MIN-D

NASA's Space Grant Midwest High-Power Rocket Competition

University of Illinois at Urbana-Champaign

Illinois Space Society

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1. Summary

1.1 Executive Summary

The Illinois Space Society (ISS) team designed "MIN-D" to compete in the 2018-19 Midwest High Power Rocketry (MHPR) competition. The first competition objective is to design a rocket that achieves the highest altitude, velocity, and acceleration compared to other competing rockets using a Cesaroni 491-I-218-14A "White Thunder" motor. The second objective is to use the same rocket and a Cesaroni or Aerotech I or J class motor to achieve the most efficient supersonic flight as defined by the competition statement. The bonus challenges will also be tackled by creating a camera system and a telemetry system that communicates data back to the ground.

The ISS team consists of 26 undergraduate freshmen from the University of Illinois at Urbana-Champaign. Charlie Foster, a freshman in aerospace engineering, serves as team lead and manages the project. The team is broken down into two sub-teams: structures and avionics. The structures team, led by Tyler Yokoo, a freshman in aerospace engineering, will focus on the physical build of the rocket, as well as making sure the rocket will fulfill the competition objectives that rely on aerodynamic and structural design. The avionics team, led by Ayberk Yaraneri, a freshman in aerospace engineering, will design, manufacture and program a flight computer with data acquisition and telemetry capabilities. Throughout the year, these sub-teams will collaborate to create a rocket capable of completing all the specified objectives. Connor Latham, an ISS member in his junior year, will guide and mentor the team through his position of ISS Technical Director. He will aid the team with design, construction, testing, and analysis to ensure the rocket is completed safely and efficiently.

To achieve a minimum mass, the team chose a minimum diameter rocket design, with a 54mm Blue Tube 2.0 tube. The length of the rocket is roughly 44.7 inches. The rocket will weigh roughly 65.0oz for flight I and 72.7oz for flight II. In addition, the team decided to save mass in as many areas as possible using components such as a plastic nose cone, and a chute release, and a Blue Tube 2.0 airframe. With the reduced mass, the second launch will use the Cesaroni J430-WT motor, which will have a lower maximum thrust and total impulse. The on-board flight computer will be powered by the Raspberry Pi Zero single board computer. An array of sensors- including accelerometers, gyroscopes, magnetometers, a barometer, a camera, and a pitot-static system- will measure flight performance data. The data will then be relayed back to a ground station live through a radio telemetry system.

1.2 Illinois Space Society

The Illinois Space Society (ISS) is a professional, technical, and social student organization at the University of Illinois at Urbana-Champaign. The registered student organization manages four technical teams: NASA Space Grant MHPR Competition, Intercollegiate Rocket Engineering Competition, NASA Micro-g NExT, and NASA RASC-AL. ISS also serves to build its members' networks through prior members and current professionals in industry. One opportunity for networking is through ISS's mentorship program which pairs underclassmen with upperclassman who have experience in the aerospace industry. Lastly, ISS inspires the surrounding community. Educational Outreach is further detailed in Section **Error! Reference source not found.**. The Illinois Space Society – through technical projects, career connections, and educational engagement – has brought together a community of individuals curious and passionate about space exploration and enabled them to achieve great success.

1.3 Educational Outreach

Educational outreach is a large part of the Illinois Space Society's mission, and members of the ISS Space Grant team frequently volunteer at various community outreach programs. Space Grant members bring a motivated and exciting energy to events such as Illinois Space Day, the Air and Space Fair, and K-12 after school programs, where rocketry principles are taught through demonstration of the team's rocket design. Illinois Space Day (ISD) is one of ISS's largest educational outreach events. At ISD, over 150 students toured various space-related exhibits ranging from learning how orbits work to watching a hybrid engine firing. This year, the students and the Space Grant team were fortunate enough to have Paul Keutelian, a lead engineer at SpaceX, attend ISD and discuss his experience in the industry. This past semester, the team also partnered with a separate RSO, Aerospace Outreach, in organizing the Air and Space Fair. Members of the Space Grant team spent the day teaching K-12 students about propulsion, demonstrating the parts and missions of the old and current Space Grant rockets, and even building model rockets with the students. These topics were of interest to the Space Grant team, who made up half of the volunteers participating in the rocket tract.

Figure 1: The Space Grant Team at the Air and Space Fair

2. Structural Rocket Design

2.1 Mission Statement

The objective of this year's competition is to build an efficient, supersonic, high-power, single-stage, dual-deploy rocket that will complete two flights. Structurally, the rocket will have to be made as light as possible to accommodate a less powerful motor. In addition, the airframe will have to be strong enough to withstand the harsh environment generated by supersonic flight. Initially, several different research teams were formed to thoroughly analyze the advantages and disadvantages of certain components including nose cone shape, fin shape, airframe material, motor selection, recovery technique, safety, and deceleration capability. The structural sub-team has reorganized since then into new research teams including simulations, construction procedures, and recovery system implementation.

2.2 Competition Constraints

Each year, the competition posts a set of criteria each team needs to fulfill before the competition. Table 1: Competition Constraints as Stated in the Competition Handbookshows the requirements set by the competition and which section that requirement is addressed.

Table 1: Competition Constraints as Stated in the Competition Handbook

Category	Constraint Details	Section Addressed
Pre-Competition Prep	Each team must assemble, fly, and successfully recover their fully-functional competition rocket at least once.	2.8 Recovery System
	In addition to a faculty adviser, every team is required to have a non-student mentor with high-power rocket experience	1.1
	Analysis of non-“pre-qualified” components must be included in written reports and also be available at all safety reviews.	2.4 Airframe Components and Materialsand 5.1.2 Pre-flight Checklist 1. **Initial Rocket Inspection** a. Inspect all shock cord connection points. b. Close rear coupler with plastic rivets. 2. **Avionics Inspection** a. Inspect all wiring connections and mounting hardware. b. Test all battery voltages. c. Connect batteries to the avionics. d. Power on all systems. e. Confirm correct beep sequences from commercial altimeters. f. Confirm successful telemetry connection to the Telemetrum. g. Confirm successful telemetry connection to the non-commercial system.

		h. Ensure GPS location accuracy from the Telemetrum and the non-commercial system. i. Power all avionics off. j. Connect pitot tube to differential pressure sensor. k. Insert avionics sled into upper body tube. 3. **Recovery System Inspection** a. Mount Parachute in Chute Release. i.) Power Chute Release on. ii.) Wrap Chute release around parachute. b. Fold main parachute into the body tube. c. Fold drogue parachute into the body tube. 4. **Assembly Inspection** a. Insert nose cone with plastic rivets. b. Wire all charges to the terminals. c. Insert Recovery Insulation. d. Insert upper section into lower section. e. Insert shear pins into upper coupler. 5. **Launch Pad Inspection** a. Assemble and install motor. b. Place rocket on launch rail.

		c. Power up commercial altimeters and confirm correct beep sequences. d. Power up non-commercial avionics system. e. Keep rocket stationary during startup and calibration sequence. f. Launch! **5.1.3 Post-flight Checklist** 6. **Tracking** a. Locate rocket using radio telemetry system. b. Record landing GPS coordinates. c. Travel to landing site. 7. **Rocket Inspection** a. Inspect rocket for any damage. b. Check that there are no remaining live charges. c. Take a picture of the rocket. d. Ensure all avionics data is stored on onboard memory. e. Power off avionics systems. f. Disconnect spent charges from electronics. 8. **Judge Inspection** a. Bring recovered rocket to post flight check in table. b. Remove any plastic rivets from nosecone to take apart rocket for inspection.

		c. Take engine casing out of the rocket. d. Retrieve all flight Data. 5.1.4 Material Handling
	Each team, with their rocket, must participate in the Safety Review the day before the competition launch.	5.1 Safety
Rocket Design	Each team must be able to fully prepare their rocket for flight within one hour and fly at least twice during the launch window.	**Error! Reference source not found.**
	The static margin of the rocket must be between 1 and 3 at launch (i.e. at rocket maximum weight).	2.5.1 Stability Analysis
	Drogue is deployed at (or just past) apogee and descent speed under drogue is deemed reasonable (> 50 ft/sec) and main parachute is inflated between 800 and 500 ft AGL	2.8 Recovery System
	Electronic ejection of a drogue parachute no earlier than apogee using a commercial rocketry altimeter	3.2.1 Commercial Altimeters
	Must use an I or J class Cesaroni or AeroTech motor for the second flight	2.6 Motor Decision

2.3 Dimensions and Weights

The dimensions and predicted weights of all the structural components of the rocket can be viewed below in Table 2 and Table 3, respectively. Overall, the rocket is 43.7 inches long, with a maximum diameter of 2.264 inches. With the provided Cesaroni 491-I-218-14A “White Thunder” motor, the rocket is predicted to weigh 65.0 oz. With the second motor, which was chosen to be the Cesaroni J430-WT, the rocket is predicted to weigh 72.7 oz. See Table 9 for the weights of the avionics ’components.

