MIN-D

NASA's Space Grant Midwest High-Power Rocket Competition

University of Illinois at Urbana-Champaign

Illinois Space Society

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Table of Contents

1. Summary of Design

After submitting PDR, the team realized that certain changes were needed to ensure that MIN-D met the competition's expectations. Numerous structural components of the rocket had to be altered, such as the distribution of mass components, to change the location of the center of gravity and magnitude of overall rocket stability. Many avionics elements, such as the attachment of the battery to the PCB, also had to be fixed to ensure that the team will receive data from the flight.

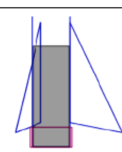
1.1 Structures

1.1.1 Design and Dimensions

A few changes involving dimensions and mass occurred since the submission of the PDR. After the rocket was built, the team weighed and measured each of its components to account for human error and inaccuracies in estimated weights from vendors. The OpenRocket file was subsequently updated with the actual masses and dimensions.

Figure 1: Completed MIN-D at Test Launch

The total mass was reduced by 4.58 ounces, causing the center of gravity (CG) to move towards the bottom of the rocket by about 0.7 inches. The size of the motor retainer was updated, accompanied by a slight adjustment to the fins' location. Additionally, the mass of the avionics bay was more accurate after weighing the assembled avionics panel. The tracker was relocated to the nosecone and held in place by Styrofoam and a centering ring. Metal BBs (referenced as Bebes in the diagram below) were placed inside the nosecone to improve the stability of the rocket, and the bulkhead holding the pitot tube was removed. Two comprehensive rocket diagrams of the dimensions and components of the rocket are shown below in Figure 2 and Figure 3.

ISS SpaceGrant 2019 Rocket "MIN-D" Diagram			
Other Dimensions		**Fins Zoomed In**	
Nose Cone: Plastic 4:1 Ogive **Body tube(3 sections):** Material: Blue Tube 2.0 ID: 2.14" OD: 2.264" Thickness: 0.062"	**Coupler(x2):** Material: Blue Tube 2.0 ID: 2.026' OD: 2.15" Thickness:0.062"		**Number of fins:** 3 **Material:** Plywood with Carbon Fiber wrapped tip to tip **Root chord:** 6" **Height:** 3" **Sweep Length:** 6.6" **Sweep Angel:** 65.6 degrees **Thickness:** 0.17"

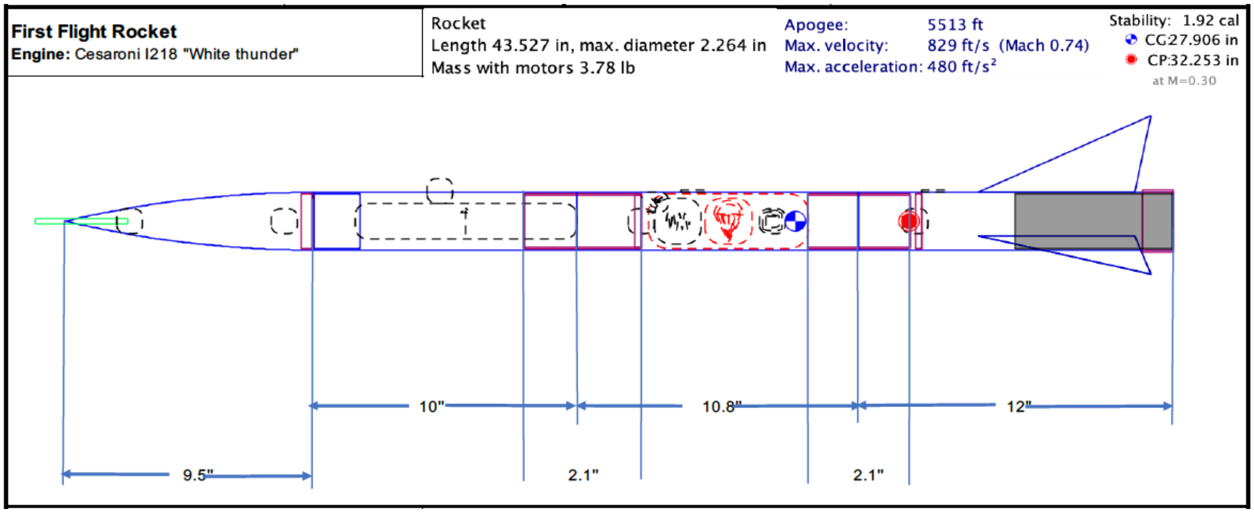


Figure 2: MIN-D Dimensions with I218 configuration

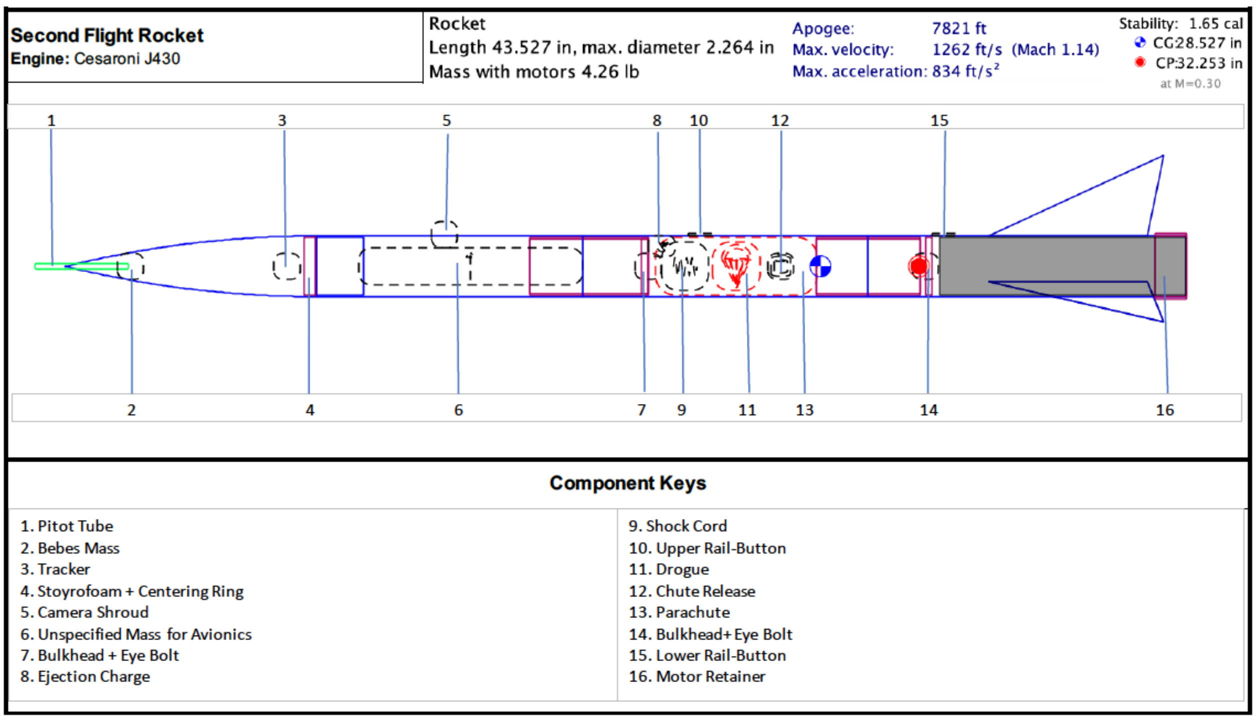


Figure 3: MIN-D components with J430 configuration

1.1.2 Stability Analysis

The stability values of the rocket changed from those predicted in the PDR as a result of mass underestimates. While running OpenRocket simulations post-construction, the stability vs. altitude graphs indicated that the rocket would have a stability of 0.83 off the launch pad with the J430 motor, which is well below the allowed amount for a safe flight of 1.0 or more calibers. To account for this error, 2.8 oz of BBs (small metal balls) were secured with 5-minute epoxy inside the nosecone. This moved the center of gravity upwards, thus achieving an adequate stability of 1.2 calibers off the launch pad. Following this change, as shown in Figure 4, the rocket maintains a stability coefficient greater than 1 until the recovery system deploys.

