University of Illinois at Urbana-Champaign

NASA Space Grant Midwest High-Power Rocketry Competition 2016

Illinois Space Society

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Table of Contents

Executive Summary……………………………………………………………….3

Review of Rocket Design……………………………………………………………4
Dimensional Specifications
Recovery System
Propulsion System
Payload Design
Discussion of Drag System
Mass Statement
Budget
Constructed for Safe Flight and Recovery

Rocket Operation Assessment…………………………………………………15
Launch and Boost Analysis
Coast Phase Assessment
Separation Assessment
Drag System Assessment
Recovery System Analysis

Actual vs. Predicted Performance………………..……………………………18
Flight Prediction
Launch Analysis
Flight Analysis

Findings and Future Work……………………………………….…………23
Key Findings
Potential Design Improvements

Executive Summary

The Space Grant Midwestern High-Powered Rockery Competition is held annually by the Minnesota Space Grant Consortium. It challenges teams from educational institutions across the United States to meet a competition-specified function. This year's challenge is to successfully design, construct, and launch a high-powered rocket containing an active drag system that allows for the manipulation of the vehicle's apogee.

The Illinois Space Society (ISS) team conducted their test launch on Friday, May 6, 2016. The rocket has an overall length of 70 in, an outer diameter of 4.104 in, and a mass of 10.813 lbs. The test launch performed agreeably with past simulations, reaching an initial altitude of 4157 ft. This is an indicator that despite a necessary change in motor type, the rocket will fly smoothly. All systems were designed and constructed to ensure two safe, successful launches. These launches will fulfill the competition objective complete with accurate data collection and recovery of the vehicle.

Traditionally, the Illinois Space Society (ISS) team has been composed of freshmen with a single upperclassman to guide them through the design process. This year, the greater complexity of the desired function demands a team with more experience than the past. This year's team is composed of four freshmen, one sophomore, one junior, and one senior. The older members all have experience in high power rocketry through various other competitions, which maximizes the team's chance of success.

Review of Rocket Design

Dimensional Specifications

The rocket consists of two major sections: forward and aft. The forward section includes the nose cone and payload, which contains the active drag system and avionics. The aft section houses the recovery system and the propulsion system. All body tube sections are made of Blue Tube that has an outer diameter of 4.014 in and an inner diameter of 3.913 in.

The forward section is 41.5 in long with three subsections: the nose cone, active drag system, and avionics bay. The fiberglass ogive nose cone is both friction-fit and epoxied into the body tube. The avionics bay contains the radio transmitter and the AltimeterTwo, as mandated by the competition, and the drag system's electronics, including 14.8-volt lithium polymer battery source for the actuator, the 9-volt battery source for the Arduino, the Arduino controller, the accelerometer, and SD shield. Within the payload bay is the active drag system. This consists of a 4 in stroke linear actuator, which pushes down on three 3-D printed wedges to create the active drag force on the structure. To both guide the movement of the push and to provide stability within the structure, three threaded rods run along the entirety of the section, bulkhead to bulkhead. Directly below the wedges is located the Stratologger used for determining the ejection charge.

The aft section contains the recovery system and the propulsion system. The recovery system consists of one 52" parachute, a shroud protector, and a JollyLogic Chute Release. The parachute will be folded and stored in compliance with the delayed chute release device. It will be tethered to a bulkhead in the aft section of the rocket and will be ejected by the motor ejection charge. The propulsion system contains the motor. The motor casing is stabilized by four plywood centering rings and capped off by a motor retainer. Three laser-cut, plywood fins have been sanded down to rounded edges to decrease the drag they create. Included in the design of each fin is a fin tab, which has been used as an insert attachment between the centering rings to provide a larger surface area for epoxy and make it less likely for them to shear upon impact. Epoxy filler is additionally used as a fillet material to create a smooth, round transition between the fins and the body tube.

Recovery System

The recovery system will consist of one 4 and 1/3 ft parachute. The parachute will be tethered to a bulkhead in the aft section of the rocket and will be ejected by the motor ejection charge at a pre-determined altitude with the use of an altimeter. This parachute will slow the rocket's velocity to 18 ft/s, which is within the range of acceptable descent rates as specified by the competition criteria.