Table 2:Dimensions of Rocket and its Components

	Dimensions (inches)
Overall	Length: 43.7, Max diameter: 2.264
Nose Cone	Length: 9.50, Base diameter: 2.26, Shoulder length: 1.75, Shoulder diameter: 2.14
Nose Cone Bulkhead	Thickness: 0.729, Diameter: 0.0790
Upper Body Tube	Length: 10.0, Outer diameter: 2.264, Inner diameter: 2.14
Upper Coupler	Length: 4.50, Outer diameter: 2.14, Inner diameter: 2.02
Coupler Bulkhead	Thickness: 0.250, Diameter: 2.02
Middle Body Tube	Length: 10.787, Outer diameter: 2.264, Inner diameter: 2.14

Tube Bulkhead	Thickness: 0.250, Diameter: 2.13
Lower Coupler	Length: 3.94, Outer diameter: 2.14, Inner diameter: 2.02
Lower Body Tube	Length: 12, Outer diameter: 2.264, Inner diameter: 2.14
Motor Case	Cesaroni 54mm diameter 1 grain case, length: 5.6 Cesaroni 54mm diameter 2 grain case, length: 8.9
Motor Retainer	Length: 0.6, Outer diameter: 2.62, Inner diameter: 2.264
Fins	Root chord: 6, Tip chord: 0, Height: 3, Sweep angle: 65.6°, Thickness: ~0.125

Table 3:Design Weights for Structural Components

	Weight (oz)
Overall Predicted Mass (with electronics)	Flight I, 65.0 Flight II, 72.7
Nose Cone	3.50
Nose Cone Bulkhead	0.106
Upper Body Tube	3.11
Upper Coupler	1.01
Eye-Bolt (x2)	1.06
Upper Bulkhead	0.529
Lower Bulkhead	0.494
Plastic Rivets (x6)	negligible
Shear Pins (3x)	negligible
Middle Body Tube	3.34
Lower Coupler	8.81
Lower Body Tube	3.72
Motor Case	Cesaroni 54mm 1-grain case, 2.05 Cesaroni 54mm 2-grain case, 4.25
Motor Retainer	1.55
Fins (3x) (includes epoxy and layering)	6.00
Epoxy (estimate)	3.53
Additional mass *	4.42

(*) This is an estimate of how much the mass of the rocket could grow during the build, which is 10% of the mass of the rocket without motors

2.4 Airframe Components and Materials

After thorough consideration of the criteria and constraints for the competition, the rocket will have the smallest diameter possible and the body tube itself will act as the motor mount. The model of the rocket is shown in Figure 2. The structure of the rocket is composed of a nose cone, three body tubes, two couplers, motor assembly, and fins. The main flight prediction data is detailed in Table 6.

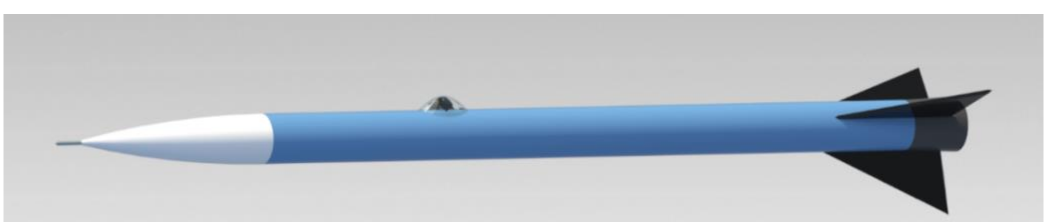

Figure 2: Siemens NX 12.0 Model of Rocket

The nose cone is an ogive-shaped high-impact plastic nose cone. The shape was chosen due to its online availability given the diameter of the rocket. Plastic was chosen instead of fiberglass due to its lower density and its supersonic capabilities. The shoulder of the nose cone will be fully encapsulated by the upper body tube and fixed to the tube with removable plastic rivets so the nose cone will not detach from the body tube during flight. There will be a small bulkhead inside the nosecone to hold the pitot tube (see 3.2.6 Pitot-Static System).

The couplers and body tube of the rocket will be made of Blue Tube. Blue Tube is made of vulcanized cellulose, which is 36% lighter than fiberglass. Additionally, it is abrasion-resistant, guaranteed Mach capable, and easy to work with. It is also significantly cheaper than fiberglass. The upper body tube will house the avionics system of the rocket with dimensions specified in Figure 3: Upper Body Tube Dimensions (inches). The volume of the tube is small, so the electronic components will be arranged in a "single decker" configuration (see Section 3. Avionics System Design), minimizing space and securely storing every electronic component.

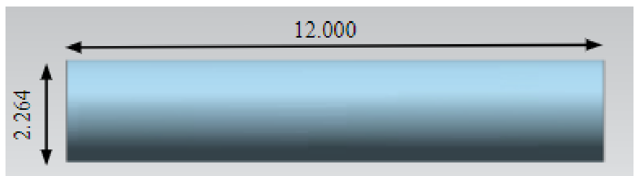

Figure 3: Upper Body Tube Dimensions (inches)

The competition requires a dual deployment system, so the rocket will have a coupler (shown in Figure 4) to connect the middle body tube with the upper body tube. When the ejection charge for the dual deployment system releases, the coupler will remain attached to the upper body tube. It will be secured to the upper body tube with epoxy and to the middle body tube with three nylon shear pins. These pins require a force of 64.24 lbs to cut in half, allowing them to withstand drag forces pulling the coupler and the middle body tube apart during flight. Eventually, they will break due to the force produced by the ejection charge. At the lower end of the coupler, there will be a ¼ inch plywood bulkhead to separate the avionics system from the recovery system and to ensure that the electronics won't be damaged by the ejection charge. Additionally, a forged steel eye bolt will be attached to the bulkhead for the recovery system to be attached to the upper body tube.

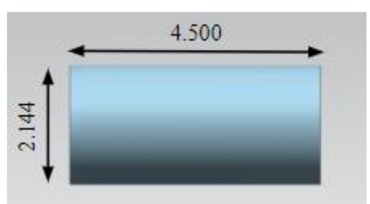

Figure 4: Coupler Dimensions (inches)

The middle body tube houses the recovery system consisting of a main parachute and a drogue, which is further explained in

The competition calls for a Cesaroni 491-I-218-14A "White Thunder" motor for the first flight. Since the motor needs to have a low impulse but still reach supersonic speeds, every I or J class Cesaroni and Aerotech motor was first analyzed by their speed-to-impulse ratio using a control rocket. The motors were then tested on their ability to reach supersonic speed without going too far above Mach 1. Through testing, only 2-grain motors allowed the rocket to fly within the target velocity. In the end, two motors, the J430 and J1055, were considered. In this analysis a sample score was generated for both the J430 and the J1055 using the maximum altitude, impulse and thrust under each motor for the prototype rocket made in OpenRocket. The J430 was then chosen because it generated a lower sample score than the J1055 and was guaranteed to make a supersonic flight.

2.7 Motor Retainer

Two options for a motor retainer were considered: a rear facing retainer and an internal retainer. A rear facing retainer was chosen because of its relatively low mass as well as low cost. Since the rocket will go supersonic, it is extremely important that the body tube be streamlined because drag forces will exponentially increase just before Mach 1. As such, a Slimline motor retainer will be used because it minimizes the diameter discrepancy between the body tube and retainer cap in minimum diameter rockets. The retainer cap will be raised only .09 inches from the body tube. Additionally, the fin tip-to-tip procedure outlined in **Error! Reference source not found.** will cause the diameter of the body tube to be raised .09 inches as a result of the carbon fiber layup, eliminating the diameter discrepancy.