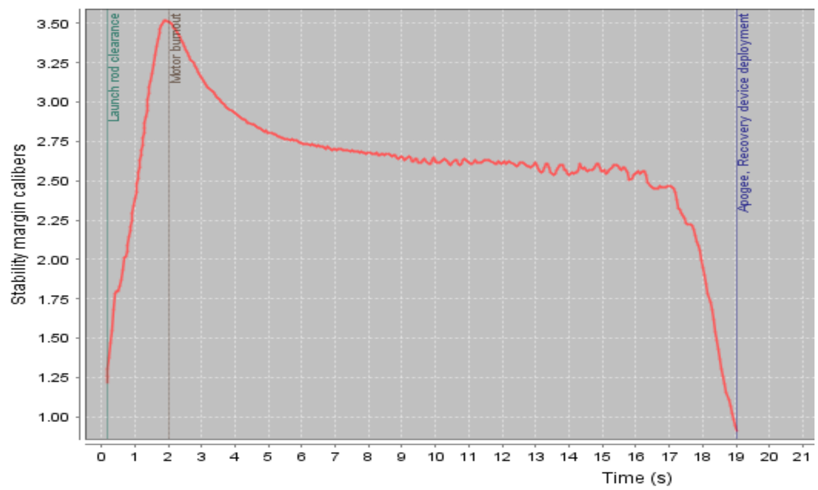


Figure 4: Graphs of Stability Margin (y) vs Time (x) During Simulated Flight with the J430 Motor

1.1.3 Recovery System

The competition requires a safe recovery of the rocket via a drogue and a main parachute with a descent rate no greater than 24 ft/sec when the main parachute is deployed. The parachute system consists of a 30-inch main parachute from Fruity Chutes wrapped in a Chute Release and a 9-inch drogue parachute from Top Flight Recovery. This system allows a quick but safe descent of the rocket while minimizing the drift distance from the launch site to 1500ft. The parachute system was predicted to travel up to three times less distance under Chute Release rather than one with a single chute deploy at apogee. According to the manufacturer's website, the drogue parachute alone is expected to keep the rocket at a constant descent speed of 100 ft/sec (see section 6.1), while the descent rate of the main parachute is expected to be 20 ft/sec.

Both parachutes are situated in the middle airframe. The recovery system is held by a .23" Kevlar shock cord, which is tethered to the rocket via 0.25-inch forged eyebolts to the upper and lower couplers. The ideal length of shock cord for a safe descent is anywhere between three and five full rocket lengths, as recommended by the team's mentors. Based on this, the shock chord for this rocket is 15 feet long, which is the equivalent of 4.2 rocket body lengths. Figure 5 shows where the shock cord is attached with the respect to the upper and lower airframe when the parachute is deployed. The longer end of the shock cord is attached to the lower body tube so that it hits the ground first, leading to less damage to the pitot tube.

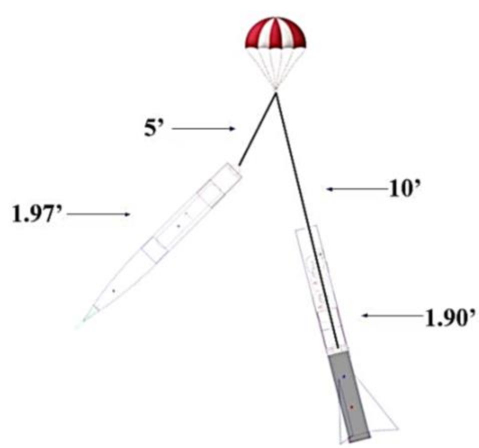


Figure 5: Shock Chord measurements (ft), not to scale

1.2 Overview of Telemetry and Camera Subsystems

1.2.1 Camera

The competition awards bonus points for the addition of a camera system that can see the flames as well as the ground receding during launch, the deployment of both parachutes, and impact with the ground. Based on these guidelines, the team designed a single-camera system that utilizes a triangular mirror piece in order to record video in both directions. The triangular mirror piece is placed outside of the rocket body with a clear, aerodynamic shroud placed on top. The shroud is vacuum formed over a 3D-printed mold and is made from clear PET-G plastic.

1.2.2 Real-Time Telemetry System

The competition offers extra points for the ability to relay flight performance to the ground during flight using a radio telemetry system. The RFM96W 433 MHz LoRa Radio Module will perform this task. Data from all sensors in the non-commercial sensor suite will be transmitted as frequently as possible from the air to the ground station.

2. Avionics Bay Design

2.1 Overview

The Raspberry Pi Zero is the main flight computer. The StratoLogger CF triggers the primary ejection charge once the rocket is at apogee. An Altus Metrum Telemetrum serves as a redundant backup altimeter that deploys a separate electronic ejection charge shortly after reaching apogee, and records acceleration-based velocity measurements.

The team's avionics bay utilizes a Printed Circuit Board (PCB) as the sled along which all electrical connections are routed. All non-commercial components and sensors were soldered directly to the designated pads on the PCB. The PCB circuitry is designed to incorporate three LEDs and a buzzer, programmed to display the status of the flight computer and the health of all batteries. The PCB is secured inside the bay via lightweight, yet sturdy plywood "rails" glued along the upper airframe tube (see section 4.5.4). The components along the PCB are detailed in Figure 6.

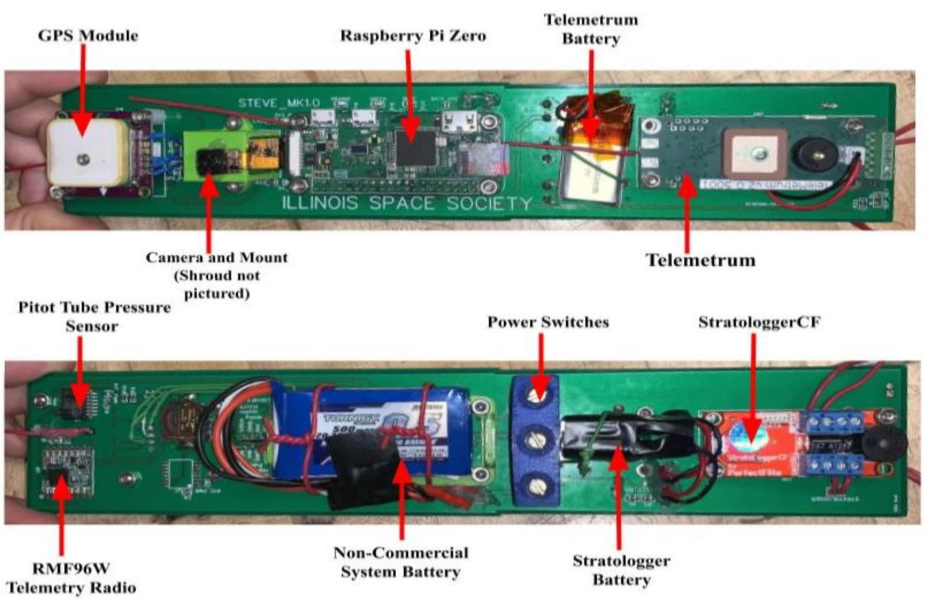


Figure 6: PCB and labeled components

2.2 Power Systems

The avionics package incorporates three separate power systems: one for each altimeter, and one for the non-commercial sensor suite (Figure 7). Each power system has its own switch and operates independently. An analog to digital converter (ADC) is also integrated into the non-commercial sensors suite which will measure battery voltages when the system is powered. This will allow the avionics package to detect battery failure and alert the team through telemetry and the on-board LEDs and buzzer.

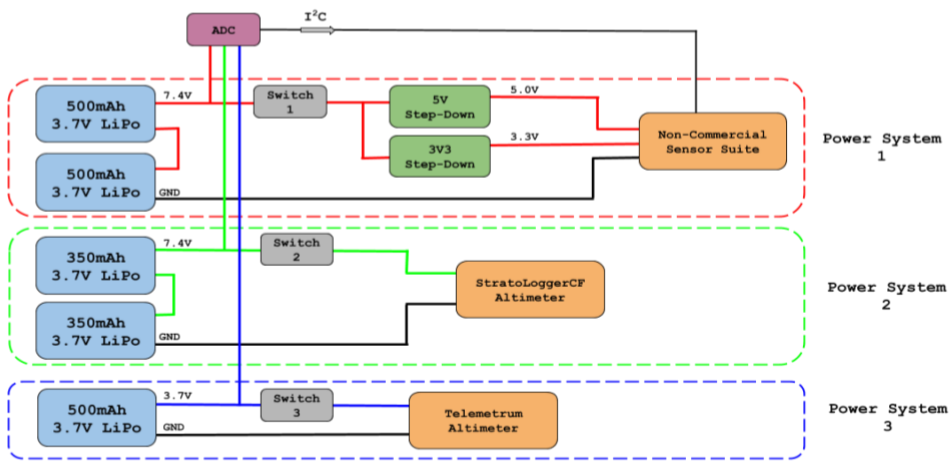


Figure 7: Schematic of the avionics power system

2.3 Non-Commercial Sensor Suites

The competition mandates the integration of a non-commercial sensor suite into the avionics package. A variety of sensors were considered based upon their cost, measurement accuracy, ease of use, and the amount of documentation available. Detailed in Figure 8 is a wiring diagram of all on board data connections.

