 competition.

Construction of Rocket

Physical Construction

Quantum Heavy utilizes the Arcas HV kit from MadCow Rocketry. "ARCAS" stands for "All-Purpose Rocket for Collecting Atmospheric Soundings." The fiberglass airframe is 2.6 inches in diameter and has two main parts: an upper and lower airframe. We used an eight inch coupler tube to house our avionics bay and a six inch coupler tube to house our flywheel system. The nosecone is a secant-ogive shape and is also made of fiberglass. The rocket has four fins made of G10 fiberglass. All centering rings used were also made of fiberglass. We used 3M Scotch-Weld DP420 epoxy throughout the build process on the airframe, and we used JB Weld epoxy to attach the motor retainer system to the motor mount tube.

The first step in our construction was to prepare the motor mount tube for placement into the lower airframe. We epoxied a centering ring one inch from the foremost end of the tube, and once dry, we affixed a forged eyebolt to this centering ring for attachment of the shock cord which connects the lower airframe to the avionics bay. After the shock cord was attached to the eyebolt with a secure knot and a drop of epoxy, the motor mount tube was epoxied into the lower airframe using epoxy fillets. We used strapping tape tabs on the lower centering ring to allow us to remove it after it was used to keep the tube centered in the lower airframe during drying, and during the attachment of the fins.

Figure 5. — Fillet joints on the upper centering ring on the motor mount tube.

The next step in constructing the lower airframe was to attach the fins. In an attempt to reduce innate spin of the rocket, we used a vertical knee mill in order to keep the fins aligned as straight as possible while the epoxy was drying. For three out of the four fins, we first used a butt joint to attach the fins to the motor mount tube through the pre-slotted airframe. For one of the fins, we neglected to do this, but attempted to make up for it by making the fillet joints on this fin more robust. For all fins, we then used fillet joints on the exterior of the rocket on either side of the fins as well as interior fillet joints on both the inside of the airframe and on the exterior of the motor mount tube.

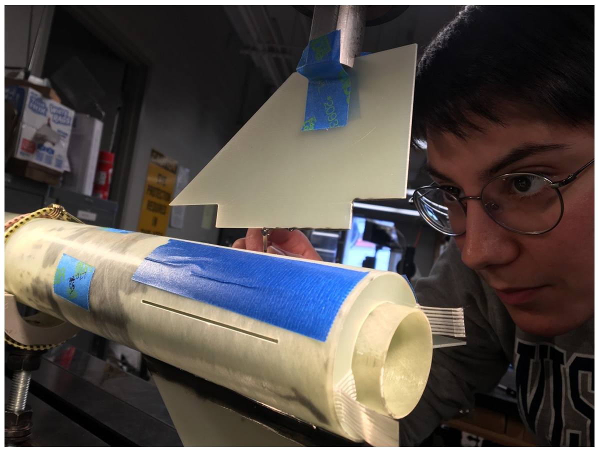

Figure 6. — Team member Alyssa in the process of attaching a fin.

Once the fins were attached and excess epoxy was sanded down, the lower airframe was almost finished, save for a few smaller tasks. First, we shortened the fore end of the lower airframe by four inches such that its final length was 22 inches. We did this in order to bring the center of pressure closer to the center of gravity to increase our stability. We epoxied a small wood block into the lower airframe for attachment of the lower rail button. We also drilled three quarter-inch vent holes into the lower airframe because we anticipated our payload bay to be tightly packed, but on the day of our first test launch, we were advised to cover these with tape and epoxy them closed for launch. After we no longer needed to access the area around the motor mount tube, we epoxied the lower centering ring flush with the aft end of the lower airframe.

We then turned our attention to the nosecone, upper airframe, and flywheel cage. We made a few modifications to the nosecone, including cutting out an access port on the side of the shoulder, and sealing the shoulder end of the nosecone with a bulkplate to allow for a data logger and radio beeper to be placed inside. We epoxied this bulkplate in and attached an eyebolt to it, facing into the nosecone for the electronics to be tied to. At this point, we also filled the nosecone with packing peanuts.

Figure 7. — The nosecone, with epoxy ready for the bulkplate to be placed.

The upper airframe did not require much modification besides holes being drilled for our camera mount. Before drilling these holes, we epoxied a wood block inside the upper airframe to which we attached the exterior camera mount. For our flywheel cage, we mounted a stepper motor to a bulkplate via mounting screws on the motor. The bulkplate is epoxied into the flywheel cage such that the motor faces inward. An extension of the axle is connected to a bearing on the upper end of the cage, which rests in a yoke that is affixed to another bulkplate. This bulkplate rests on a centering ring, and the construction of the system allows the flywheel to be removed.