2.8 Recovery System. Another coupler also separates the middle and lower body tube, enabling easy access to the recovery system when assembling the rocket. This coupler is attached to the lower body tube with epoxy and to the middle body tube with removable plastic rivets such that the two tubes will not separate during the entire flight. An exploded view of these three components can be seen in **Error! Reference source not found.**. Since the lower body tube acts as a motor mount, the motor will be held at the bottom with a motor retainer, rather than by centering rings. The functionality of the retainer will be further explained in

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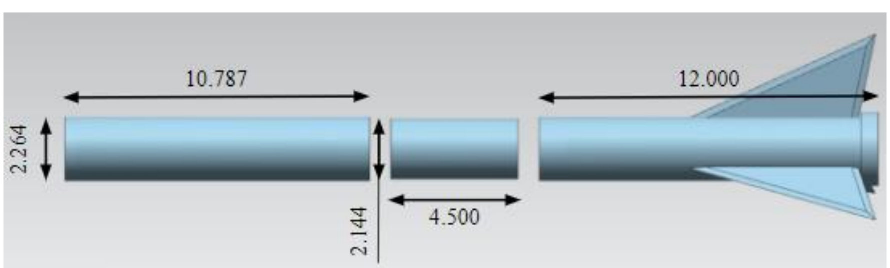

Figure 5:Middle Body Tube, Lower Coupler and Lower Body Tube with Dimensions (inches)

The fins will be made from a ⅛ inch plywood core covered with 3 layers of laminated carbon fiber to improve the rigidity of the fin and avoid structural damage due to aeroelastic fin flutter. The overall thickness of the fin will be roughly the same as the thickness of the core. There will be two separate fin tabs along the root edge of each fin such that they will fit into slots on the lower body tube designed to hold them 120 degrees apart. The attachment of the fins will be reinforced through a technique called tip-to-tip, where a combination of carbon fiber and epoxy will be layered on the fins as shown in Figure 6.

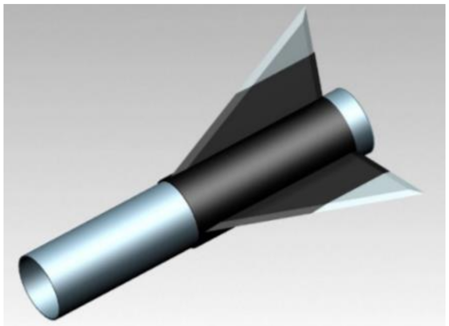

Figure 6:Siemens NX 12.0 Rendition of Tip-to-Tip Attachment, Layering Shown in Black

2.5 Fin Design

The design was finalized to a slightly swept back triangular shape, as shown in Figure 7. The team utilized FinSim, a fin flutter and loads analysis software, and Open Rocket to test the design of the fins. The software analysis is detailed in 4.3 FinSim Simulations. The triangular shape was chosen to minimize fin flutter because its shape creates the largest root edge, meaning that more of the fin is attached to the body of the rocket. The slightly swept back design was chosen to improve the rocket's maximum speed. The fins will also have a 15-degree taper on both edges to reduce drag at near-supersonic speeds. The final design and dimensions are shown in Figure 7.

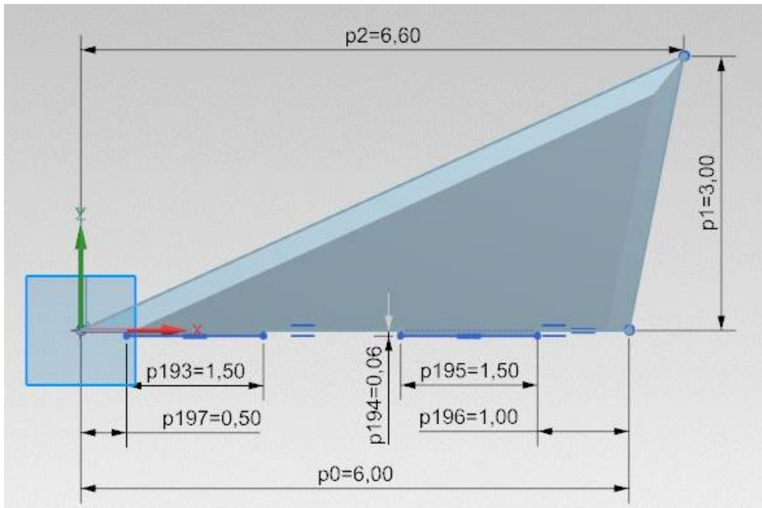

Figure 7: Fin Dimensions (inches)

2.5.1 Stability Analysis

This specific fin shape design also takes stability into account. The stability of the rocket is very important because the rocket must be able to correct itself from a gust of wind or an unexpected angle of attack. This design instantly provides the rocket with a stability of 1 at launch, while still increasing its stability as the motor burns out. This ensures that the rocket will correct itself during launch and mid-flight, which will minimize the angle of attack caused by wind.

2.6 Motor Decision

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2.8 Recovery System

The recovery system will consist of a main parachute and a drogue parachute both made of ripstop Nylon. Both parachutes will be in the lower body tube, attached to a 0.4 m shock cord. The shock chord will be tethered to the rocket by a quick link attached to a 0.25-inch forged eye bolt. The eyebolt will be screwed and epoxied into the rear bulkhead of the avionics coupler and attached to another eyebolt on the forward closure of the engine casing. A Kevlar shock cord with a weight of 0.07 ounces was selected in order to keep the system light without sacrificing the strength of a thicker tubular nylon system. The dimensions and weight of the recovery system components were carefully examined and tabulated to maximize efficiency for the design. Specific information can be viewed below in Table 4: Recovery System Components.

Table 4: Recovery System Components

Parachute	Material	Diameter (in)	Drag Coefficient	Number of Shroud Lines	Weight (ounces)
Main Parachute	Ripstop Nylon	30	1.5	8	2.08
Drogue Parachute	Ripstop Nylon	9	1.25	6	1.05

An onboard Telemetrum will deploy an ejection charge at apogee, which is estimated to be 5300 feet for the I-class motor and 7820 feet for the J-class motor. Once the rocket design is finalized, the team will estimate how much black powder is necessary for the main and backup electronic charges to separate the airframes and deploy the drogue parachute. A Jolly Logic Chute Release will keep the main parachute bundled until deploying at an altitude between 1000-500 feet at a descent rate of 95 ft/sec. The final descent rate after the release of the main parachute is expected to be between 20 ft/sec for the I-class and J-class motors. The rocket is expected to drift a total of 400 feet from the launch site for the J-class launch and 230 feet for the I-class launch. All estimations were calculated and simulated using OpenRocket.

The parachute will be protected with a 0.53-ounce Sunward Group 9-inch by 9-inch parachute protector. This will be used with 0.35 ounces of cellulose insulation, which acts as recovery wadding, to ensure the safety of the parachute.

3. Avionics System Design

3.1 Avionics System Hardware

3.1.1 Avionics Bay Configuration

The team's first course of action was to consult the structures sub-team to determine specific design constraints that the avionics package must abide by. This meeting emphasized that volume would be scarce, and that payload mass must be minimized. On this note, the team iterated over several conventional and non-conventional avionics bay configurations, eventually settling on a

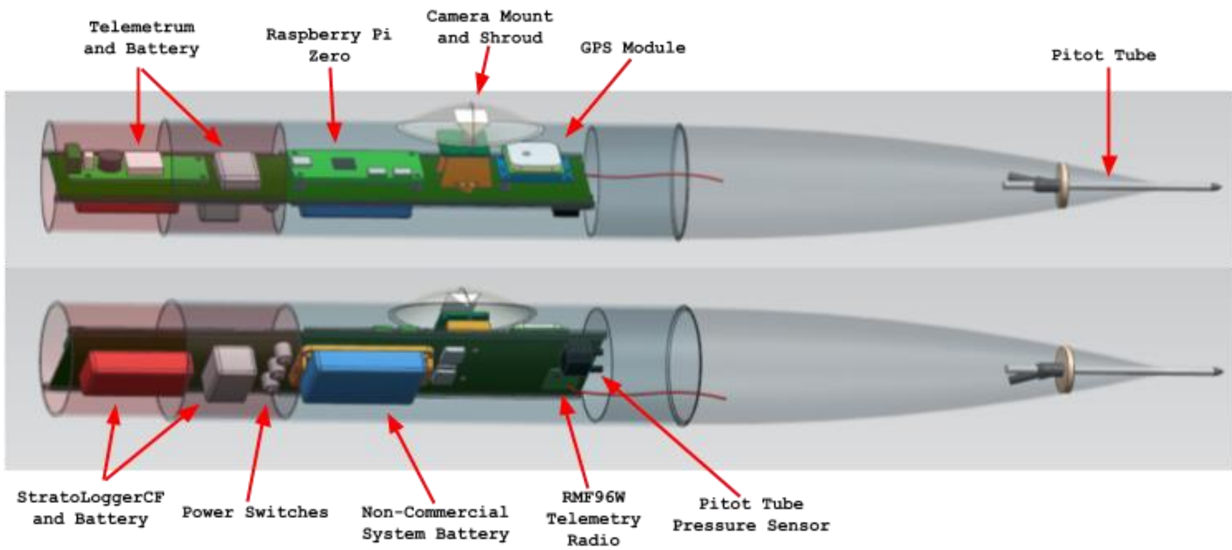
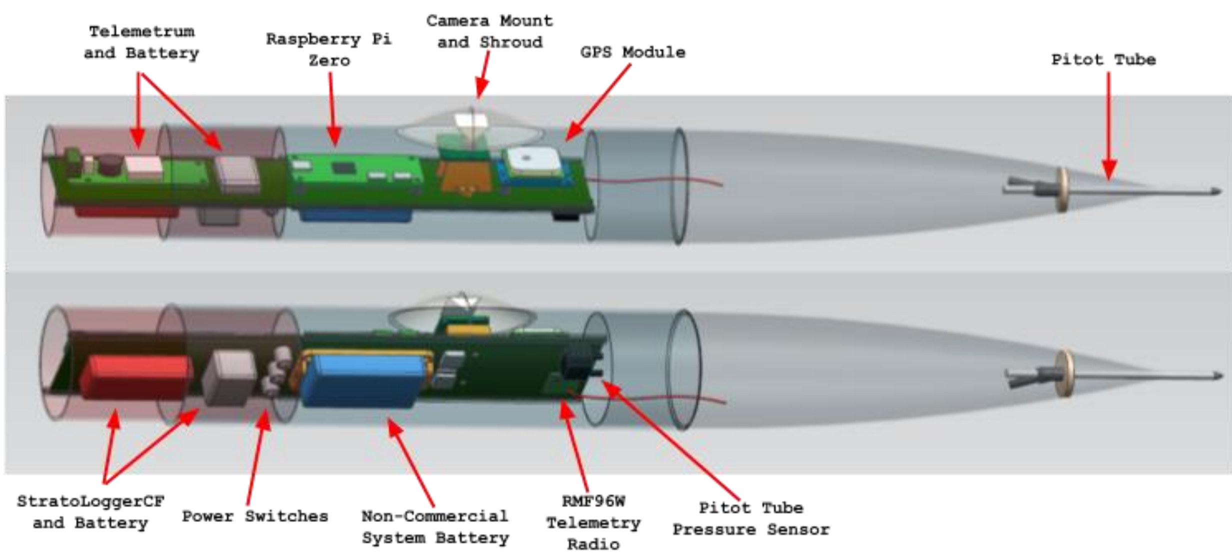