The parachute will be deployed by black powder charge triggered by a StratoLogger altimeter 16.5 seconds after burnout, or 3 seconds after apogee, at an altitude of 3890 ft. This timing was chosen to ensure that electronic deployment precedes the rocket motor's built in ejection charge. The motor ejection charge will serve as a failsafe in case of any impedance in the recovery system electronics.

An analysis using a custom MATLAB script that inputs average wind speeds at the competition site (about 15 miles per hour) reveals that deploying the parachute near apogee charge can cause drifts of up to 5300 ft, an unnecessary and unacceptable drift distance. To reduce this distance, a Chute Release device manufactured by Jolly Logic will be used to delay the full deployment of the parachute until the rocket falls to an altitude of 500 ft, significantly reducing the initial drift distance; the updated analysis indicates a drift of around 2200 ft. While this still entails a large drift distance, delaying deployment of the parachute any longer risks the chute not deploying fully before landing.

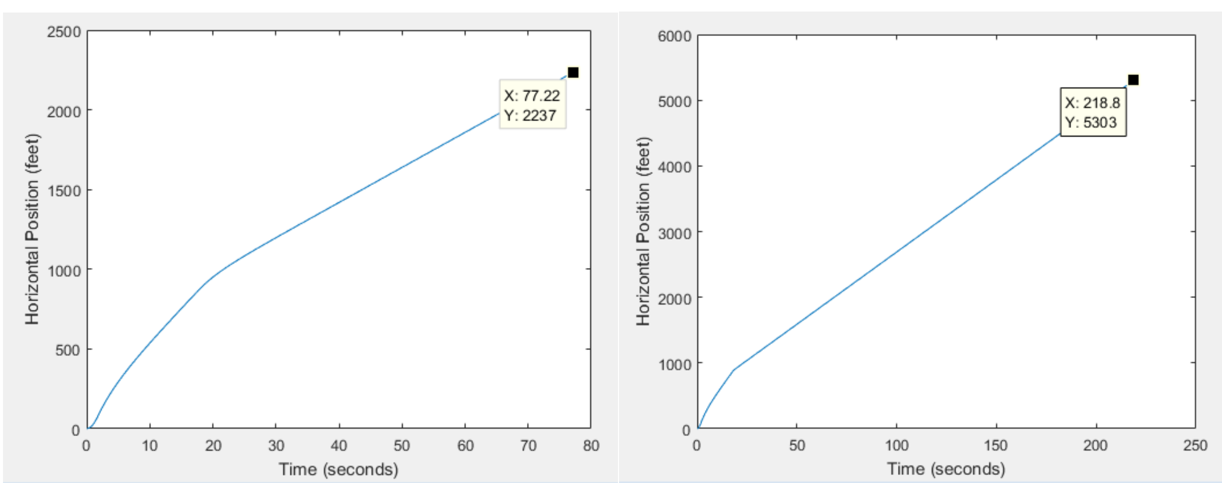


Figure 1. Rocket drift vs time of parachute deployment.

The size of the rocket and significant forward mass necessitates the use of shear pins to prevent drag separation. The calculations for shear pins and ejection charge requirements are calculated in Table 1 below.

Table 1. Shear Pin and Ejection Charge Calculations

Mass in upper section [lbf]	4.41
Peak Acceleration [G]	4.08
Force Required [lbf]	20
Parachute Tube Length [in]	15
Body Tube Diameter [in]	4
Desired Pressure [psi]	7.96
Number of 2-56 Nylon Screws	**4**
Black Powder [lbm]	**0.0017**

The recovery system includes a radio transmitter within the systems compartment. This will enable the team to locate the rocket wherever it lands by indicating its direction and distance from the radio receiver possessed by the team after the launch. It ensures that the rocket is located if not visibly seen, reducing time it takes to locate the rocket.

Propulsion System

The Cesaroni 1261-J449-15A is considered a Level 2 high-powered rocket motor. It boasts an average thrust of 757.7 N, with a maximum thrust of 937.3 N. The propellant will burn for a total of 2.8 s, which provides a total impulse of 1260 Ns. Its total mass is 1122 g; at 624 g, the propellant mass is slightly larger than half that amount. Other dimensions of the motor include a diameter of 2.12 in and a length of 12.64 in.