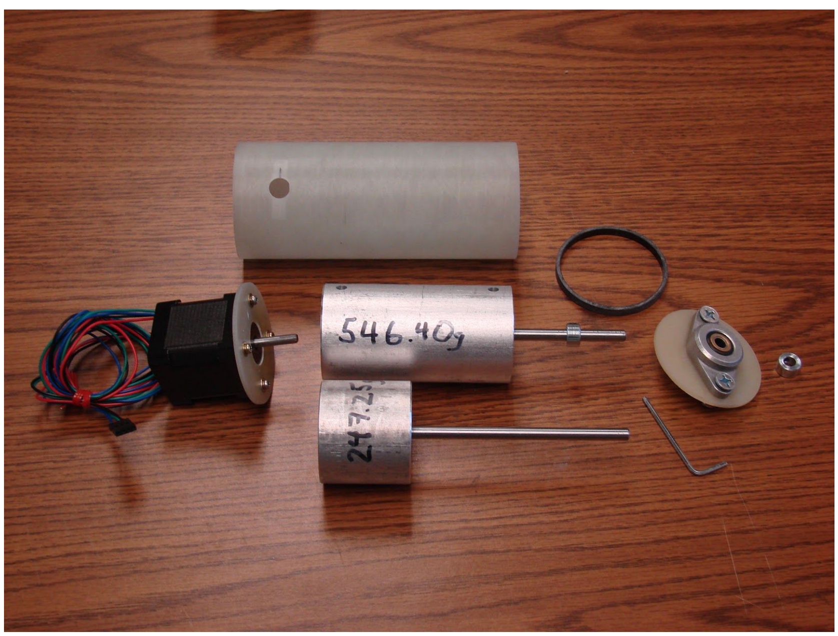

Figure 8. — The components of our flywheel cage, including two different flywheel masses.

At this point in our construction, we took time to drill holes for rivets in various places in the rocket. Our nosecone is attached to our upper airframe with two rivets that go through the shoulder of the nosecone. Our flywheel cage is riveted into the upper airframe with four rivets, and the avionics bay is also riveted into the upper airframe with four rivets. Our avionics bay sits in the lower airframe via a friction fit. After holes were drilled for rivets, we epoxied the upper rail guide at the experimentally-determined center of mass of the rocket which happened to be at the fore end of the lower airframe, and construction switched focus more fully to the avionics bay.

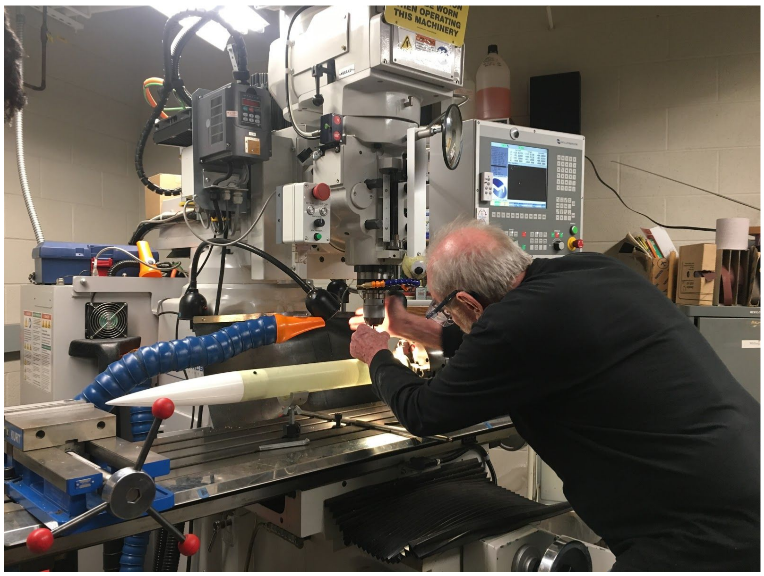

Figure 9. — Our technical advisor Ken Moffat helping us to drill holes through fiberglass safely.

Programming

Using a Raspberry Pi, we created a Python file to run over the course of the flight. The program's goals were to both read and write sensor data, in addition to managing the rotation of the motor which turns the flywheel. The sensors were read mostly using libraries we found online to interface. We then wrote that data to a file on the Pi so we could analyze it later. After a bunch of initialization of importing those libraries, setting up variables, and calibrating the gyroscope, we enter a preflight stage where the program continuously takes altitude data and analyzes it to see if it remains below a certain value (approximately 50 meters above ground level of the launch site). The program continues looping over this data until it senses the rocket is above that height, and therefore after liftoff. The program then progresses to the main loop, where it begins logging all sensor data, and then after the specified wait time as per competition guidelines, the program begins to execute the motor turn sequence.