Figure 8: CAD Model of the Avionics Configuration

single sled design as detailed in Figure 8.



This single sled configuration consists of a printed circuit board (PCB) shown in grey, to which all the components will be attached. This PCB will route all internal electrical connections and act as the sled when mounted in the airframe. This PCB sled will ride on plywood "rails" glued into the upper airframe tube. The avionics package will then be secured using 3D-printed mounts glued to the upper airframe tube. This rail system is expected to improve assembly and disassembly duration while at the flying field, which will aid in troubleshooting efforts. Additionally, this design incorporates substantial weight savings compared to traditional avionics bay configurations, as it does not require the use of steel rods or similar structural components for reinforcement.

3.1.2 Avionics Bay Rails

In order to securely hold the avionics sled, the team developed a detailed procedure to attach rails to the airframe. Four laser-cut plywood rails will be slid into two laser-cut jigs that are shown in Figure 9. The jigs give the rails the exact positions and spacing to securely hold the sled. Epoxy will be applied to the rails' outer edges. The rails, still sitting in the jigs, will then be slid into the rocket and pushed against the sides of the tube. After the epoxy has cured, the jigs will be removed.

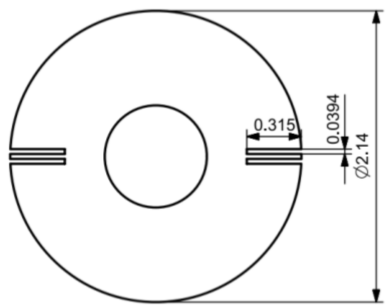


Figure 9: Rail of Construction Jig

3.2 Avionics Component Selection

3.2.1 Commercial Altimeters

This year, the competition rules mandate the use of an altimeter capable of accelerometer-based measurements to detect Mach 1, as well as to log altitude and velocity data. However, the rules also require the use of a commercial tracking component which would relay GPS coordinates to a ground station to aid in recovery. In order to satisfy this requirement, the avionics bay will incorporate an Altus Metrum TeleMetrum as the primary altimeter, and a Stratologger CF which will serve as a redundant backup altimeter that will deploy a separate electronic ejection charge.

The TeleMetrum, shown in Figure 10 on the left, will be configured to trigger the primary ejection charge while the rocket is at apogee. The StratoLogger, shown in Figure 10 on the right, will be configured to trigger the backup ejection charge after the rocket descends a pre-determined amount after reaching apogee. This will be done to allow the flight computer to determine which ejection charge succeeded in separating the rocket body which is discussed further in Section 3.2.3 Separation Detection. The pre-determined offset will be calculated later in the construction phase of the rocket, when a more accurate weight estimate can be made.

Figure 11: The TeleMetrum (left) and the StratoLogger CF (right)

3.2.2 Flight Computer

The biggest design choice that the avionics team had to make was the selection of the main flight computer. Multiple options were evaluated based on price, ease of integration, documentation, and team members' experiences. Among microcontrollers like the Arduino and the STM32, the Raspberry Pi Zero shown in Figure 12 stood out to the team due to its small form factor, powerful processor, and affordable price. Additionally, the Raspberry Pi Zero's integrated features such as the SD Card reader, camera compatibility, and Wi-Fi connection capability allowed the use of fewer components to accomplish operational requirements.

Figure 12: Raspberry Pi Zero W Single Board Computer

3.2.3 Separation Detection

One opportunity to obtain extra points is through detecting whether the primary or the backup ejection charge succeeded in separating the rocket. To achieve this, the avionics package will utilize a phototransistor, shown in Figure 13, directed into the lower body tube of the rocket. A phototransistor is a light-sensitive semiconductor that conducts electricity only when there is light shining on it. This phototransistor will be connected to the GPIO pins of the Raspberry Pi flight computer.

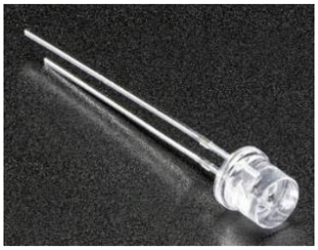


Figure 13: Phototransistor

After separation, the phototransistor will begin conducting electricity and will raise the voltage of the signal line connected to the flight computer. This will result in the flight computer reading logic high, which will mean that separation has occurred. The flight computer will then store the time at which separation has occurred in the on-board memory chip and will relay this information to the ground station through telemetry.

Whether the primary or the backup ejection charge succeeded in separating the rocket will be determined by evaluating the time between apogee and successful separation. If this time interval is below a pre-determined threshold, then the flight computer will conclude that the primary ejection charge was successful as it will be configured to trigger at apogee. Otherwise the flight computer will conclude that the backup charge was successful.

3.2.4 Inertial Measurement Unit

The inertial measurement unit (IMU) consists of two sensor components: the MPU9250 by InvenSense and the H3LIS331DL by STMicroelectronics. The MPU9250 was chosen as it integrates a 3-axis accelerometer, a 3-axis gyroscope, and a 3-axis magnetometer into a single component. Also, the MPU9250 features a variety of configurable built-in noise filters which will help in isolating noise and vibrations from flight data.

However, the MPU9250's accelerometer component can only measure up to a magnitude of 16g, which the rocket is expected to surpass during its boost phase. Therefore, the team voted to incorporate the H3LIS331DL 3-axis accelerometer into the sensor suite, which can accurately measure up to a magnitude of 400g. Thus, the Raspberry Pi microcontroller will utilize the MPU9250's accelerometer to measure acceleration data along the X and Y vectors due to its more sophisticated filters, but it will utilize the H3LIS331DL to measure acceleration along the Z vector.

3.2.5 Power Circuit

The avionics package will incorporate three completely redundant power systems: one for each altimeter, and one for the non-commercial sensor suite as detailed in **Error! Reference source not found.**. Each power system will have its own switch and will be able operate independently.