The motor used in competition are reloadable and will be provided by competition coordinators. In accordance with the Tripoli Code for High Power Rocketry, this particular motor requires a minimal diameter clearing of 50 ft with a minimal personnel distance of 100 ft.

The change in selection of rocket motor is due to the halting of J760 motor, following an incident at the Cesaroni facility. Despite a lower total thrust and longer burn profile, the J449 was chosen based on its similar thrust curve and total impulse. This ensures a competition flight performance similar to the test flight.

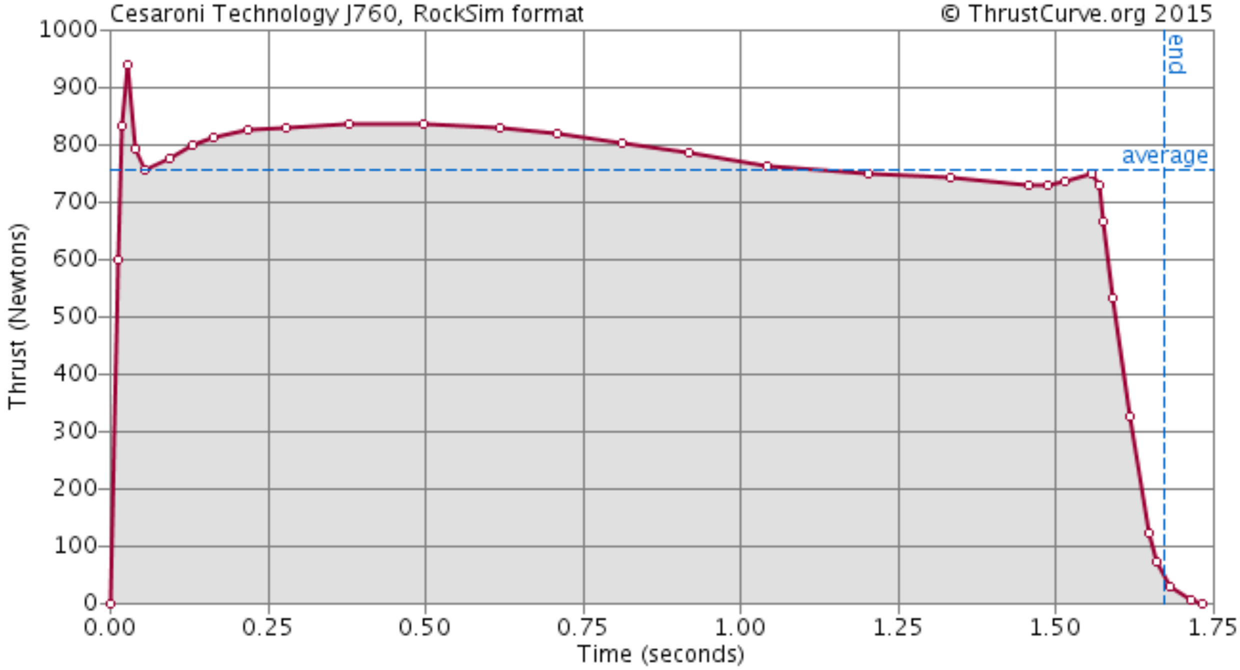
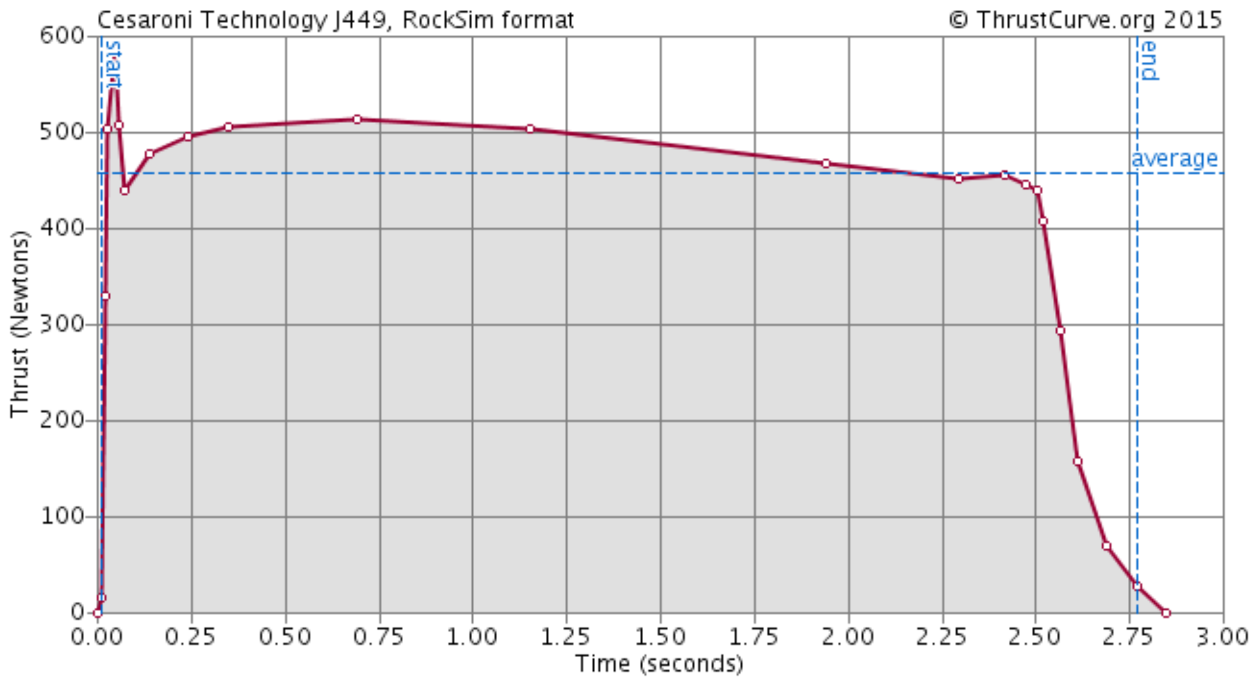