Concurrently, tests occur at specified intervals with the altitude data to determine if the rocket has reached apogee. When it has, the rocket breaks from wherever it is at in the main flight motor function (if it has not already completed) and writes all of the data to a file on the Pi for later analysis.

Wiring and Connections

The wiring in the avionics bay of Quantum Heavy is color-coded for efficiency and clarity. Red refers to positive power from any battery while black is common ground for the system. Green refers to SCL connections, blue to SDA connections, and white to reference voltage for the motor driver chip, and white are all data from the flight computer to The Pi is connected to all of the sensors in the lower half of the avionics bay (the magnetometer, altimeter, and gyroscope), which allows for sensor data to be transmitted to the Pi. The Pi is powered with a LiPo battery. The Pi is also connected to the motor driver chip. The motor driver chip is wired to the stepper motor through four wires which pass through the top of the avionics bay; the hole that these wires pass through is closed with putty before flight.

The screw switch controls power going to the Raven3 altimeter. The Raven3's apogee terminal is connected to the ejection charge just outside of the lower avionics bay using an e-match which must be wired for every flight. The hole that the e-match passes through is closed with tape and putty before flight to ensure the electronics inside the avionics bay are not affected by the ejection charge.

Construction of Avionics Bay

The first step of the physical construction of the avionics bay was to make a few adjustments to our LiPo battery cases. We first sanded down the tops and bottoms of the cases, which were the widest parts of the cases, in order to allow them to fit into the coupler tube. Then, we soldered wires onto the terminals of the battery cases to allow various components, including our terminal block, to have easy access to power and ground. We drilled holes in plywood sleds for mounting our electronics (the Pi and the motor driver chip on the upper sled, and the magnetometer, altimeter, gyroscope, and Raven3on the lower sleds). We also made sure to attach the screw and threaded rod to the middle bulkplate before attaching the sleds.

We epoxied the upper electronics sled to both the upper and middle bulkplates, and we epoxied one battery case to that sled. We also epoxied a terminal block and screw switch to this sled. We used a dremel tool to create an indentation for the rounded side of the screw switch to rest in, and epoxied both the underside of the screw switch as well as the sides to the upper sled. To prepare the lower half of the avionics bay, we epoxied the two lower battery cases to the middle sled. We then epoxied the lower sleds to the sides of the battery cases, making sure to roughen the surfaces of the battery cases and the wood before attaching. To finish off the construction of the avionics bay, we drilled three static port holes each with diameter 11/64'' in the coupler tube, and matching holes in the upper airframe. We also epoxied an ejection charge cap to the lower bulkplate of the avionics bay.

Active Roll-Angle Monitoring System

Design

We decided to use a flywheel to orient our rocket because it was the simplest and safest method we had available to us. We considered using compressed gas or canards, but found that compressed gas was not a feasible option because of the scale of our rocket, and canards, if implemented incorrectly, could have unwanted consequences for the pitch and yaw of our rocket during flight. Since a flywheel cannot cause a rocket to go ballistic if its spin is not controlled correctly, we chose to build a flywheel.

The design of our flywheel began as a cylindrical mass affixed to the axle of our stepper motor. We quickly discovered that we had to elongate the axle with an aluminum rod that was attached to the flywheel itself. With guidance from our Technical Advisor, Ken Moffat, we designed a system to allow this rod to be held in place by a bearing at the top of the flywheel "cage" (a coupler tube that is riveted into the upper airframe of Quantum Heavy). This design is shown in Figure 3.

In thinking about how to spin the flywheel in order to get the rocket to spin, we decided to create three different masses of equal radius (1.0935 inches) to have options in case we needed a specific combination of flywheel volume and rotation speed. Our three cylindrical masses were about 250 grams, 400 grams, and 550 grams (these masses are not exact, as it is difficult to machine aluminum cylinders to these masses exactly). The system was designed such that these masses are removable and interchangeable. For the current working design of the flywheel system, we are using the nominal 550 g weight (actually 546.40 g), which does not need to be sped up as quickly in order to induce the same torque as a flywheel of a smaller mass.

Operation

The flywheel uses the conservation of angular momentum to change the orientation of the rocket mid-flight. If the flywheel accelerates to some rate in one direction, the body of the rocket will experience a torque in the opposite direction. Thus, we can accelerate and decelerate the flywheel by certain amounts in order to orient the rocket to a specific orientation, given a specific starting orientation.

At the moment, this system is partially functional. We can demonstrate quick movements of the upper airframe by suspending it to a modified nosecone with a bearing at the top. When securing the bearing with a clamp and running pieces of code to control the motor, we are able to show the upper airframe moving. However, this movement is not in a controlled manner at this time. Further refinements are necessary.