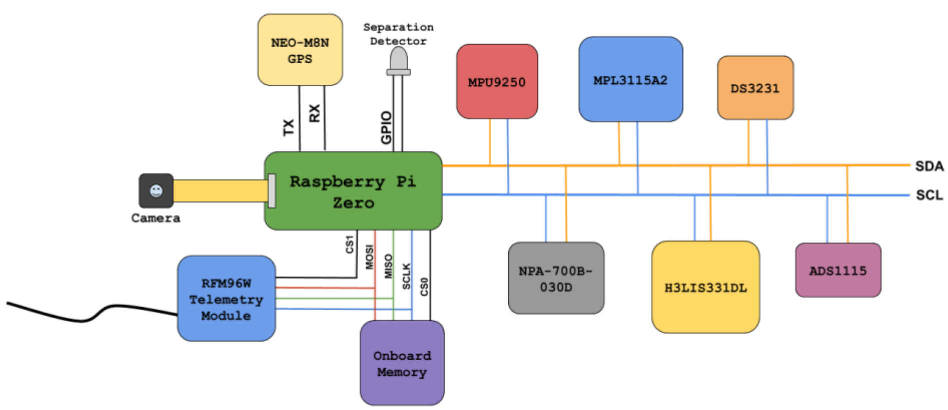


Figure 8: Wiring diagram of on-board data connections

2.3.1 Inertial Measurement Unit

The team decided to use two different Inertial Measurement Units (IMUs) for our rocket. The MPU9250, which has a maximum acceleration reading of 16G, is used in tandem with the H3LIS331, which has a maximum acceleration reading of 400G. The MPU9250's gyroscope will be calibrated at the ground to account for any error since its initial calibration at a factory setting. The gyroscope's data from the

MPU9250 will be integrated continuously to find an accurate reading of the rocket's current heading. This method is only accurate on small time scales as gyroscope sensors are prone to drift over time.

2.3.2 Pitot Static System

The NPA-700B-030D Differential Pressure Sensor is attached to the end of the PCB for ease of access to the nosecone, while the tubes from the pitot tube are attached to the barbs of the sensor. The Raspberry Pi will read the difference between static and total pressures measured by the sensors and transmit the data to the ground. A relationship between Mach number and the pressure ratio measured by the sensor will be derived using the pitot tube formula for subsonic flow and the Rayleigh Pitot Tube Formula for supersonic flow. The pressure data received will then be used to calculate the current airspeed of the rocket.

In the graph below, the team took these data points and interpolated in order to approximate the Mach number. This operation will be performed on the ground with a higher performance computer to reduce the workload on the Raspberry Pi on the rocket.

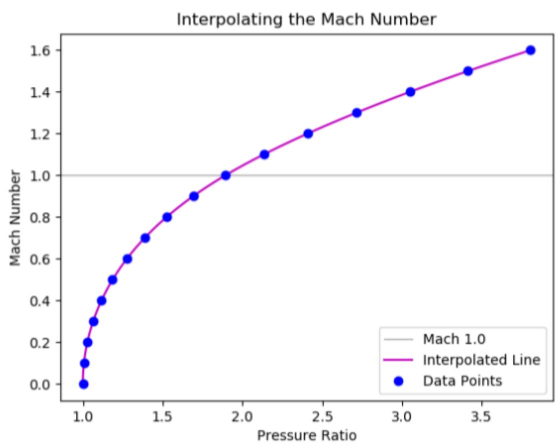


Figure 9: Mach Number approximation

2.3.3 GPS

A NEO-M8N GPS module is used in the non-commercial sensor suite to obtain absolute location and altitude. The location data that will be received from the GPS module will also be sent through the telemetry connection to the ground station, which will aid in recovery efforts. Preliminary testing on campus revealed an accuracy of two meters or better for the GPS module.

2.3.4 Separation Detection

The sensor suite incorporates a phototransistor connected to a GPIO pin of the Raspberry Pi to detect the separation of the upper airframe. A phototransistor is a light sensitive semiconductor that conducts electricity only when light above a certain intensity is shining on it. This device is positioned inside the coupler section directed radially outwards through a hole. This will allow the Raspberry Pi to detect when the upper airframe has successfully separated, as the phototransistor will detect light and conduct electricity. The backup commercial altimeter will be configured to deploy the ejection charge with a 2 second delay after apogee. As a result, the flight computer will determine which ejection charge successfully separated the upper airframe depending on when separation occurred relative to the rocket reaching apogee. This functionality was not implemented during the test launch due to time constraints but will be implemented for the competition flight.

2.3.5 Onboard Memory

Although the Raspberry Pi flight computer features an onboard SD card slot, this method of storage was deemed unreliable due to risk of in-flight vibrations causing intermittent connection losses. The team elected to utilize a W25Q64 SPI Flash Memory chip for high bandwidth data storage which is soldered directly on the PCB ensuring a reliable connection throughout the flight. The onboard video recorded by the Raspberry Pi, however, is recorded on the onboard SD card to not impede flight data during recording processes. After the rocket lands and the flight computer detects that the rocket is stationary, all the data recorded on the Flash Memory chip will be copied into the SD card for convenient data recovery.

2.4 Flight Algorithm and Data Acquisition Cycle

The flight algorithm on the non-commercial sensor suite consists of two major stages. The first stage is the initialization stage where the Raspberry Pi attempts to connect and read data from all sensors. If any discrepancy is detected during this phase, the flight computer will alert the team through the on-board LEDs/buzzer. Once the initialization phase has completed, regardless of whether a fault was detected or not, the algorithm will enter a flight loop. Data from all sensors will be collected at each cycle and stored on the on-board memory chip. A portion of the acquired data will be relayed to the ground station through Telemetry.

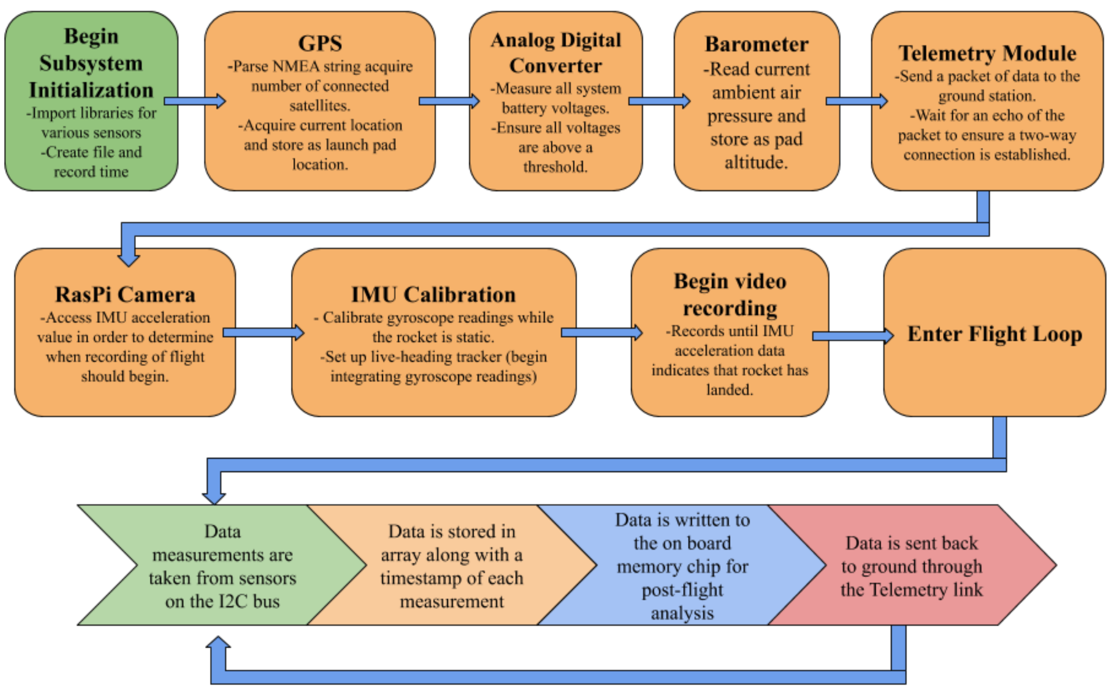


Figure 10: Initialization Flowchart and Data Acquisition Cycle

3. Post-PDR Pre-Test Flight Changes

3.1 Structures

As the rocket was being constructed, changes were applied to the structure and materials of the rocket to optimize its structural integrity, stability, and prevent significant damage to the airframe. These changes include the epoxy used, fin attachment, motor retainer fillets in the lower body tube, material of the lower bulkhead, and added weight to the nosecone.