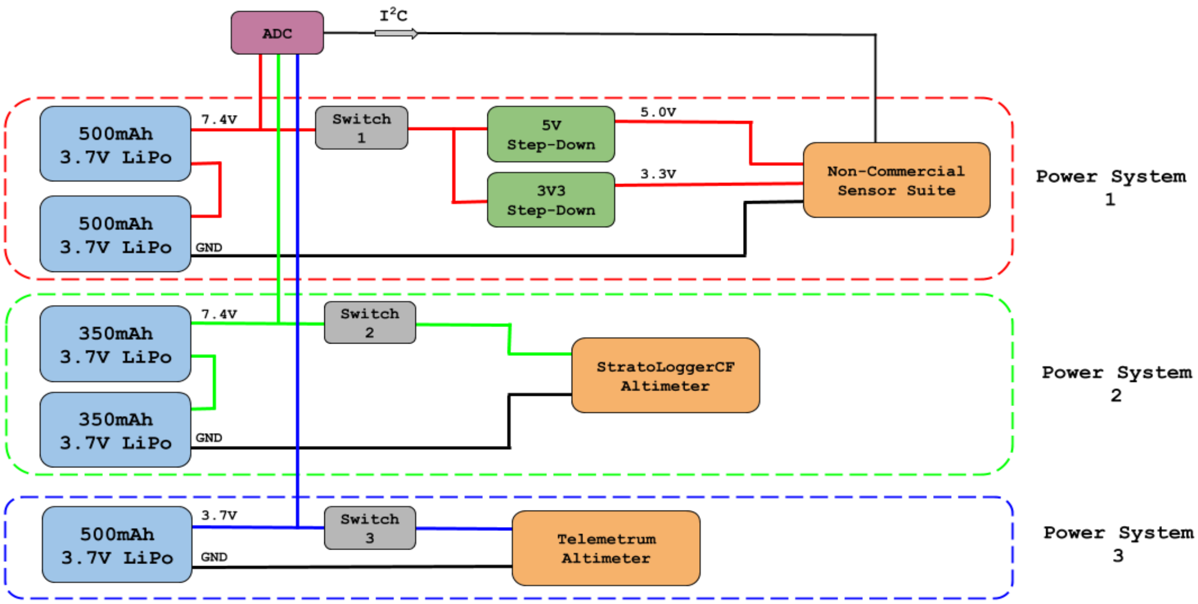


Figure 14: Power System Schematic

To power the avionics package, the team elected to utilize lithium polymer (LiPo) batteries shown in **Error! Reference source not found.** over the more commonly used alkaline batteries. This was done due to the substantially higher energy density of modern lithium-based batteries. Using a lithium polymer battery will allow a smaller and lighter battery to be used while providing the same energy capacity as standard alkaline batteries.

Figure 15: A 3.7V LiPo battery cell.

One inherent problem with LiPo batteries is that they must be handled with care. and they are prone to failure if not used within their specifications. LiPo batteries must not be over or under charged at any time and may only be charged and discharged at specified rates. Failure to abide by these specifications can result in a reduced lifespan of the battery and can even lead to combustion in extreme cases.

To ensure operation within safe parameters, a battery monitoring system is integrated into the power circuitry of the avionics package. This system consists of an ADS1115 analog to digital converter (ADC). The ADC will monitor each battery's voltage and health and will communicate to the flight computer through I_2C. The flight computer will then relay this information to the team through telemetry and onboard LED indicators. This will allow the team to diagnose a battery failure and take appropriate action without removing the avionics package from the airframe.

3.2.6 Pitot-Static System

This competition places heavy importance on the accuracy of data collection. The avionics bay will incorporate an IMU which allows the measurement of velocity through the integration of acceleration. However, due to inherent measurement errors and electrical noise, integrating acceleration will compound error over time. In order to more accurately determine airspeed, the team elected to incorporate a pitot-static system in the avionics package. This system consists of a pitot probe located directly at the tip of the nose cone and a differential pressure sensor. This placement allows the pitot-static tube to access airflow undisturbed by the rocket body.

An NPA-700B-030D Differential Pressure Sensor is used measure the difference between static and total pressure from the pitot tube. The pitot static system will also incorporate an MPL3115A2 Barometric Pressure Sensor which will measure static pressure inside the avionics bay and the ambient temperature. These sensors will communicate with the on-board flight computer using I_2C communications. The flight computer will then store the data in an on-board memory chip and relay the measurements to the ground through telemetry. The ratio of total-to-static pressure, as well as an air temperature measurement will then be used in Equation 1 and Equation 2 for supersonic and subsonic airspeed calculations, respectively. This approach reduces the calculations that must be made by the flight computer, reducing communication latency.

In the equations below, γ represents specific heat of the air, M represents the Mach number, and p_{01} and p_{02} represent the total pressure at subsonic and supersonic speeds, respectively. Furthermore, p_1 represents the static pressure, R represents the gas constant for air, T represents the temperature in Kelvin, a represents the speed of sound, and v represents the airspeed of the rocket.

$$\frac{p_{02}}{p_1} = \left(\frac{(\gamma+1)^2 M^2}{4\gamma M^2 - 2(\gamma-1)}\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{1-\gamma+2\gamma M^2}{\gamma+1}\right)$$

Equation 1:The Rayleigh Pitot Tube Formula for Supersonic Flow

$$\frac{p_{01}}{p_1} = \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

Equation 2:Pitot Tube Equation for Subsonic Compressible Flow

$$a = \sqrt{\gamma R T}$$

Equation 3:Formula for the Speed of Sound in Relation to Atmospheric Variables

$$v = M * a$$

Equation 4:Velocity Equation

3.2.7 On-Board SPI Flash Memory

The team investigated multiple methods of storing flight data on board the rocket. An SD card was deemed unviable as the spring-loaded contacts in SD card readers are prone to having intermittent connection losses in high vibration environments. The team instead elected a much more secure option, choosing to integrate a W25Q64 SPI Flash Memory chip into the avionics package. This chip can store up to 64 Mb of data and can communicate with the flight computer through the serial peripheral interface (SPI). This chip was favored for its small size, low power consumption, and high data bandwidth capability. As this chip will be directly soldered onto the PCB, the risk of in-flight connection loss is eliminated.

3.2.8 Real-Time Telemetry System

An onboard RFM96W 433MHz LoRa Radio Module, will relay data to the ground during flight. This telemetry system was selected over the commonly used XBee radios after hearing about the intermittent connectivity issues that last year's team faced. The RFM96W radio also has equal or smaller size and weight, as well as lower power consumption, compared to similar alternatives. With a very simple wire antenna, the radio module is guaranteed to achieve a connection range of two kilometers. This range can be further extended using higher gain antennas.

3.2.9 Onboard Video System

The camera system's goal is to capture footage of take-off, the deployment and inflation of each parachute, and landing. The Raspberry Pi Camera was chosen for its small size and easy integration into the Raspberry Pi Zero. Technical information can be seen below in

Table 5. In order to see both upwards and downwards while capturing these events, two mirrors

Weight	2Lens Diameter	Field of View
1.1g	0.27 inches	38.16° x 24.5°

will be placed inside a clear shroud at a 45-degree angle relative to each other, as shown in Figure 16.

Weight	2Lens Diameter	Field of View
1.1g	0.27 inches	38.16° x 24.5°

Table 5: Technical data for Raspberry Pi Camera Module

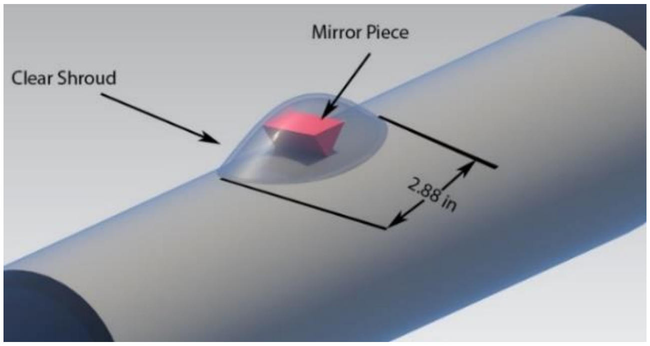


Figure 16: Render of the Shroud and Mirror on the Rocket Body

3.3 PCB Design

To minimize wiring complexity and the possibility of in-flight connection losses, all avionics system wiring will be routed through the PCB shown in Figure 17: Avionics PCB Design. Additionally, the PCB will act as the sled to which all the components and commercial altimeters will be mounted. All sensors and electrical components pertaining to the non-commercial avionics system will be soldered directly to designated pads on the PCB. Furthermore, the PCB circuitry is designed to incorporate three LEDs, programmed to display the status of the flight computer and the health of all batteries. A wiring schematic of the non-commercial system's data communications are shown in Figure 18: Non-Commercial Sensor Suite Data Connection Schematic.