Figure 10. — The assembled flywheel system, minus the coupler tube that surrounds it.

Logic

The motor is interfaced through a library we have for the motor driver chip, which the program uses to give alternating up/down power signals that create the micropulses which spin the stepper motor. By reducing or increasing the delay of those up/down signals, we increase the time between microsteps and therefore accelerate or decelerate the motor. By interfacing with the gyroscope at the same time, we can measure the amount of spin we have induced and adjust intelligently.

Completed Rocket Photographs

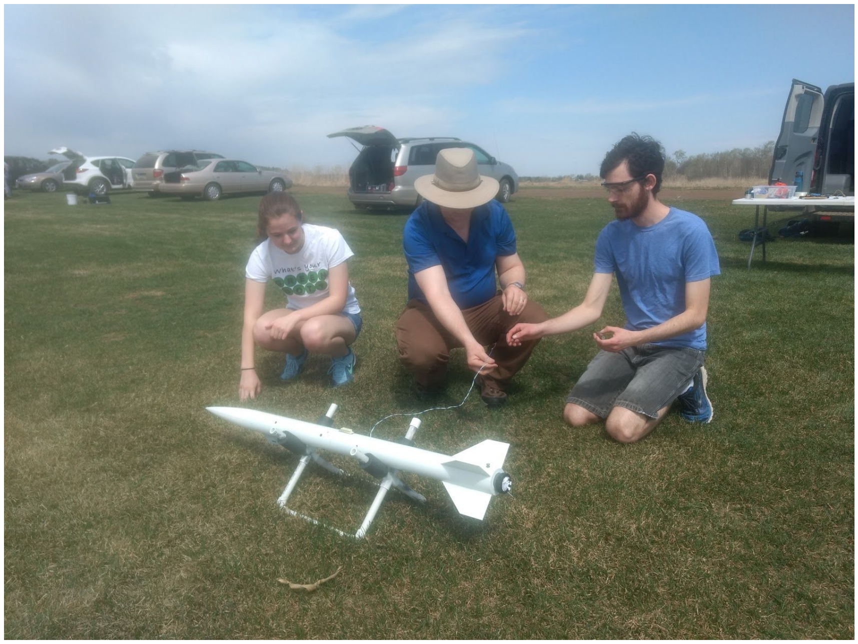

Figure 11. — Team members Maya (left) and James (right) with Dr. Flaten (center), who helped us to conduct an ejection charge test to make sure our ejection charge would separate the rocket. Our initial calculation for the mass of ejection charge needed (0.6 g) was insufficient and failed to separate the rocket, but increasing the amount of ejection charge to 1.2 g and covering the bleed holes we drilled was sufficient for separation.

Figure 12. — From left to right: team members Maya, Alyssa, James, Jack, and Luke standing next to Quantum Heavy on the pad at our first test launch on May 5, 2018.

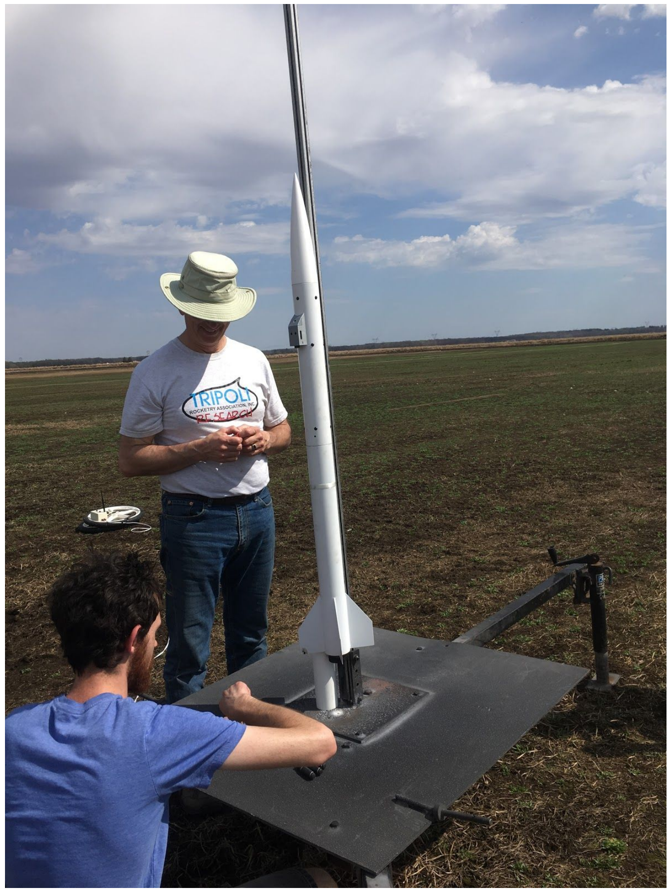

Figure 13. — James (left) and Gary Stroick on the launch pad

Test Flight Report

Our preflight and postflight checklists are as follows.