3.1.1 Epoxy
The epoxy of choice for the construction of the rocket was J-B Weld. The fillet, however, created to hold a bulkhead inside a coupler failed because J-B Kwik was used instead of J-B Weld by mistake. Fortunately, the Illinois Space Society had an abundant amount of G5000 Rocketpoxy left over from previous projects, and the Rocketpoxy fillets were able to withstand any attempt of separation performed by the team.

3.1.2 Lower Body Tube & Bulkhead
The number of carbon fiber layers applied to the plywood core of the fins and the tip-to-tip attachment changed from 3 to 2 layers. Unlike what the team predicted in the Preliminary Design Report, the tip-to-tip layering described in Section 4.3.7, produced a minimal increase in the outer diameter of the airframe. Thus, the team applied fillets to blue tube between the retainer and the airframe to create a smoother transition in diameter. Additionally, the material of the bulkhead closest to the motor was changed from plywood to fiberglass, since it is a stronger and a more heat resistant material and it did not add any additional weight to the rocket.

3.1.3 Nosecone
Once the rocket was fully assembled, the height of the motor retainer in the OpenRocket file was found to be significantly less than its actual height, meaning that the fins were placed above their expected placement. Along with an overestimation of the mass of the upper tube section, this change in placement decreased the stability of the rocket. At the launch pad the stability was predicted to be 0.83 calibers, so the team decided to add approximately 2.8 oz of BBs and epoxy inside the tip of the nosecone as explained in Section 1.1.2 and Section 4.5.6.

3.2 Avionics
The team made several changes in the avionics design to match the rocket's structural changes and to correct design flaws. These changes include altering the shape of the PCB and sled rails, affixing casing around the LiPos, adding cushioning around the avionics bay, adding switch holes, and altering the bulkhead and terminal wires.

Prior to the test flight, the geometry of the PCB and sled rails had to be altered to accommodate the upper coupler. The section of the PCB that rests inside the coupler was made slightly narrower in the second iteration because the coupler changes the inner diameter of the rocket by .062 inches, so the rails and PCB were designed to create a slight "zig-zag" type shape (see Figure 17). The rails also ensure that the avionics sled does not rotate in between the pre-flight procedures and the placement of the rocket on the rail.

Following the test flight, the team decided to add cushioning around the avionics bay to prevent damage during flight. The team plans to add vibration-dampening rubber O-rings around the mounting hardware of the commercial altimeters.

4. Construction of the Rocket

4.1 Airframes
The airframes for the rocket were cut into three parts: the top, middle, and bottom airframes. For the top, a length of blue tube was measured to be 10.04 in. long, and a piece of masking tape was wrapped around the tube to guide the cutting. Then, once it was secured to a table clamp, the tube was cut using a hand saw. Both the middle and bottom airframes were cut using the same procedure, with lengths of 10.79 in. and 12.00 in. respectively. Once the cuts were complete, the ends of the Blue Tube pieces were sanded down to get rid of jagged and non-leveled edges. After this was completed to satisfaction, the tubes were ready to be used.

4.2 Lower Airframe

4.2.1 Launch Rail Guides

The rail guides could not be directly attached to the airframe since the engine retainer's thickness interfered with the rail. Instead, the guides were epoxied to a separate section of blue tube using J-B Weld and then attached to the lower airframe to provide enough clearance for the rail. A Dremel and hand saw were used to cut the blue tube segment. The two rail guides were then vertically aligned on the lower body tube with a short rail and a straight edge. The lowest one was placed between two fins while the other one was placed 7 inches above it, around where the center of gravity was located. After the epoxy cured, the guides were found to be slightly misaligned, so spare guides were attached to another side of the airframe. After the new guides cured, the faulty ones had to be removed from the airframe. Finally, fillets were created between the rail guide and the airframe using J-B Weld, as shown in Figure 11.

Figure 11: Launch Guides on airframe with fillets (left) and team members attaching the rail guides (right)

4.2.2 Lower Coupler and Bulkhead

The lower coupler was inserted into the rocket to ease access to the parachute before and after flights. Given the option to attach the bulkhead and eye bolt to either the coupler itself or the rocket frame, the team decided to attach them to the coupler. This would reduce stress on the epoxy fillets as the coupler stops the bulkhead from sliding up from shock chord stress. The bulkhead was first attached to the bottom of the lower coupler by epoxying its rims into the coupler and epoxy fillets were created where the bulkhead meets the coupler.

4.3 Fins

Since the rocket must withstand the massive drag forces and a 25.91 Gs acceleration that come with supersonic flight, the fins were made from a ⅛ inch plywood laminated with 2 layers of carbon fiber instead of 3 as detailed in the previous report. The team made an estimate of how much the tip-to-tip wrapping and carbon fiber layering on each fin would weigh if 3 layers were applied. However, the maximum velocity and stability coefficient were not as high as expected. As a result of these low values, the team decided to use 2 layers instead of 3, which raised both the maximum velocity and the stability coefficient.

Fin tabs were also incorporated into the design of the fins to create a better attachment to the airframe of the rocket. The tabs were cut at a depth equal to the thickness of the airframe to ensure that the motor casing would not be nesting against the fin tabs. Other than epoxying the fins to the airframe, the team employed a technique called tip-to-tip to secure the fins to the airframe. Details of the process for tip-to-tip will be explained in Section 4.3.7.

4.3.1 Fin Lamination

The shape of the plywood core was created in Siemens NX 12.0 to replicate the chosen design for the rocket's fins. It was then exported as a PDF and laser cut on a ⅛ inch birch-plywood. The plywood core of the fin is shown in Figure 12. The carbon fiber was then layered onto the plywood core of the fins using

Aeropoxy 2032, with the 3660 hardener. First, the fin was placed on parchment paper. The exposed side was abundantly covered with epoxy with a brush, and a single sheet of carbon fiber was layered on top of the plywood. The carbon fiber had been previously cut to a size that is marginally bigger than the fin itself to save as much material as possible. After some compression, more epoxy was applied to the carbon fiber and a second layer was placed on top (Figure 12).

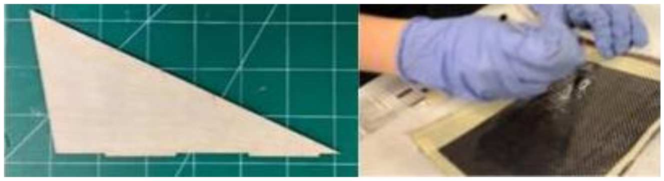


Figure 12: Plywood core (left) and Fin Lamination (right)

After putting more epoxy on the second layer of carbon fiber, peel ply was placed on the fin with small amounts of epoxy. Finally, parchment paper was layered on top of the peel ply and the fin was carefully turned upside down. The same layering technique was applied to the other side. After both sides had been laminated, two small plywood boards were placed on the top and bottom of the fins and were clamped together with wooden clamps. Each fin was compressed for a minimum of 24 hours.

4.3.2 Sanding

Once the fins fully cured, the excess carbon fiber was cut off and sanded using Dremel tools and sandpapers until the fins returned to their original shape. Any residuals were vacuumed throughout the entire process to avoid particulate matter spreading into the air. For a couple of the fins that the team constructed, the carbon fiber did not laminate perfectly to the plywood core, so they had to be remade. This occurred because the fins were not always properly compressed due to the shortage in clamps. The team planned to use wooden clamps that covered the entire fin and spread out the compression more evenly on the fin. However, for a couple of the fins, the team had to use smaller metal clamps that did not cover as much area as the wooden ones, so the carbon fiber was not compressed as well. Additionally, parchment paper was not always on the peel ply, which made the peel ply and the carbon fiber stick to the compression system.