Figure 2. J760 Thrust Curve.

Figure 3. J449 Thrust Curve.



Payload Design

The payload is integrated as its own modular section of the rocket. Consisting of the avionics, the active drag system and the Stratologger board, the payload section of the rocket can be found positioned in the center of the rocket, between the forward and aft sections. Spanning 25 in in length, and weighing about 2 lbs, the payload occupies a significant portion of both space and weight in the rocket body.

The avionics bay is located forward of the active drag system. The key purpose of the avionics bay is to collect data, deploy the drag system after fuel burnout, and retract the linear actuator before the rocket's apogee. Components of the avionics bay include the ADXL377 accelerometer, Arduino Uno, MD10C motor drive, 9 V battery, and 14.8 Lipo battery. All the electronics used run on batteries with the correct safety ratings to ensure that the components do not degrade before use during the competition in Minnesota. The code in the Arduino has three main duties: convert the data received from the accelerometer to G force, call the correct functions to deploy and retract the actuator, and communicate these functions to the motor drive. The MD10C motor drive is key to the avionics bay because it allows the Arduino to communicate when to deploy the drag system to the linear actuator. Because of the MD10C's high voltage rating, it also allows the team to use the 14.8 V Lipo battery without damaging the Arduino, which can only handle 9V.

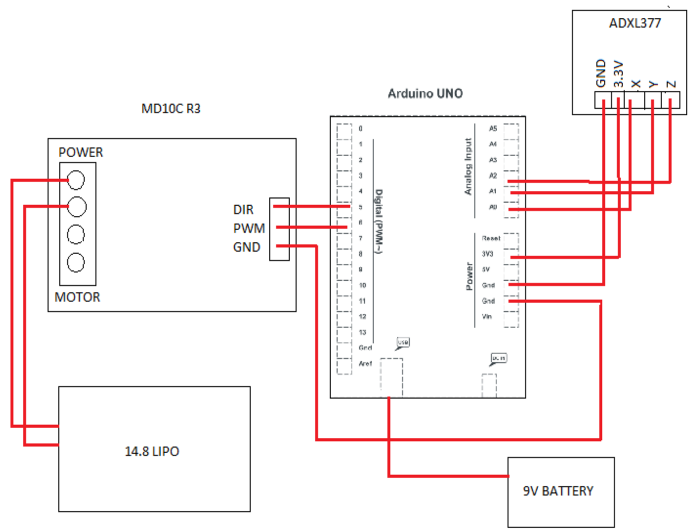


Figure 4: Avionics Schematics.