Preflight Procedure

- ❏ Electronics
  - ❏ Power the AV Bay
  - ❏ Interface with Flight Computer via SSH and laptop
  - ❏ Connect main electronics outside of rocket (exception: Raven3)
  - ❏ Run ground test program (sensors calibration, LEDs, flywheel)
  - ❏ Connect Raven3 to power and listen for startup sequence
  - ❏ Disconnect Raven3 (via screw switch)
  - ❏ Disconnect flywheel from Flight Computer
  - ❏ Load flywheel in upper airframe
  - ❏ Insert LEDs into upper airframe
  - ❏ Connect flywheel and LEDs to Flight Computer
  - ❏ Ready Avionics Bay inside coupler tube
    - ❏ Pull ejection wires from Raven3 through lower bulk-plate
    - ❏ Connect wires to ejection charges seated in the canister on the lower bulk-plate
    - ❏ Tape down wires
    - ❏ Screw eye bolt in place to secure the Avionics Bay
  - ❏ Load Avionics coupler tube into the upper airframe
  - ❏ Run ground test program
  - ❏ Ready nose-cone with data logger and radio beeper, stuffed with packing peanuts
  - ❏ Load nose-cone in upper airframe
- ❏ Main Rocket
  - ❏ After electronics loaded, tie shock cord to avionics bay eyebolt via figure eight follow-through knot.
  - ❏ Inspect and fold parachute, due to space considerations, wrap excess shock cord around motor casing before packing the parachute inside the lower airframe
  - ❏ Connect upper airframe and lower airframe, check friction fit of avionics bay to lower airframe
  - ❏ Inspect rail guides
  - ❏ Inspect camera mount
  - ❏ Install motor
  - ❏ After everything has been loaded, check center of mass lines up with marked center of mass
- ❏ On the Rail
  - ❏ Turn on camera and start recording
  - ❏ Turn screw switch, powering the Raven3 and listen for correct sequence of beeps
  - ❏ Take picture
  - ❏ Stand back and press the button

Postflight Procedure

Should stage separation not have occured, approach with **EXTREME CAUTION** as live charges may still be inside the airframe.

- ❏ Recovery
  - ❏ Take a picture
  - ❏ Conduct visual inspection of the airframe
  - ❏ Retrieve Data Logger
  - ❏ Turn off camera
  - ❏ Retrieve camera SD card
  - ❏ Turn screw switch to the off position (Raven3)
  - ❏ Take out Batteries from AV Bay (Power off everything else)
  - ❏ Examine shock cord/parachute for damage
- ❏ Data
  - ❏ Retrieve video data from camera SD card
  - ❏ Retrieve data from nosecone data logger
  - ❏ Retrieve data from systems controlled by the Pi
    - ❏ Magnetometer
    - ❏ Gyroscope
    - ❏ Altimeter
  - ❏ Retrieve data from the Raven3
- ❏ Review data
- ❏ If launching twice, refer back to preflight checklist

Flight Performance

In examining video footage of the launch from a good distance away, we find that the rocket seemed to ascend relatively smoothly. There was very little wobble, and the motor seemed to burn without trouble. The rocket ascended almost straight up. The beginning of the coast phase also seemed to go smoothly, but we lost sight of the rocket fairly quickly after motor burnout.

Recovery System Performance

After losing sight of the rocket, we noticed a puff of smoke, which meant that the upper and lower airframes had separated. Unfortunately, we saw no parachute; our parachute did not deploy. This is probably due to the fact that we need to pack the parachute very tightly in our lower airframe in order for it to fit. Surprisingly, it seemed like the ejection charge on the top of our motor also did not fire (which might have contributed to the parachute not deploying). One piece evidence for this is that the red cap on the fore end of the motor retention unit was still placed on the end of the motor retention unit (however, a theory on how this could have happened is that the altimeter-controlled ejection charge pressurized the lower airframe such that the red cap was forced back onto the motor retention unit after the motor charge had blown). Another more convincing piece of evidence is that the small white sticker we used to secure the black powder in the motor ejection charge was unpunctured and seemed to have not been in any sort of explosion. It was under the red cap where we had originally placed it when we removed the motor after recovery.

Regarding recovery, once we noticed a lack of parachute deployment, it was only a matter of time until we saw the rocket (now separated into two components connected by a shock cord) again. It reached the ground with a larger velocity than anticipated, but we reacted to this landing like we would any other landing. We took a picture of the rocket and inspected the airframe. We noted a few repairs that needed to be made and then began moving through our postflight checklist. This procedure seemed to work quite well, and we will use it going forward for our next test launch and continue to make improvements upon it.