Figure 13 shows the entire lamination process. Going from left to right, the fin was laser cut out of plywood and laminated. Then exposed edges were cut and sanded down to the right shape, and the edge attached to the airframe was cut and sanded down.

Figure 13: Fin Lamination Process (from core to complete lamination)

4.3.3 Tapering

The fins require a 15-degree taper on the leading and trailing edge. To make a precise taper, a platform was built from wood to aid the sanding process. As shown below in Figure 14, the fin was clamped to the inside edge of the wooden fixture. From there, sandpaper fastened to a plywood section was placed on the 15-degree angle created by the fixture. Checking constantly for preciseness, the edges of the fins were sanded to create the taper. With all three fins laminated and tapered, they were attached to the lower airframe of the rocket.

4.3.4 Fin Fixture

To ensure that the fins would be equally spaced on the airframe with exactly 120-degrees between each one, a fin fixture was designed in Siemens NX 12.0 (Figure 14) and laser cut on a 0.2 inches thick foam panel. The design is comprised of two 11.8 inches by 11.8 inches foam squares and four 11.8 inches by 1.18 inches foam rectangles. The panels have a cut out at their centers outlining of the horizontal section view of the rocket, one of them including space for the fins to rest in. There are slots at the midpoint on each side of the main panels and along the four foam pieces such that the panels would be held at a set length of 10 inches apart.

4.3.5 Fin Slots

The fins were first attached to the airframe by using J-B weld. Using the fin fixture as a guide, slots were traced on the airframe where the fins would be attached. Using a Dremel tool, the slots were carefully cut from the tube such that the fin tabs can rest in them (Figure 14).

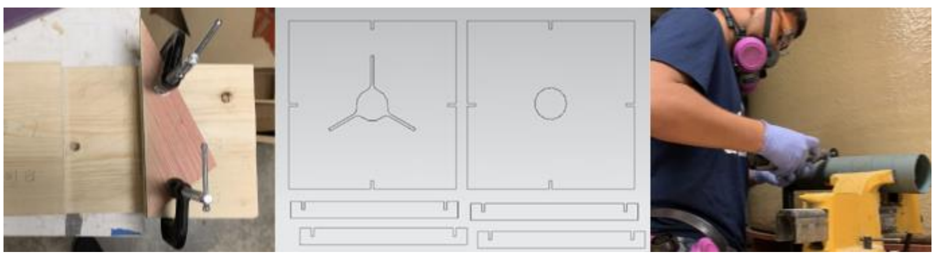


Figure 14: Fin Taper set up (left), NX 12 design of Fin Fixture (middle), and Fin Slots being cut with Dremel (right)

4.3.6 Fin Tabs Attachment & Fillets

Once the fin slots were cut on the airframe, the rocket was placed inside the main panels of the “fin fixture” while the fins were epoxied to the airframe (Figure 15). Masking tape was used to avoid getting any J-B Weld on other parts of the tube. Because the fins are in direct contact with the motor casing, they experience drastic temperature change during the flight. However, if equal parts of J-B Weld are mixed, the epoxy can withstand up to 287.8 degrees Celsius after curing. Therefore, the team is confident the epoxy will not fail from heat exposure.

Figure 15: Fin being held in Fin Fixture after attachment (left) and tape removed from fin after curing time (right)

After the fins dried, fillets were created. Before applying the fillets, new score lines made with masking tape were placed ¼’’ from the bottom fin on both the airframe and the fin to contain the epoxy. The parts of the airframe where the epoxy was applied were sanded for a better surface bonding between the epoxy, fins, and airframe. After 24 hours, the tape was removed (Figure 15) and the excess J-B Weld was sanded to minimize discrepancies to ensure a smooth tip-to-tip process. The team noticed that some epoxy dripped inside the airframe. Thus, a metal file and sand paper were used to get rid of the excess such that the motor case would slide in and out of the airframe without any issues.

4.3.7 Tip-to-Tip

The next step to further secure the fins onto the airframe is a process called tip-to-tip. First, six pieces of carbon fiber cloth were cut to the size that exactly matches the area from one-half of the height of one fin, airframe area in between the fins, and the one-half height of another fin. Epoxy was lavishly applied layer by layer in between the layers of carbon fiber like what was done to the plywood core of the fins. While applying laminating epoxy, wooden popsicle sticks were used to smoothen the surface to make sure that the carbon fiber and airframe were in full contact before applying another layer. After both layers of carbon fiber were fully attached to the airframe, a sheet of peel ply and parchment paper were then layered on top for a clean finish.

Once all the layers of fabric were on the rocket, compression was needed for a few reasons. It helps ensure a complete adhesion of the fabric to the surface, smooth small imperfections that could damage the rocket's stability and squeeze out the extra epoxy which saves weight. To accomplish this task, a 3D-printed fixture (Figure 16), consisting of two sets of two mirrored pieces that fit the airframe's curvature and lined up with the fins, was created. Then, after the epoxy and layering was done, the fixture was put on the rocket and secured with a couple of clamps so that equal pressure was applied to all parts of the compression system. After these were set up appropriately, the rocket was positioned in such a way to allow the epoxy to fully set and cure evenly.

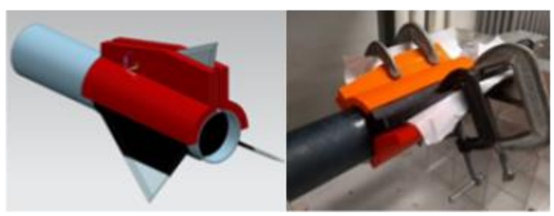


Figure 16: NX 12 model of Fin Compression Fixture and Rocket in Fin compression fixture (right)

After the tip-to-tip application was completed, there were holes in the carbon fiber that needed to be filled up to make the carbon fiber wrapping flush. To do so, J-B Weld was added to the holes and sanded down to make it flush with the rocket once cured. In addition, the part of the carbon fiber wrapping closest to the top of the rocket was also sanded down in order to create a shallow gradient going from the outer radius of the blue tube to the top layer of carbon fiber. This was done to ensure better performance in supersonic flight, as a gradual change in rocket diameter creates less drag. The final product is shown in Figure 17.

Figure 17: Post tip-to-tip and epoxy fillings

4.4 Middle Airframe

4.4.1 Parachute & Shock cord

The parachute system consists of a main parachute, drogue parachute, parachute protector, shock cord, and Jolly Logic Chute Release. The system initially utilized a quick link to tie everything to the shock cord, but it was too large and obstructed the packing process. As a solution, the shock cord is directly tied to the button-hole slot of the parachute protector using a self-tightening bowline knot. Eliminating the quick link saves space and weight in the rocket, but also limits the ability of attaching and detaching the parachute in case of entanglement. The first step of the installation of the shock cord is to tie the lower end of the cord to the lower eye bolt with a bowline knot. The shock cord is then fed through the middle airframe and the top of the shock cord is attached to the top eyebolt with the same knot. The packed parachute is placed inside the airframe, and the packing process is detailed in Section 5.1.1.

4.5 Upper Airframe and PCB

4.5.1 Upper Coupler & Bulkhead

In order to provide a secure point of attachment for the shock cord, a forged eye bolt is threaded through a 0.25-inch-thick plywood bulkhead. The eye bolt's thread was cut to the minimum length necessary to accommodate a hex nut and washer on both sides. The eye bolt was then tightened and further secured using epoxy resin. The bulkhead and eye bolt assembly were then epoxied into the upper coupler, 0.25 inch in from the edge of the coupler tube. The bulkhead had to go inside the coupler instead of flush against the coupler so the shear pin holes could be drilled below the bulkhead. This way the bulkhead protects the avionics from damage resulting from the ejection charges. A 3D printed ring with .25-inch length was created to easily epoxy and fillet the bulkhead in the proper position.

After the epoxy dried and the coupler was confirmed to be secure, a .25-inch diameter hole was drilled in the upper bulkhead to route ejection charge wires through. Two wire terminals were then epoxied on the bulkhead to allow for convenient ejection charge connections.