At the forward end of the active drag system, a plywood bulkhead rests atop a 3 in coupler. This bulkhead acts as the base on which the linear actuator is mounted, and also has holes drilled through it to connect to necessary avionics and to anchor three ¼ in threaded rods which serve as structural reinforcements throughout the section. As further reinforcement, coupler extends throughout the entire section.

The force required to deploy the airbrake wedges is supplied by a linear actuator. Manufactured by Firgelli Automations, the actuator provides a 4 in stroke capable of up to 15 lbs of force, although based on the theory of mechanical advantage, its equivalent pushing ability will theoretically be much greater due to placement. As an isolated component, the linear actuator's output arm is too narrow to interact with the airbrake wedges. To solve this problem, a custom head was designed and 3D printed to fit onto on the actuator's arm. The head greatly extends the cross-sectional area of the arm, allowing it to push down on the wedges. The head has a flat face every 120 degrees, which acts as the contact surface for the wedges to meet.

The airbrake wedges are the component of the active drag system that physically slow the rocket down. When a downward force is applied to the innermost face of three wedges, mounted radially to the inside of three cutouts in the body tube, they pivot outwards. These extended cutouts block the flow of air around the rocket body and increase the drag of the vehicle. In order to allow the wedges to pivot about the curved edge of the body tube, they are attached to the tube via a hinge made of reinforced fiberglass strapping tape.

In a similar fashion to the forward bulkhead, the aft bulkhead has holes drilled in it to anchor the 1/4" structural rods. Also, along with providing a base for the Stratologger board to sit atop, the aft bulkhead also protects the board from the parachute ejection charge. Two charge caps are epoxied to the underside of the aft bulkhead, holding the parachute ejection charges in place. Between these two charge caps, a 1" diameter eyebolt secures the payload to the aft section of the rocket via Kevlar chord.

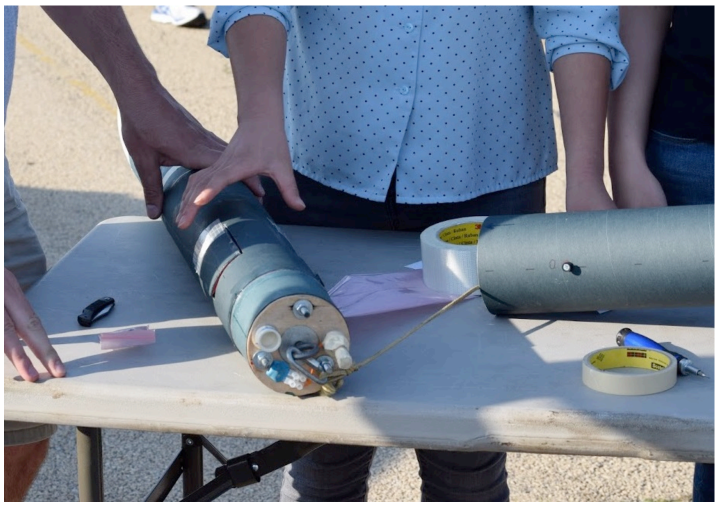
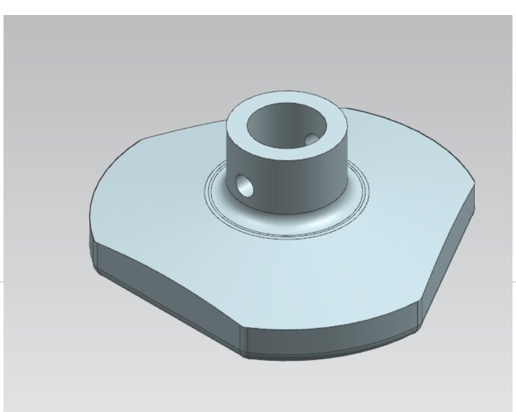


Figure 5. The aft bulkhead.