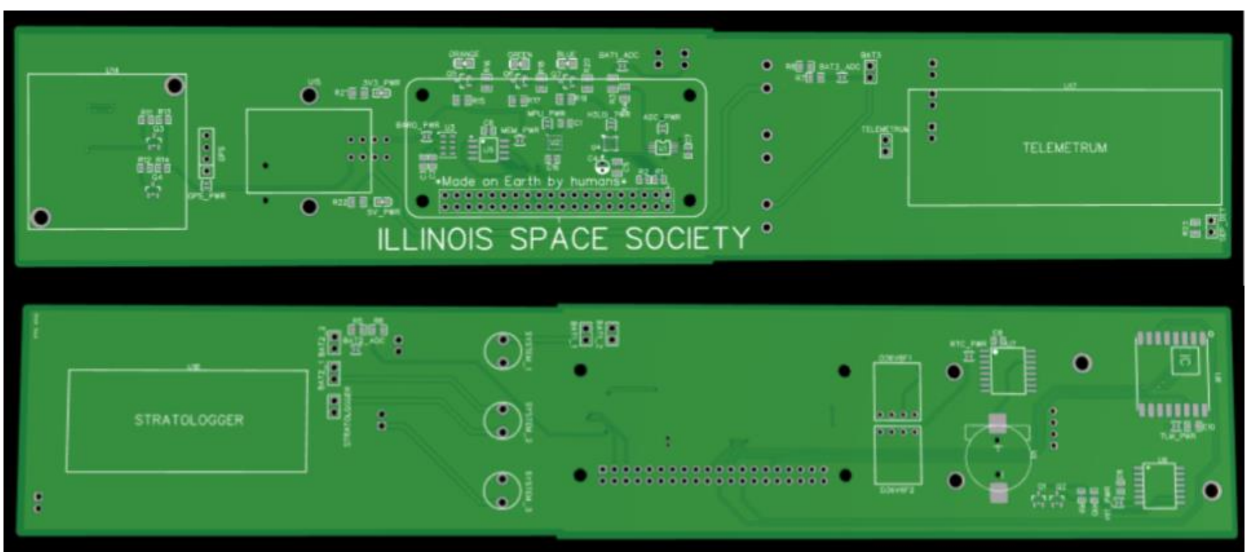


Figure 17: Avionics PCB Design

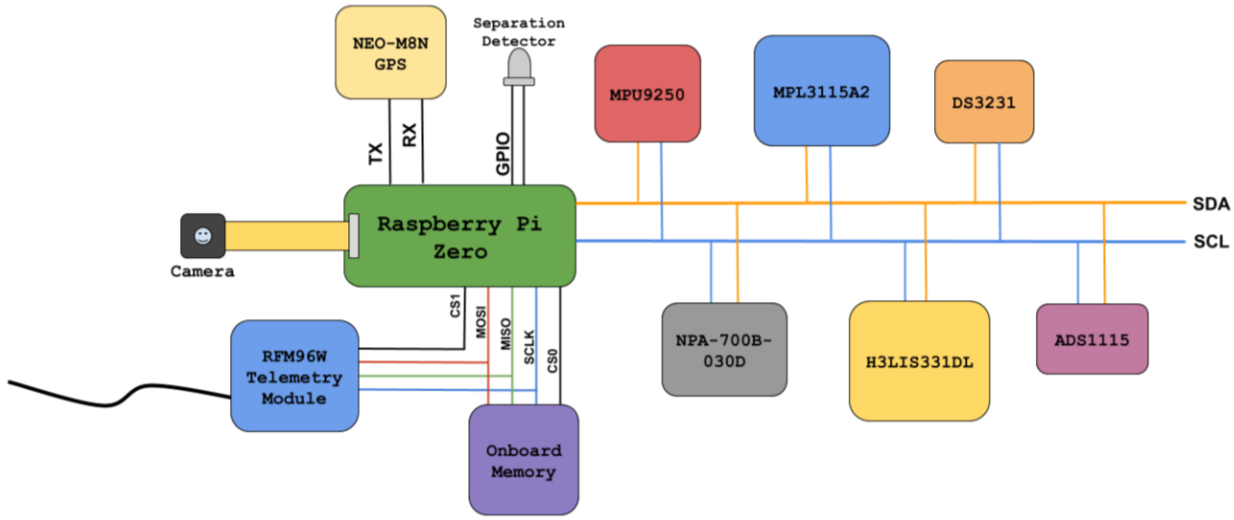


Figure 18: Non-Commercial Sensor Suite Data Connection Schematic

4. Predicted Flight Performance

4.1 OpenRocket Designs

The team designed the rocket in OpenRocket to reach an optimal layout. The software estimates the rocket's theoretical apogee, maximum velocity, maximum acceleration, and stability. OpenRocket also pinpoints the locations of center of pressure and center of gravity of the rocket. This year's competition consists of two flights, each with different motors. Figure 19 and Figure 20 show the finalized 2-D design for both rockets in OpenRocket.