Table of Flight Characteristics

First Test Launch of Quantum Heavy, May 5, 2018

Mass of rocket	Motor	Maximum Altitude	Maximum Velocity
3214* g	J420-R (Aerotech)	4045 ft	572 ft/s

*This is a nominal mass, from our simulation. We expect the actual mass to be slightly larger as our simulation uses a does not account for the weight of the radio beeper, AltimeterThree, camera mount, or AV bay sleds. Due to oversight on launch day, the rocket was not massed before launch, however, the rocket's center of mass was checked and was within 0.25" of the expected position.

Roll Control Statistics

As we did not test our roll-control system during this test launch, we do not have any data on how it performs during a flight.

Discussion of Results

Flight Characteristics

Figure 14 shows a model of a flight of Quantum Heavy made with OpenRocket. From this simulation, we read a maximum altitude of 4500 ft, a peak velocity of 672 ft/s, and a peak acceleration of 574 ft/s^2. We can also read a descent speed of –32 ft/s. Figure 15 shows flight data taken with a Raven3 altimeter during our test flight. From our data, we read a maximum altitude of around 4045 ft, a peak velocity of 570 ft/s, and a descent speed of around –50 ft/s. The data table from the altimeter gives a minimum velocity of –47 ft/s, as well as a maximum acceleration of around 18 axial G's (upon liftoff) and 43 lateral G's (upon landing).

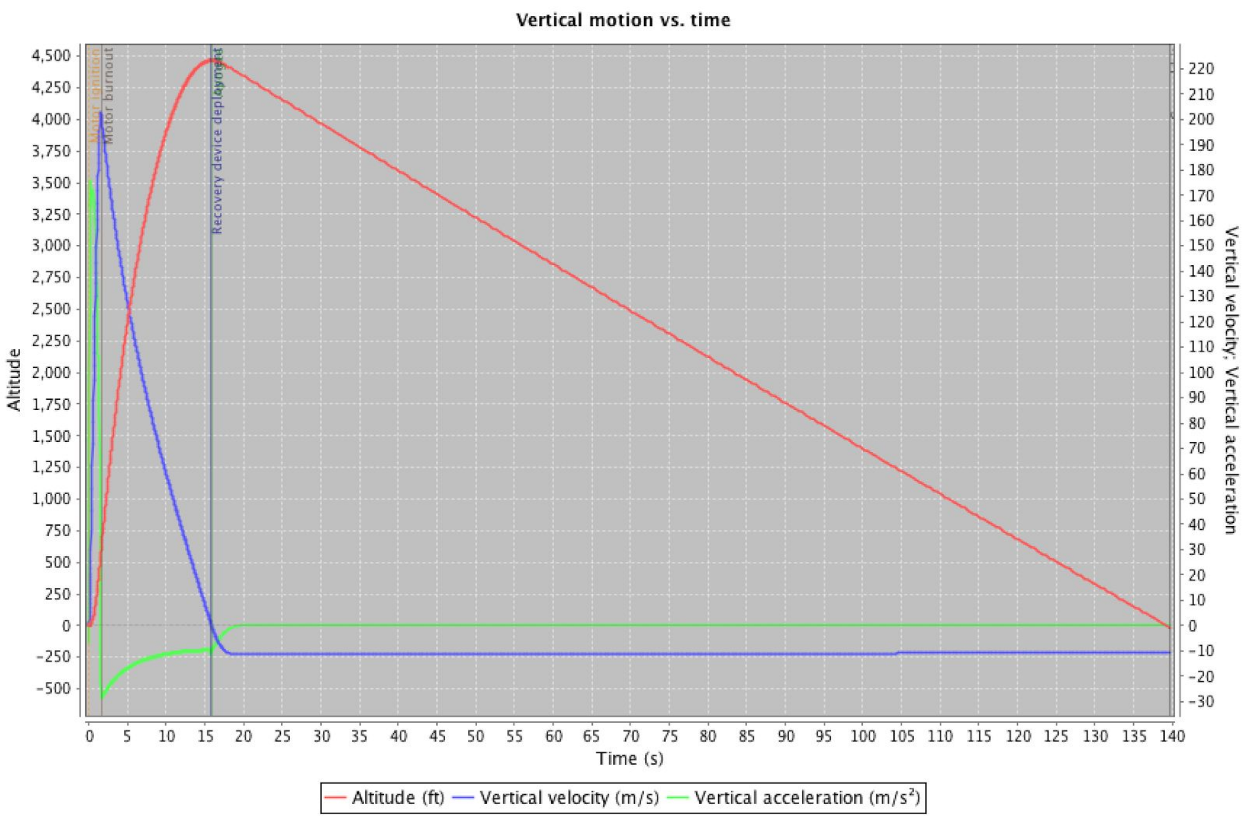

Figure 14. — A model of a flight of Quantum Heavy created in OpenRocket.