Changes to Payload Design

The payload is where the majority of changes were made. The linear actuator was changed almost immediately following the submission of the preliminary design. It was decided that a 4 inch linear actuator as opposed to an 8 inch, would provide an adequate amount of force for the wedges and also lessen the overall mass of the rocket. The actuator head was also redesigned in discovery that the original design blocked the wedges from closing completely, even when the actuator was completely retracted.



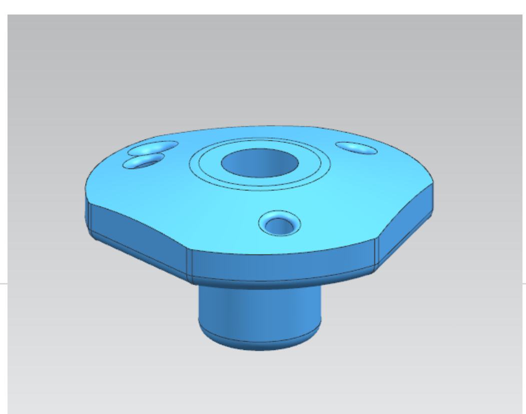


Figure 6. Old actuator head design (left) compared to new (right)

In regards to the avionics, there have been a few notable changes. As written in the PDR, the Arduino is placed at the bottom of the rocket along with its connected components. However, during the building stages of the electronics payload, it became apparent that the space set aside for the electronics (6 in x 3.5in) at the aft of the payload section was not sufficient. Because of this, only the Stratologger CF is located in the bottom of the payload section. The brain of the drag system is instead placed in the space just under the nosecone, forward of the payload. This change also improves the stability of the rocket by moving the center of gravity towards the top. In the forward section of the rocket, the electronics are also surrounded by significantly more open space, making them easier to access in the turnaround time following the first launch.

The parameters for which we will deploy the drag system has also been altered. In the PDR, it was stated that the “code in the Arduino will calculate the required airbrake deployment angle to lower the rocket’s apogee to exactly 75% that of the first flight”; however, upon the attempt to carry out this task, it was decided that this method was overly complicated for what it was trying to achieve. Instead, the wedges responsible for creating drag will be at its full angle. The instant at which the wedges will be deployed is based purely on the acceleration data sent to the Arduino from the accelerometer. Said data was found through accurate simulations from the program OpenRocket.

Discussion of Drag System

As outlined above, the active drag system consists of a linear actuator, a custom fabricated actuator head, custom fabricated wedges, the Arduino assembly, and the lithium polymer battery. The drag system in its simplest sense features a linear actuator that exerts a downward force to deploy a set of wedges. These wedges, which serve as the air brakes, protrude from the side of the rocket when deployed, disrupting the flow of air and greatly increasing the drag on the rocket. The individual components of the drag system were selected and designed to function in a harsh environment where they will be subject to high stress.

The decision as to when to utilize the drag system will be based solely on live streaming accelerometer data. Based on custom MATLAB script, in order to reach 75% of the apogee of the initial altitude, the rocket must deploy the drag system at motor burnout until apogee. (Deployment is characterized by a 20 degree opening of the wedges.) The input for these values are taken from simulations made in OpenRocket. The first input, the parameter at which the system will deploy, is taken when acceleration goes from a positive to negative value, which occurs at motor burnout. The second input, the parameter at which the system will retract, is taken as the rocket approaches a 1g acceleration – indicating apogee. Using this streamlined system ensures that the drag system is within rules of the competition while still being as precise as possible.