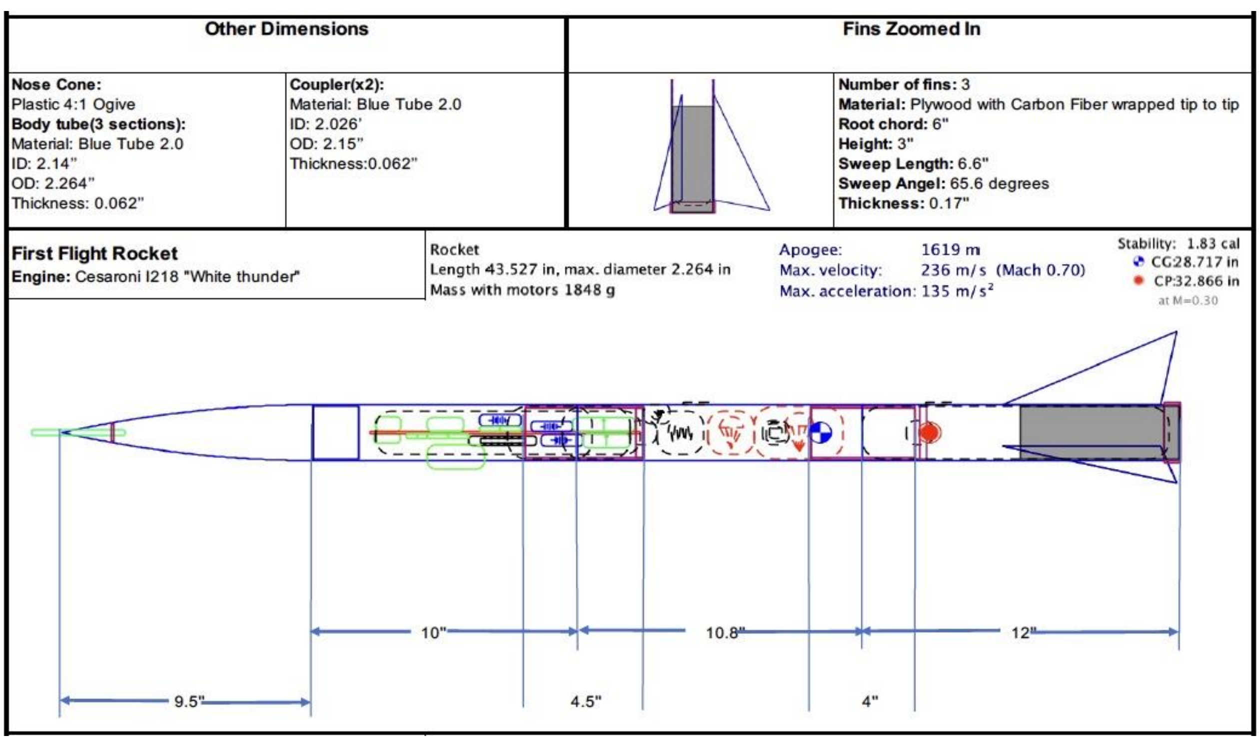


Figure 19: OpenRocket Design Dimensions

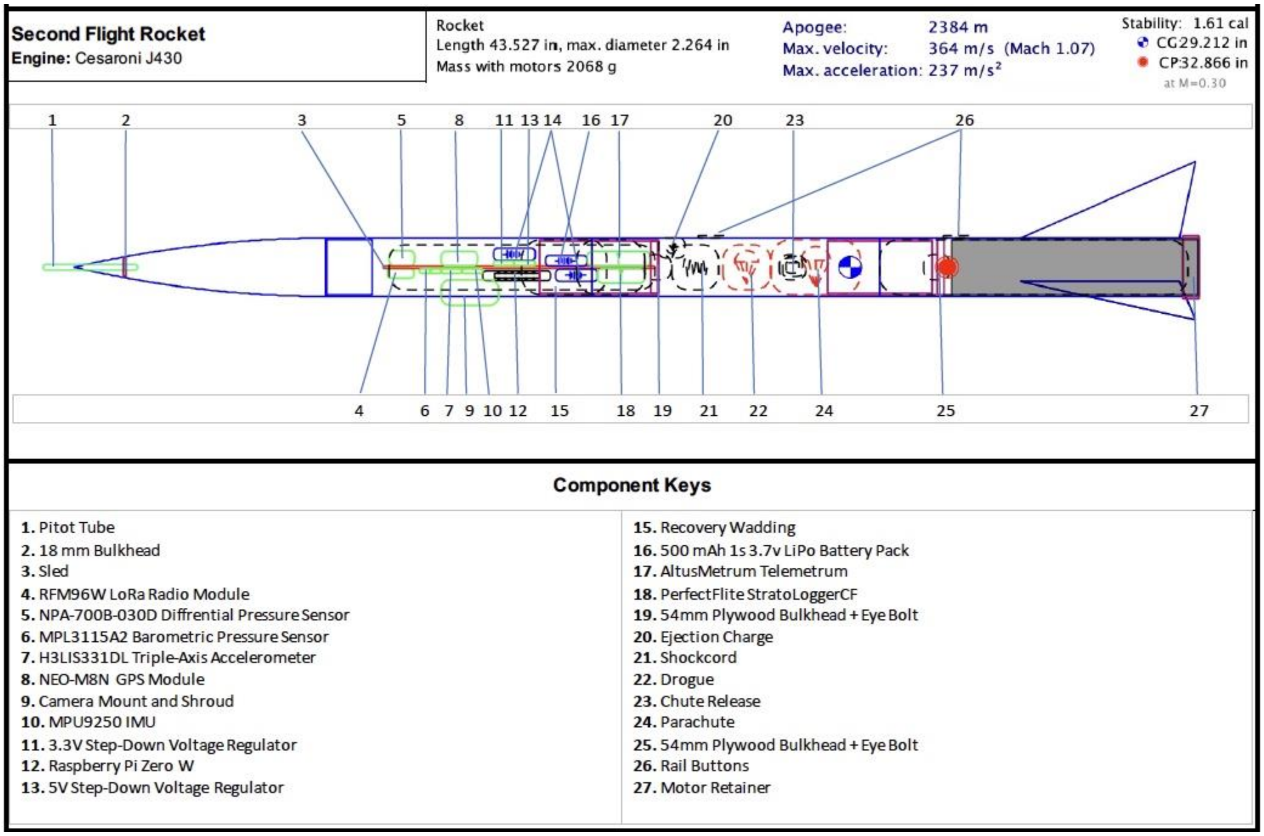


Figure 20: OpenRocket Diagram with Labels

4.2 Flight Predictions

Table 6: OpenRocket Simulation Statistics of MIN-D's Flights shows flight predictions for the rocket with both motors. Made in OpenRocket, the simulations use environmental parameters and conditions that will be similar to launch day, including predicted temperature, wind speed, launch rod length, and angle of launch.

Table 6: OpenRocket Simulation Statistics of MIN-D's Flights

	Flight I	**Flight II**
Motor	Cesaroni I128WT-4	Cesaroni J430-WT-18A-16
Apogee (ft)	5305	7821
Maximum Velocity (ft/s)	774.2	1194
Maximum Acceleration (ft/s2)	554.0	777.6
Stability at launch (calibers)	1.243	1.119
Max Stability (near burnout)	2.750	3.323
Burnout Time (s)	2.210	1.921
Velocity off Rod (ft/s)	50.85	67.9
Total Flight Time (s)	131.0	160.0
Drogue Chute Descent Velocity (ft/s)	95.20	98.30

Main Chute Descent Velocity (ft/s)	20.00	20.00

4.3 FinSim Simulations

The team utilized FinSim and OpenRocket to finalize the design of the rocket fins. FinSim estimates the divergence Mach and flutter Mach of the fins when given parameters relating to the fin geometry and strength. The fin number, root chord, tip-chord, semi-span, sweep length, and fin thickness were all tested in FinSim to achieve the highest possible divergence and flutter Mach for a greater safety factor for aeroelastic fin stability. The divergence Mach number represents the speed at which the fin drag coefficient suddenly increases due to shock waves and flow separation. The increase in drag will make the rocket unstable, which will inevitably lead to a change in trajectory and potential structural damage. To prevent this effect, the divergence Mach number needs to be higher than the maximum speed of the rocket. In addition, the flutter Mach number represents the speed at which the fins will start to flutter. As the fins flutter, there is a dangerous risk of rocket instability and structural failure of the fins. Like the divergence Mach number, the flutter Mach number needs to be higher than the maximum speed of the rocket to ensure integrity.

The divergence Mach achieved through the input of the fin dimensions to be 1.35 and the flutter Mach to be 1.85. These numbers are not entirely accurate, as multiple fin materials (plywood with carbon fiber wrapping) cannot be inputted at the same time due to software constraints. The simulation also assumes that the fin is only made from plywood. This is safe to do because these numbers will only increase after adding carbon fiber wrapping, since carbon fiber is stronger than plywood. These dimensions also maintain an acceptable average stability between 1 and 2 calibers, and a maximum velocity of Mach 1.1 in OpenRocket to ensure the rocket reaches target Mach 1 during competition.

4.4 Environmental Conditions

The rocket launch will take place in North Branch, MN on May 18-19, 2019 with a rain date on May 20, 2019. The launch site is 899 ft above sea level. This elevation is slightly greater than that of the test site, meaning the air pressure at launch will be lower than during testing. This means the rocket motor will produce a slightly greater thrust than the test flight. However, this likely won’t be an issue, as the team’s rocket and avionics systems will take this into account and adjust accordingly. The pressure difference is considered when calculating velocity via the team’s pitot-static system because that measures velocity via the pressure difference in the air. The average weather on these dates is a high of 70° F and a low of 46° F, which will not affect the flight of the rocket. The average wind speed is 10.2 mph. Strong winds may cause the rocket to fly at an angle of attack, increasing instability. In case of large drift, the GPS system in the avionics bay will be used to locate exactly where the rocket lands.

5. Construction Progress and Execution Plans

5.1 Safety

5.1.1 Risk Assessment

The team used a 1-5 scale to assess safety concerns. A level 1 event is considered highly unlikely, or a minor problem if it occurs. A level 5 event is considered highly likely, or a major problem if it occurs.

Table 7: Failure Modes and Mitigation

Failure	Likeliness (1-5)	Severity (1-5)	Impact	Mitigation
Ejection charges cause failure of components within rocket	2	5	Possible destruction of rocket	Protect all internal components of the rocket from heat and explosions by using bulkheads and wadding above the ejection charges.
Rocket fins detach	2	5	Instability of the rocket, inability to recover and fly again	Securely attach fins and test before flight
Parachute does not open	2	5	Destruction of rocket	Fold and roll the parachute neatly and keep internal components of the rocket out of its way
Electrical equipment failure	3	2	Velocity sensor does not measure speed, altimeter reads incorrect altitude	Testing on the ground and with test flights
Shock cord failure	2	5	Complete separation of rocket, damage upon landing	Securely attach cord, run tests at expected forces from rocket separation
Rocket spins on long axis	2	3	Rocket spins, thereby inducing drag and reducing speed	Make sure that there is no cant angle when mounting fins (securely mounting fins with stand)
Nosecone buckles	1	5	Destruction of rocket	Testing on the ground to ensure strength of the nosecone
Nosecone fails due to thermal stress	1	5	Destruction of rocket	Testing on the ground to make sure the plastic nosecone can survive the needed temperature (160°F for 4 seconds)

Engine shoots up through the rocket	2	5	Destruction of rocket	Ensuring that engine retention system is strong enough for peak force induced on the engine & with ground testing

5.1.2 Pre-flight Checklist

9. **Initial Rocket Inspection**
    a. Inspect all shock cord connection points.
    b. Close rear coupler with plastic rivets.
10. **Avionics Inspection**
    l. Inspect all wiring connections and mounting hardware.
    m. Test all battery voltages.
    n. Connect batteries to the avionics.
    o. Power on all systems.
    p. Confirm correct beep sequences from commercial altimeters.
    q. Confirm successful telemetry connection to the Telemetrum.
    r. Confirm successful telemetry connection to the non-commercial system.
    s. Ensure GPS location accuracy from the Telemetrum and the non-commercial system.
    t. Power all avionics off.
    u. Connect pitot tube to differential pressure sensor.
    v. Insert avionics sled into upper body tube.

11. **Recovery System Inspection**
    a. Mount Parachute in Chute Release.
        i.) Power Chute Release on.
        ii.) Wrap Chute release around parachute.
    b. Fold main parachute into the body tube.
    c. Fold drogue parachute into the body tube.

12. **Assembly Inspection**
    f. Insert nose cone with plastic rivets.
    g. Wire all charges to the terminals.
    h. Insert Recovery Insulation.
    i. Insert upper section into lower section.
    j. Insert shear pins into upper coupler.

13. **Launch Pad Inspection**
    g. Assemble and install motor.
    h. Place rocket on launch rail.
    i. Power up commercial altimeters and confirm correct beep sequences.
    j. Power up non-commercial avionics system.
    k. Keep rocket stationary during startup and calibration sequence.
    l. Launch!

5.1.4 Post-flight Checklist

14. **Tracking**
    d. Locate rocket using radio telemetry system.
    e. Record landing GPS coordinates.
    f. Travel to landing site.