4.5.2 Ejection Charge & Shear Pins

The black powder charges are mounted behind the parachutes in the lower coupler. This decision came after ejection charge testing, described in Section 5.1.1. When assembling the rocket, the black powder charge in an e-match would first be wired to the terminals on the upper bulkhead. The completed primary and backup charges then were taped to the inside of the bottom coupler.

Once the ejection charge goes off, the upper and the middle airframe must separate to let the recovery system deploy. The team used 3 2-56 shear pins to hold the two sections together. 3 holes were drilled 120 degrees apart in the upper airframe and the upper coupler.

The ejection charges were sized using a combination of calculations, ground testing, and drag estimates. Three pins can withstand up to 64.24 lbs of shearing force, which is enough to hold the components together against the drag forces pulling them apart. Using Table 1, the team computed that a minimum of 0.01975 ounces of black powder is needed to break the pins apart. It is important to note that using the minimum amount will not cause pins to completely shear. So, the primary ejection charge is 0.02645 ounces of black powder and the back-up is 0.03527 ounces.

$$\frac{[\text{Pressure (psi)} \times \text{Diameter(in)} \times \text{Length(in)}]}{28.35} = \text{Mininum mass of Black Powder (oz)}$$

Equation 1: Black powder calculations

Table 1: Shear Pins and Ejection Charge Description

Flight: Parachute Deployment and Separation of Middle and Upper Airframes	
Tube Diameter (in)	2.264
Tube Length (in)	10.79
Desired Pressure (psi)	25.00
2-56 Nylon Pins Shearing Force (lbf)	64.24
Results: Use 3 2-56 Nylon Screws and Use Minimum .01975 Ounces of Black Powder	

4.5.3 Camera Shroud

The shroud was constructed from clear Pet-G vacuum-formed over a 3D-printed mold. The mirror piece was then epoxied into the center of the shroud. Finally, epoxy was added to the inner rim of the shroud, placed onto the upper airframe and left to cure (Figure 18).

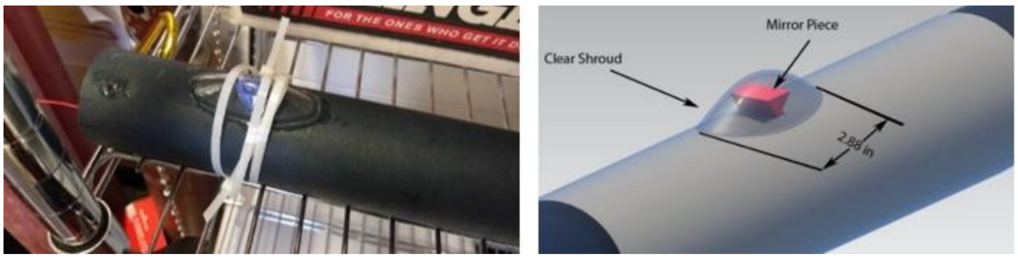


Figure 18: The shroud tied to the airframe while the epoxy cures (left) and CAD render of shroud on body (right)

4.5.4 Avionics Rails

A bend was added to the plywood rail design to fit the inside of the coupler and upper airframe. The fixtures used to insert the rails were modified from the original procedure to have empty centers, which allowed for easier removal of the fixtures once the rails were epoxied in place. To implement the rails, they were first slotted into and lightly glued to the fixtures using CA glue. Hexion epoxy was then applied to the rails, as shown in Figure 19, and the fixtures were slotted into the airframe. The rails were broken away from the fixtures to fit against the inner rocket walls. Once the fixtures were removed, epoxy fillets were applied along the rails to further reinforce their connection to the blue tube.

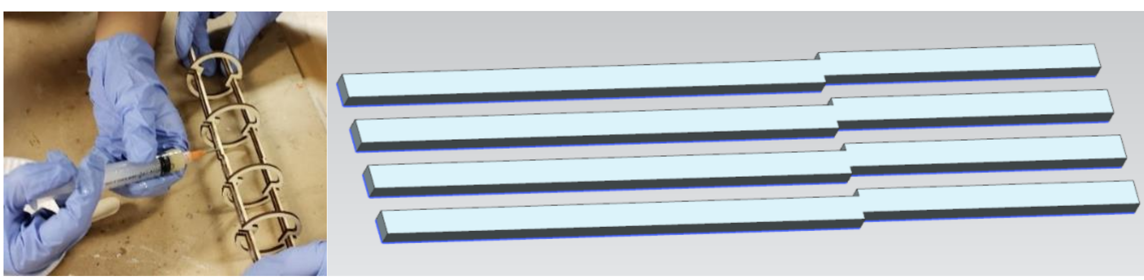


Figure 19: Epoxy being applied to the avionics bay rails (left) and a CAD model of the rails (right)

4.5.5 Switch Holes

Switch holes were drilled into the upper airframe directly above the switches that turn on the power for the PCB. A printed plastic guide was attached to the PCB which guides a screwdriver to the switch heads. The power can then be turned on and off with the PCB inside the upper airframe by poking a screwdriver into the holes in the upper airframe through the holes in the plastic piece above the switches and turning the switch. Since both altimeters and the non-commercial sensor suite have integrated buzzers, the power will be confirmed to be on when the buzzers are heard.

4.5.6 Nosecone and Pitot Tube

Due to the small diameter of the nosecone, the team ran into issues with the size of the pitot tube. To account for the narrowness of the nosecone, the plastic piece on the pitot-static tube was remodeled to have two barbs pointing vertically down from the pitot tube toward the PCB.

A hole in the tip of the nosecone was drilled for the pitot-static tube. Masking tape was applied all around the protruding section of the pitot tube to prevent epoxy from entering the static ports during the procedure. The nosecone was suspended between two shelves on a tabletop to ensure stability. G5000 Rocketpoxy was applied around the pitot tube inside of the nosecone.

4.5.7 PCB Assembly

The assembly of the PCB was conducted in two stages. The passive components (resistors, capacitors, etc.) were the first to be populated on the board as they are small and do not impede the placement of larger components. Next, the more intricate components like sensors and integrated circuits were populated. This order reduced the amount of heat stress on the more sensitive components. All components were soldered onto the board using solder paste and reflowed using hot air.

5. Test Flight

5.1 Pre-Test Flight

5.1.1 Recovery System Testing

The parachute needed to be packed in such a way that would minimize the space occupied inside the tube. The main parachute, the drogue, and the Chute Release device were tied to the knot on the shock cord that holds the parachute protector. The main parachute is then untangled, spread out, and folded to keep the shroud lines inside the folds. The rolled-up parachute has a diameter of about 2 inches and a length of 4 ½ inches. The Chute Release is tied around the parachute to hold it as it is. Then, the drogue is folded inside the parachute protector and the main is placed on top, as shown in Figure 20.

Figure 20: Main parachute packed, then being rolled up in the protector with drogue, and inserted in the tube

Finally, the contents inside the protector are rolled up such that the protector covers every part. The team practiced this procedure several times and tried blowing the parachute out of the tube to ensure smooth deployment during flight. The shock cord attachment is detailed in Section 4.4.1Parachute & Shock cord.

To ensure successful separation of the rocket, the team must perform ejection charge testing at least 24 hours before the launch. For testing, the rocket is fully assembled with recovery system and shear pins, and two electronically activated charges are installed in the lower airframe below the parachute. Initially, the charges were installed above the parachute, which separated upper airframe, but the recovery system was not deployed. Due to this failure, for the second test, the ejection charge was moved behind the recovery system, ensuring that the ejection charge force will push the recovery system out of the airframe. In this test, the upper airframe failed to separate altogether, indicating that the friction force created by the packed parachute was too great. In the third attempt, the ejection charge remained behind the recovery system and the parachute packing method was changed to pack the recovery system even more than before. The final ejection charge test succeeded in separating the rocket and deploying the recovery system (Figure 21).

Figure 21: Successful Ejection Charge test (Nosecone and Upper Airframe separate)

5.1.2 Preflight Procedures

At the test flight location, the preflight procedures followed the same structure as the procedures outlined in the Preliminary Flight Report. During the test launch however, revisions were made to make certain steps more detailed and easier to comprehend. These changes are described in Section 5.1.7.

5.1.3 Flight Information

The team's test flight took place in Tab, Indiana, where MIN-D was launched along with many other rockets from various groups. On the day of the launch, scattered cloud coverage was observed but the skies were ultimately very clear and safe for launch. The team immediately set to work on assembling the rocket and came prepared with multiple cameras to document the launch, as detailed below.