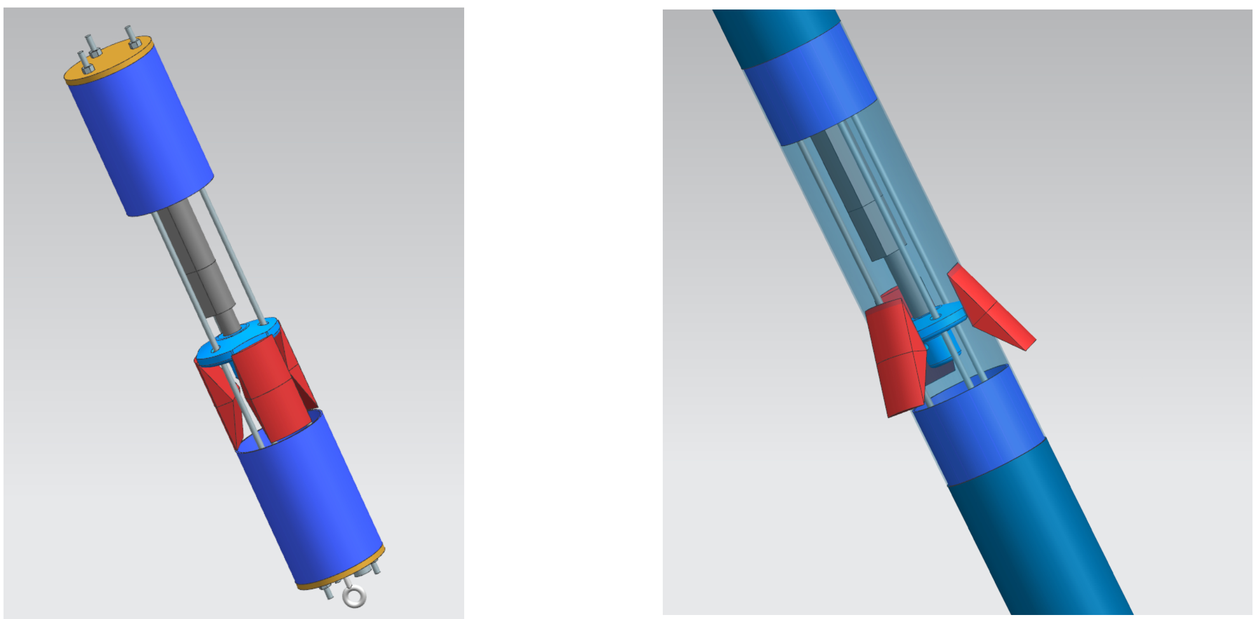


Figure 7. The payload undeployed (left) and deployed within the rocket (right)

Mass Statement

The mass of the completely assembled rocket with fully loaded motors as calculated by OpenRocket software comes out to be 10.125 lbs. With the motor having fully discharged, the mass of the rocket is roughly 8.3125 lbs.

Table 2. Mass of Components

Component	Mass (lbs)
Nose Cone	0.6125
Airframe (Blue Tube)	1.8812
Airframe Coupler	0.2717
Fins	0.5071
Wedges (3)	0.1656
Actuator Head	0.1764
Coupler Bulkhead	0.1202
Kevlar Cord	0.0441
Parachute	0.7624
Linear Actuator	1.3001
Batteries (2)	0.3241
Motor	2.3739
Chute Protector	0.1058
Motor Casing	0.1933
Centering Rings	0.1217
Motor Mount	0.1422
Chute Release	0.0386
Accelerometer	0.4409
Altimeter	0.0282
Arduino	0.0551
Camera	0.1001
Total	**10.8378**

Budget

For this project, each team was allotted $1000 for all expenses, excluding the two rocket engines to be used at the competition. A significant amount was saved by using and reusing parts in the Illinois Space Society inventory. All told, $953.49 was spent on project parts, leaving $46.51 unspent.

Constructed for Safe Flight and Recovery

FEA analysis and risk mitigation provided useful information regarding possible points of failure during flight. In response to each possible situation, a theoretical solution was formulated and input into any change in design or construction method. Plastic rivets were added to the forward section of the rocket to ensure that it does not come apart during the launch. The wires in the electronics, especially the ones connected to the LiPo battery, were checked to be fully covered with no fraying wires visible to ensure that they do not touch during flight and cause a fire. The LiPo battery is also firmly secured with epoxy to the electronics board and further tied down with two zip ties perpendicular to each other. In addition to these safety measures, a pre-flight and post-flight checklist was created and followed to guarantee a safe flight.