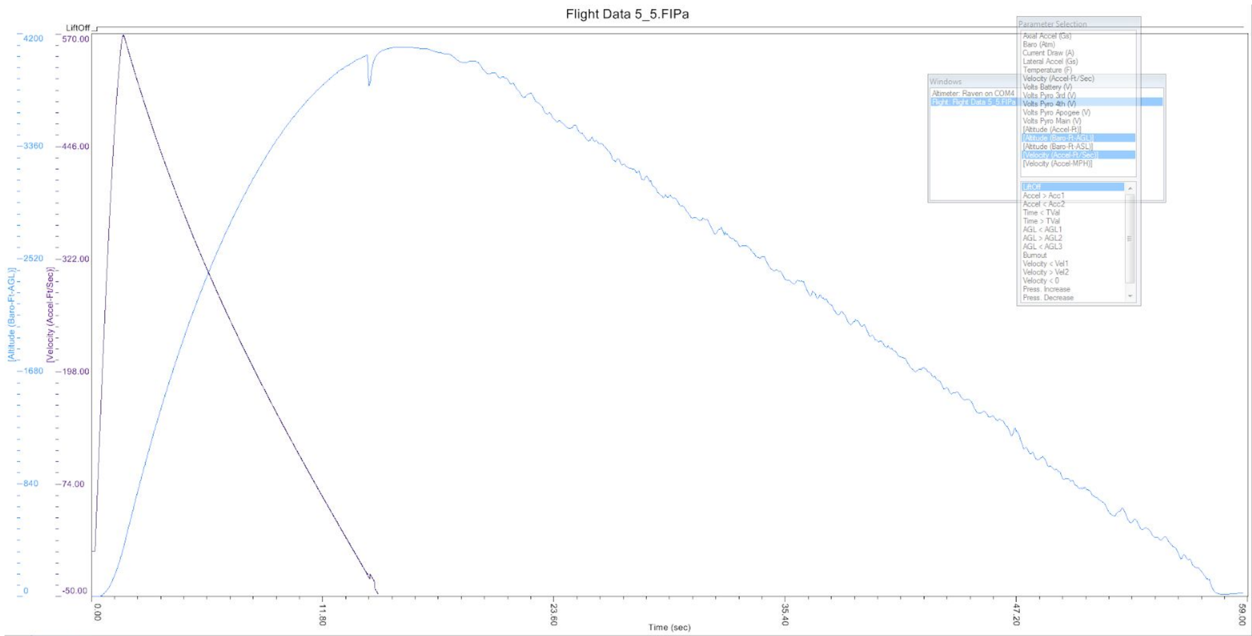

Figure 15. — Flight data on altitude and velocity collected from our first test flight of Quantum Heavy with a Raven3 altimeter.