Figure 22:Avionics installation (left) and assembled rocket (right)

5.1.4 Launch & Boost Phase

During the launch and boost phase, the rocket performed as expected and flew off the launch rail at approximately 3 degrees south. With the assist of the wind, which was blowing at a ground speed of approximately 12 ft/s northeast, the rocket achieved a nearly vertical flight. Right at lift-off, however, the team lost connection with the avionics bay and could not receive any data.

Figure 23: Pictures from test launch

5.1.5 Coast & Descent Phase

The videos of the launch show the rocket going beyond the broken clouds and out of sight. Beyond this point, it is unclear what happened to the rocket. The rocket's parachutes might have not deployed, and the rocket might have come down ballistic. They could have also deployed prematurely, and the rocket could have drifted far away. The team is confident that the rocket came down ballistic because the tracker suddenly lost signal about 30 seconds after launch, meaning that the tracker most likely hit the ground with a large impact at that time. No one at the launch site was able to see the rocket come down, likely due to everyone's gaze being fixed upwards. There was also no reported noise of the rocket crashing down.

5.1.6 The Search

After no one at the launch site was able to spot the rocket on its way down, the team spent several hours searching for it. The GPS data only had the coordinates of the rocket on the pad, but the tracker showed that the rocket went slightly east. The tracker, however, did not give evidence of the rocket drifting far.

In response, the team used a methodological approach to find a hole in the ground with a rocket. Each person lined up five to ten feet apart and thoroughly searched for holes which was ultimately unsuccessful.

5.1.7 Pre & Post Launch Procedures assessment

During the test launch, the pre and post launch procedures were followed such that they simulated the competition. Following each step one by one, several adjustments were made to the procedure in order to maximize efficiency and clarity. Several mistakes were found in the recovery system procedure that caused the parachute to have to be packed multiple times at the test launch site. Out-of-order steps also caused unnecessary wait times between components of the rocket. The post flight procedure was also not followed since the rocket signal was lost. The revised pre and post launch procedures are found below in Table 2: Revised Flight Procedures

Table 2: Revised Flight Procedures

Avionics Launch Procedures		**Signed off by Team Lead (Y/N)**
Step Number	Description	
Off Pad		
Telemetrum		
1	Orient avionics bay vertically and power on Telemetrum	❒
2	Attempt to connect through telemetry radio	❒
3	Ensure correct call sign and adequate battery voltage	❒

4	Ensure Telemetrum in launch mode	❐
Stratologger		
1	Power on Stratologger	❐
2	Listen to beep sequences and ensure adequate battery voltage	❐
Non-Commercial Systems (Raspberry Pi)		
1	Power up non-commercial sensor suite	❐
2	Observe LED blink sequence through camera hole	❐
3	Ensure solid green light continuously on	❐
Structural		
1	Confirm structural integrity of circuit board	❐
2	Confirm battery connections and securement	❐
3	Ensure adequate securement of SD Card	❐
4	Ensure all telemetry antennae are connected and stowed securely	❐
5	Place tracking radio in nosecone and secure with lightweight reinforcement	❐
6	Ensure pitot tube hoses are connected to DPS	❐
7	Attach long wires to Stratologger and Telemetrum terminals	❐
8	Thread wires through avionics bulkhead	❐
9	Insert avionics package into upper airframe	❐
10	Check alignment of camera	❐
11	Mount and secure nosecone using rivets	❐
12	Cut excess wire, strip, and attach to terminals on the bulkhead	❐
13	Confirm ejection charge wire connection	❐
14	Install tracker in the nosecone	❐
15	Turn off all avionics before bringing the rocked to the pad	❐
Structures Launch Procedures		
Engine Assembly		
1	Inspect the motor casing for damage, discard if damaged	❐
2	Remove Ejection charge from charge casing	❐
3	Twist bare ignitor leads several times before proceeding with installation	❐
4	Uncoil ignitor leads	❐
5	Remove any kinks and straighten the wire for 24”	❐
6	Remove nozzle cap from motor, feed ends of ignitor through engine hole	❐
7	Insert ignitor head into nozzle until it stops on ignitor pellets	❐
8	Bend a loop one cap length from the nozzle exit	❐
9	Slide nozzle cap up to the loop of wire, push the cap over nozzle and loop	❐
Parachute and Middle Tube Assembly		
1	Re-tie parachute to the shock cord	❐
2	Pack parachute temporarily to pass it to through the middle body tube	❐
3	Tie shock cord to the bottom coupler	❐
4	Turn on the chute release	❐
5	Put main, drogue, and remaining shroud lines inside chute protector	❐
6	Pass the parachute through middle tube	❐
7	Roll up chute protector on one side, fold left and right sides in	❐
8	Roll on the other side to close the protector	❐
9	Get upper body tube from Avionics	❐
10	Feed the wire through middle tube and	❐
11	Attach charges to the side of the bottom coupler	❐
12	Attach lower body tube to middle airframe with plastic rivets	❐
13	Feed bottom shock cord and parachute protector through the middle tube	❐
14	Feed leftover shock cord above the parachute protector	❐
15	Tie shock cord to the upper coupler	❐
16	Assemble primary and backup black powder charges, secure to terminals	❐

Lower Body Tube Installation		
1	Insert fully assembled engine into the lower body tube	❒
2	Put on both retaining rings	❒
On Pad (Both subteams)		
1	Turn on Telemetrum	❒
2	Turn on Stratologger	❒
3	Tun on Raspberry Pi	❒
4	Put the rocket on the rail	❒
5	Remove the shunt and separate wires when the rocket is installed on pad	❒
Post Flight		
1	Locate rocket and assess major rocket damage	❒
2	Remove plastic rivets from lower body tube and check for unexploded charges	❒
3	Take out spent motor casing	❒
At Inspecting Table		
1	Carefully remove plastic rivets from the upper body tube	❒
2	Remove PCB from rails and inspect avionics	❒
3	Retrieve any data on the PCB that wasn't captured by the telemetry	❒

6. Discussion of Results

6.1 Open Rocket vs RASAero 2 analysis

After the test flight yielded little data on the telemetry of the rocket, the team proceeded to find another simulation software to ensure that the rocket would reach supersonic speeds and compare those flight values to the ones predicted by Open Rocket. The most accurate was found to be RASAero 2 since their website reports that there is only an average error of 3.68% between comparing altitude expectations between the software and real flights. Since the velocity and position of a rocket over time are related by acceleration, it can also be assumed that there would also be a similar level of accuracy in terms of top speed. The values of both simulations are listed below in Table 3. It was found that OpenRocket overestimated the speed of the rocket by Mach .03 +/- .025 and predicted a similar apogee height of 7432 ft +/- 222 ft.

Table 3: Predicted Flight Values and RASAero 2 values

Quantity/Characteristic	Open Rocket	RASAero 2
Total Mass	4.26 lbs.	4.26 lbs.
Maximum Altitude	7821 ft	7432 ft
Maximum Velocity	1262 ft/sec (Mach 1.14)	1248 ft/sec (Mach 1.11)
Maximum Acceleration	834 ft/(sec2) or 25.91 G	854.6 ft/(sec2) or 27.05 G
Drogue Parachute Descent Speed	95.25 ft/sec	100 ft/sec
Main Parachute Descent Speed	19.3 ft/sec	20 ft/sec
Time to Motor Burnout	1.98 sec	1.97 sec
Time to Apogee	18.8 sec	18.8 sec

Through analysis in RASAero 2, the team was also able to determine where the rocket might have landed. If it came down ballistic, then the rocket could have come down 900 ft away, due to the windspeed being about 12 ft/s in the northeast direction. If it did not come down ballistic, the rocket could have landed around 1500 ft away.

In the RASAero 2 simulations, the team assumed that the only source of drag, before main deployment, was the 9” drogue parachute and did not model the drag that the wrapped parachute would produce. This was due to a limitation in the software not allowing for the modeling of parachutes wrapped in Chute Release during the drogue descent phase. Therefore, the team knows that the descent values under drogue are artificially inflated and they are low enough for safe flight and recovery.

The team also tried using a software called Tracker to analyze position, velocity and acceleration of the rocket. Unfortunately, there were many errors and Tracker did not produce consistent data.