15. **Rocket Inspection**
    g. Inspect rocket for any damage.
    h. Check that there are no remaining live charges.
    i. Take a picture of the rocket.
    j. Ensure all avionics data is stored on onboard memory.
    k. Power off avionics systems.
    l. Disconnect spent charges from electronics.

16. **Judge Inspection**
    e. Bring recovered rocket to post flight check in table.
    f. Remove any plastic rivets from nosecone to take apart rocket for inspection.
    g. Take engine casing out of the rocket.
    h. Retrieve all flight Data.

5.1.4 Material Handling

Table 8: Material Handling Procedures and Safety

Hazard ID (1-4 Scale)	Toxicity/ Health	Flamm-ability	Reactivity	Protection:	Storage/Handling:
Carbon Fiber	1	0	0	Face Protection: Wear safety glasses with side shields. Skin Protection: Wear long loose clothes and that cover the body as necessary to prevent irritation.	Store in a cool, dry place. Maintain sealed against contamination from dirt and moisture.
Epoxy Resin	3	1	0	Face and Skin Protection: Avoid contact with skin and eyes. Handle with caution. First Aid for Eyes: Flush with water for 15 minutes. First Aid for Skin: Wash off immediately with soap and water.	Store in a cool dry place.
Plywood	2	1	0	Face Protection: Safety Glasses are recommended. Skin Protection: Gloves recommended. Respiratory Protection: Work in well ventilated areas only. First Aid for eyes: Flush with plenty of water. First Aid for Skin: Wash with soap and water.	Store in a well-ventilated, cool, dry place away from open flame.

Black Powder	1	3	3	First Aid for Inhalation: Move to fresh air. Eye/Skin First Aid: Wash using water. Ingestion: Drink two glasses of water and induce vomiting. Detonation: Seek immediate medical attention.	Keep clear of friction and heat sources. Use rubber gloves and non-static producing clothes. Use only in places with high ventilation.

5.2 Fin Construction

The fins will be made from a ⅛ inch plywood core covered with 3 layers of laminated carbon fiber and a layer of peel ply on each side of the fin. The shape of the plywood core was created in Siemens NX 12.0 to replicate the chosen design for the rocket's fins. The shape will be cut from a ⅛ inch plywood board using a laser cutter. The laminating epoxy that will be used to layer the carbon fiber and peel ply is Aeropoxy 2032 with a 3660 hardener. The fins will then be compressed using clamps to minimize air-bubbles and to get rid of extra epoxy. Once the fins are cured overnight, the extra carbon fiber will be cut off and the exposed edges fins tapered to a 15-degree angle. This taper will be achieved by sanding the edges on a sanding jig constructed by the team.

The fins will be attached to the body tube with fin tabs and a carbon fiber tip-to-tip layup. First, the slots on the body tube will be traced to ensure a 120-degree angle separation between each fin. Carefully, using a Dremel tool, the slots will be cut from the tube such that the fin tabs on the root edge of the fins can rest in them. Because of its high tolerance to heat, JB Weld will be used to secure the find tabs to the body tube. Any excess glue will be wiped off. JB Weld has a tensile strength of 3,960 psi, and if two equal parts are mixed, the epoxy will be able to withstand up to 287.8°C after curing. The fins are going to be held in place by a laser cut foam stand. After the epoxy is cured, a combination of carbon fiber, epoxy, and peel ply will be applied to the fins and body tube. Three separate sets of layers will be placed on the rocket between each fin, running from half of the height of one fin to half of the height of the other fin (see Figure 6 for reference).

5.3 Execution Plan and Timeline

During first semester, the entire team met for an hour each week. During these meetings, each sub-team caught up with the others' progress. New writing or design tasks were also often given to individual team members at these meetings. Outside of these meetings, structures and avionics each met for two hours per week to discuss and design their sections.

During second semester, four two-hour build sessions per month are scheduled for each sub-team. The avionics sub-team will also have weekly meetings to discuss their progress on coding with the Raspberry Pi. The deadlines and number of meetings are summarized in Table 8.

Table 8: Timeline for Construction and Writing

Month	Number of build sessions	Number of writing sessions	Significant due dates
December	None	2 (PDR)	- Finished final design - Budget draft listed - PDR rough draft
January	4	2 (PDR)	- Parts ordered - Final budget listed
February	8	2 (PDR)	- Parts received

			- Construction begins - CAD completed
March	8	2 (PDR/FRR)	- PDR due - Avionics complete - Fins constructed - Test flight
April	10	2 (FRR)	- Finish rocket building - Walk through launch procedures
May	None	2 (Oral Presentation)	- Competition - FRR submission

6. Budget

The team was given a budget of $1000 to order parts to assemble the rocket. The budget given was used on the structures and avionics parts as shown in Table 9. The two competition motors, travel expenses, and the competition fee are not included in the $1000 allotted to the team. The team estimated hotels to be $2000, the rental car to be $600 and $400.

Table 9: Parts Ordering and Avionics Mass

Avionics Budget and Mass Sheet				**Structures Budget Sheet**		
Item	**Quantity**	**Subtotal**	**Weight per Item (oz)**	**Item**	**Quantity**	**Subtotal**
Commercial Sensors and Batteries				**Nosecones**		
AltusMetrum TeleMetrum	1	$0.00	0.705	4:1 Ogive Public Missiles Heavy Duty	2	$27.90
Stratologger CF	1	$0.00	0.423	**Airframes**		
500 mAh 2s 7.4v LiPo Battery Pack	2	$21.98	1.270	Blue Tube Airframe	1	$17.64
350 mAh 1s 3.7v LiPo Battery	2	$11.98	0.282	Blue Tube 2.0 Coupler (standard)	2	$18.50
Non-Commercial Avionics Package				**Engine**		
Raspberry Pi Zero W	1	$10.00	0.317	54mm aft closure	Owned	$0.00
Sparkfun MPU9250 IMU Breakout	1	$8.49	0.095	54mm 1 grain case	Owned	$0.00
Adafruit MPL115A2 Barometric Pressure	1	$9.95	0.046	54mm 2 grain case	1	$69.19
SparkFun Triple Axis Accelerometer Breakout	1	$11.95	0.106	54mm Slimline Engine Retainer	1	$25.31
RFM96W LoRa Radio Module	1	$39.90	0.564	J430 Motor	1	$87.00
NEO-M8N GPS Module	1	$25.99	0.300	I-218 Motor	1	$70.00
Pitot Tube	4	$20.00	0.176	Bulkheads/eyebolts		
500 mAh 2s 7.4v LiPo Battery Pack	1	$10.99	1.269	1/4” Forged Eye-Bolt	3	$17.19
NPA-700B-030D Differential Pressure	1	$31.48	0.176	54mm Plywood Bulkhead + Eyebolt	4	$11.56
DS3231 Real Time Clock Module	1	$6.99	0.141	54mm Coupler Bulkhead	4	$11.56
Winbond W25Q63FV SPI Flash Memory Chip	1	$1.20	0.159	**Recovery**		

4:1 Ogive Public Missiles Heavy Duty Nose Cone	2	$55.00	Not in Bay	1500lb Force Kevlar Shock Cord	15	$15.15
ADS1115 Analog to Digital Converter	1	$2.70	0.053	12”x12” Parachute Protector	1	$8.26
Camera Supplies				Drogue Parachute	1	$5.00
Raspberry Pi Camera Module V2.1	1	$0.00	0.039	Jolly Logic Chute Release	1	Owned
Clear Plastic Shroud Material	1	$20.00	0.353	Main Parachute	1	$72.00
Vacuum Forming Supplies	1	$30.00	negligible	**Fin Making**		
Camera Mount and Mirror Mount	1	$0.00	0.353	J-B Weld	1	$29.99
Mirror	1	$10	0.353	Quarter Inch Dowel	1	$0.70
Avionics Sled				Painter’s Tape	Owned	$0.00
PCB Sled	1	$20	1.058	1/8” Plywood	1	$14.99
3D Printed Securing Mounts	4	$0.00	0.106	Aeropoxy Laminating Epoxy (1 Quart)	1	$56.00
Wiring				Peelply	1	$7.90
Wires and Pin Headers	1	$10	0.529	Parchment Paper	Owned	$0.00
Switches	3	$0.00	0.212	**Miscellaneous**		
Travel Costs	Hotel: $2000		Rental Car: $600	Surface Mounted Launch Rail Buttons	1	$6.53
	Avionics	Structures	Travel	Removable Plastic Rivets	2	$7.72
Totals	$364.00	$522.38	$3,000	“Dog Barf” Recovery Wadding	Owned	$0.00
Total Cost	$3,886.38	Avionics Bay Mass: 9.545 oz		Shear Pins (20 pack)	3	$9.66