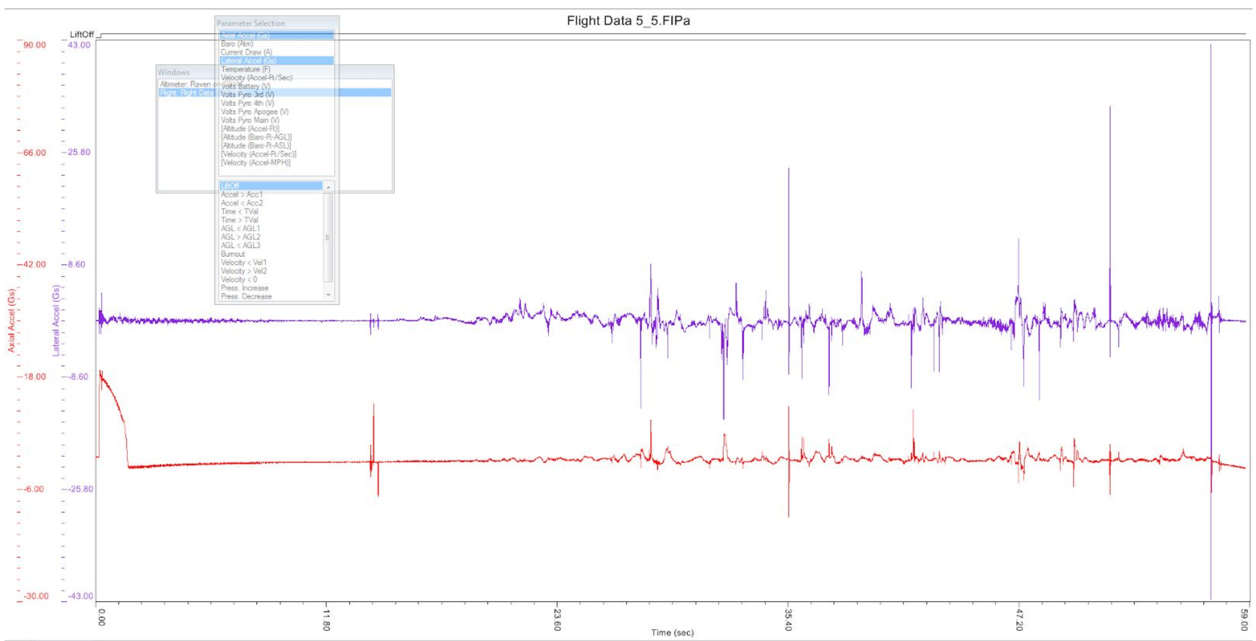

Figure 16. — Flight data on acceleration collected from our first test flight.

The difference in our predicted apogee and actual apogee are due to inconsistencies between our model and actual masses. The model we show uses a flywheel mass of 350g instead of the 550 we flew on. Additionally, further reductions in performance could be due to any imperfections in the aerodynamics of the rocket. A few of these include our camera mount system, our rivets, the tape covering our vent holes, and any epoxy that was remaining on the exterior fillet joints for the fins (although these were meticulously sanded to prevent as much interference as possible). Any addition to the drag of the rocket could cause our apogee to go down. These factors could also contribute to our decreased maximum velocity. Our maximum acceleration does not match our models well, presumably because of our unexpectedly bumpy landing. However, our acceleration upon liftoff (579.6 ft/s^2) matches the simulation well. Our descent speed was also a lot higher than the simulations, and this must be because in reality, our parachute did not deploy.

Most problematically, after the flight we found that no data had been logged from our sensors. Despite two successful pre-flight on-site test runs of the data logging program, no data was returned from the flight. Our suspicion is that the impact of the rocket landing must have caused some sort of power outage which would have prevented or interrupted the data writing. Only the Raven3 altimeter managed to record data. It is from this source that we have been able to do some after flight analysis.

Perhaps most disappointingly, the camera failed to have any flight recording. We are uncertain if this was due to a similar failure during landing or a human error for failing to turn on/off the recording correctly. We did not attempt to run a test of the active roll/orientation system during this launch. Instead, our primary intention was to test data logging features and use that data as a baseline for calculation roll control.

Changes and Improvements

Our key findings were predominantly in regards to numerous system failures that occurred that need correction before the next flight. Our parachute deployment is the biggest of those concerns. In order to ensure that this does not happen again, we will attempt to use baby powder as a non-flammable dry lubricant to ensure that the parachute will deploy. Also, we are looking into purchasing a slightly larger circular parachute protector to ensure that our parachute can be more protectively wrapped as it was damaged by an ejection charge during our test flight. Other potential improvements include securing the parachute higher on the shock cord while still maintaining that the airframes do not hit each other when the parachute is fully deployed and using a vacuum sealer to reduce the volume of the parachute when packed.

In terms of the programming, we are primarily looking for solutions regarding our lack of flight data. Assuming our working theory of a power loss being the cause, the simple solution would be to continuously write data as it is received into file. However, it was a deliberate decision earlier on in the coding process to avoid that as it was taking prohibitively long periods of time to do so, especially in the time frame of fractions of a second needed to keep consistent microsteps of the motor. The plan that we flew with was to keep all data in memory until descent; the test flight pointed out the assumption that we would have a descent of more than a few seconds. Ideally, this shouldn't be the case again and our current plan to write later will have time to execute. Our major change is to now write data as soon as apogee is sensed as opposed to after the flight has concluded.

The most probably cause of the camera failure was a human error. We are putting a great deal of emphasis on drilling thorough inspections of equipment and status on the camera to ensure functionality in further tests and in competition. Our pre- and post- flight checklists will be updated to include explicit instructions utilizing the multi-colored LED on the camera, each color corresponding to a different status of the camera. Beyond that, we also seek to do further lab testing of the motor functionality to perform an in-flight test in an upcoming test launch. Although we have achieved successful motor acceleration and deceleration, we have yet to attempt that during flight. We are further refining our ability to make accurate turns of the rocket.

Regarding the build of the rocket, in preparation for our second test launch, we will fill the vent holes we drilled in the lower airframe with epoxy so we need not tape them closed for flight. This will help with aerodynamics as well as provide a more secure seal. We also have a few repairs to make because of our rough landing, including replacing the nose cone, replacing the parachute, strengthening the epoxy connections on the lower sleds in the avionics bay, reattaching the upper rail guide, and replacing the camera mount cap.