6.2 Avionics Assessment

The rocket potentially came down ballistic due to failures in the avionics bay. The main issue is believed to be that the initial change in momentum upon launch led to a disconnection of the batteries for the TeleMetrum and Stratologger. This is supported by the immediate loss of telemetry data displayed when the rocket left the launch pad. Because the TeleMetrum's battery was wired and secured similarly to that of the Stratologger, it is likely that both lost power for the above reason. Thus, the team believes that the commercial altimeters did not have power to ignite the ejection charges and bring the rocket down safely. Additionally, an independent radio tracker placed in the nosecone lost signal about 30 seconds into flight. When compared to simulation data, which demonstrates that this is about double the amount of time necessary to reach apogee, it can be concluded that the rocket went ballistic.

6.3 Possible Sources of Error

Reviewing the rocket launch, the team believes that the Avionics Bay likely lost its ability to trigger the ejection charges, resulting in the loss of the rocket. Considering the design of the rocket, a table of potential issues including their solution and likelihood is listed below in Table 4. The Likelihood is ranked on a scale of 1-5 where an event listed as a 5 is the most likely to occur.

Table 4: Possible Issues with the Rocket and Applied Solutions to the Revised Design.

Issue	Solution	Likelihood
Li-po batteries disconnected	3D print Li-po retainers in order to better secure the Li-po batteries. Utilize proper connector hardware to minimize the risk of in-flight power loss.	**5**
Altimeters came loose	Tighten and use thread locker on the screws connecting the Altimeters to the PCB.	**4**
Terminal Wires Disconnected	Obtain higher quality terminal blocks and ensure wires are secure prior to sealing the rocket.	**4**
Structural failure of the rails	Increase the size of the rails along all dimensions within the constraints of the upper airframe.	**3**
Structural failure of the airframe	Increase the amount of epoxy to attach the couplers, increase size of vent holes in case of ejection charge failure.	**3**
PCB Structural Failure	Create new battery securement structure in order to keep the PCB as secure as possible within the upper airframe.	**1**

7. Post-Test Flight Changes

7.1 Structures

The entire rocket had to be rebuilt due to malfunctions which are explained in detail in Section 6.2. The team is currently working on assembling a new rocket with the structure and dimensions remaining unchanged. The purpose of this is to maintain consistency with the previous simulations. This time, the blue tube was cut using a Miter Saw instead of a hand saw to achieve both a smoother finish and a shorter sanding time. In addition, due to the 25.91 Gs of acceleration that the rocket experiences right after lift-off, the team will make sure that the parachute is packed more tightly and to a smaller size such that the recovery system is guaranteed to deploy when the ejection goes off.

7.2 Avionics

7.2.1 Stress Testing

To ensure that the avionics bay's structural integrity can withstand flight conditions, the team will put the rebuilt avionics bay through a carefully designed stress test. The team will calculate the maximum force exerted on each component on the PCB during flight and simulate that force by hanging weights off the attached component. By testing the security of the avionics bay before flight, the team will identify any possible structural weaknesses of the avionics bay. Any loose components will be securely fastened to the PCB using epoxy, 3D-printed retainers, zip ties, thread locked bolts, and any other means necessary.

7.2.2 Attachment of LiPos

Leading up to the test flight, a problem the team faced was the batteries on the PCB could not be charged conveniently because the LiPo's were soldered directly to the board. The redesigned PCB will not have the LiPos soldered to the board, but instead connected to the PCB using JST-PH connectors.

The team concluded that the lithium-polymer batteries likely detached from the PCB during launch. Therefore, the batteries on the revised avionics bay will be much more secure for the final launch. This will be accomplished by 3D printing retainers that will be bolted down onto the PCB so that it can withstand the 25.91 Gs that the rocket endures. The retainer will enclose the entire battery to secure attachment to the board and minimize the effects of the high acceleration. Tests will be completed with a safety factor to ensure the retainers stay on the PCB.

7.3 Execution Plan and Timeline

During the second semester, an average of 6 build sessions per month were scheduled to ensure that both avionics and structures could finish building the rocket on time.

The fins sub-team had a 4 build sessions per week in order to finish building carbon fiber overlay and tip-to-tip in a time span of two weeks. Due to scheduling issues, risk factors, the team decided to not have a second test launch. The earliest available date for the rocket launch was then May 4th and if the rocket was to be launched on or after this date, it would have been extremely difficult to fix the rocket before the competition if something were to go wrong again.

Table 5: Construction Timeline

Week	Structures Progress	Avionics Progress
3/11-3/17	- Airframe sections & eyebolts cut - Motor retainer attached - Shear pin/Plastic rivet/Vent holes drilled	- All avionics components arrived - Began populating PCB components - Conducted telemetry and GPS tests. - Epoxied rails into upper body tube
3/25-3/31	- Fins laser cut and CF layup process - Excess carbon fiber sanded - Coupler assembly built	- Populated PCB components - Troubleshot minor connection errors - Vacuum formed camera shroud
4/1-4/7 **Week of Ejection Charge Testing**	- Fin slots cut on airframe & fins attached - Carbon fiber tip-to-tip process for fins - Bottom coupler attached to airframe - Recovery system integration	- Implemented and began debugging main flight algorithm - Drilled switch and the camera holes - Glued camera shroud and mirror
4/8-4/14 **Week of Test Flight**	- Rail guides attached with fillets - BB pellets epoxied into nosecone	- Secured batteries onto PCB - Sealed Avionics package in airframe
4/15 – 4/21 **- FRR Started** **- New Parts Ordered**	- Airframe sections & eyebolts cut - Motor retainer attached - Shear pin/Plastic rivet/Vent holes drilled	- Began PCB redesign - Evaluated possible failure points
4/22-4/28	- Carbon fiber layup process completed - Excess carbon fiber sanded & fin slots cut	- PCB redesign continued
4/29-5/5	- Fins attached to airframe with fillets	- PCB was sent for manufacturing

- FRR Completed		- A new shroud was vacuum formed -Rails were epoxied to upper airframe
5/6-5/12 (Planned)	- Carbon fiber tip-to-tip process for fins - Coupler and hole integration - Recovery system integration - BB pellets epoxied into nosecone	- PCB and components arrive - PCB is populated and tested - Range testing of the telemetry and GPS radios is conducted

7.4 Post-Test Budget

Following the test flight, some of the rocket's components needed replacing. However, the team already had some components present in the previous budget, leading to less items being needed for the new budget. The bulk of this cost is due to purchasing a new TeleMetrum. Details of the pre-test flight, post-test flight structures, post-test flight avionics, and budget totals can be found in Table 6. Travel costs are estimated to be $2600.

Table 6: Post-Test Flight Structures Budget

Post-test Avionics Budget			**Post-test Structures Budget**		
Item	**Amount**	**Total Item Price**	**Item**	**Amount**	**Total Item Price**
500mAh2s 7.4V LiPo Battery Pack	1	$10.99	54mm Plywood Bulkhead and Eyebolt	4	$11.56
350 mAh1s 3.7V LiPo Battery	4	$25.96	54mm Coupler Bulkhead	4	$11.56
NP-700B-030D Differential Pressure Sensor	1	$22.27	54mm 2-Grain Case	2	$120.84
Screw Switch	3	$21.45	54mm Slimline Motor Retainer	1	$25.31
Plywood for Rails	1	$11.67	Removable Plastic Rivets	2	$7.72
M3 Standoffs	1	$5.89	Launch Rail Buttons	1	$6.53
Altus Metrum TeleMetrum	1	$300.00	SKU: BT20-5448 Blue Tube 2.0 Airframe	1	$17.64
Section		**Total Price**	Blue Tube 2.15 Coupler	2	$18.50
Pre-Test Flight Total		$886.38	¼ inch Forged Eyebolts	3	$17.19
Post-Test Flight Structures		$469.40	5-Minute Epoxy	1	$8.99
Post-Test Flight Avionics		$398.23	Drogue Parachute PAR-9 TFR	1	$5.00
Post-Test Flight Total		$867.63	54mm Aft Closure	1	$53.32
Total (not including travel)		**$1754.01**	Rocketpoxy	1	$43.75
			3K Carbon Fiber Fabric Rolls: 50 inches by 36 inches	1	$24.68
			Kevlar Shock Cord (15 ft)	1	$15.15
			Main Parachute, Model CFC-30-S	1	$72
			Shear Pins, 20-pack	1	$9.66