Stability Analysis

The center of gravity and center of pressure were calculated using OpenRocket software. The center of gravity with the motor fully loaded was calculated to be 50.4 in from the forward tip of the rocket. The center of pressure with the active drag system not deployed was found to be 62.9 in from the forward tip, thus providing a stability of 3.12 cal. With the drag system deployed, the center of pressure was located at 61.3 inches, slightly reducing stability to 2.84 cal.

Rocket Operation Assessment

Launch and Boost Analysis

The rocket left the launch pad in completely vertical flight, as shown in Figure ___. This is in spite of a slight tilt of the launch pad and 12 mph wind to the east. The boost phase lasted 1.7 s until motor burnout, at an altitude of 307 ft.

Figure 8. Liftoff During Test Flight.

Coast Phase Assessment

As expected, the motor burned out roughly 1.7 s after launch. The rocket then coasted for 14.85 s and 3850 ft, and achieved an apogee of 4157 ft.

Separation Assessment

The separation of the rocket occurred using a black powder charge triggered by a StratoLogger altimeter at the designated time. During launch, the separation occurred as planned, 16 s after launch or 3 s after apogee, at an altitude of 4158 ft. The StratoLogger altimeter successfully deployed the parachute and the rocket was able to release its parachute, allowing for a safe touchdown and successful recovery.

Due to the success of the flight test, there will no alterations to the calculations made to the deployment time or altitude at which separation of the rocket occurs. The original time intended for separation and release of the parachute is a good indicator for when the rocket should separate, even with using a different motor.

Drag System Assessment

Because of a failure to assemble the avionics board in time, the drag system was not deployed during the test flight. The wedges were also not held down by torsion springs, as originally planned, which may have caused the rocket to create unintended drag. However, upon recovery of the rocket, the wedges were discovered to still be attached to the body of the rocket, indicating the choice of using reinforced strapping tape to be adequate for the task at hand.

Recovery System Assessment

At the test launch, the recovery systems worked as intended and the rocket was recovered in flyable condition. All the recovery components consisting of the parachute, the chute protector, and the JollyLogic chute release deployed successfully and brought the rocket down at a safe descent rate. Despite a 12 mph wind during the test launch, the rocket did not drift far.

Figure 9. A successful recovery!

In accordance with the OpenRocket simulation, the parachute bundle was released by a motor ejection charge with a 3 s delay. The rocket and parachute bundle then fell until the package reached an altitude of 500 ft, at which point the JollyLogic chute release undid its hold on the parachute and allowed it to open. This minimized drift while allowing the rocket to come to a safe landing. The rocket was also relatively easy to locate using a radio transmitter, although a bright streamer of sorts will be added to more easily distinguish the parachute from the ground.

Actual vs. Predicted Flight Performance

Flight Prediction

Size is the primary constraint impacting the design of the rocket and its drag system. In this scenario every component involved in the process must fit into a 4 in tube. To work with the size constraint, space must be treated as a resource and used sparingly.

The actual length of the rocket turned out to be 5ft 11in with a diameter constraint of 4 in which fits within the predicted constraints we have set up for the rocket itself. Fitting everything within these constraints, all components were able to successfully be incorporated within the design of the rocket, showing that original set up and size limitations were well picked.

Given the extreme length of the linear actuator compared to other components in the rocket, minimizing the size of the actuator was essential. By calculating the flap size required to achieve the desired drag force, a linear actuator with the minimum stroke length required for deployment was selected in order to shorten the payload bay as much as possible. Furthermore, since the diameter of the linear actuator is sizably smaller than the diameter of the body tube, a significant portion of space within the payload bay is left open. As such, all electronic components could be fitted alongside the actuator inside the payload bay, eliminating the need for a separate electronics bay.

Although the drag system was not able to be deployed during the test flight, all components were able to fit within the body tube of the rocket, which ensures that for the competition the drag system not being able to fit within the rocket will not be a problem or an obstacle for the team to overcome in the future.

Many forces act upon the rocket and its drag system during flight and, as a result, it is critical to ensure each part is strong enough to withstand such strains. The part in particular that must endure extreme stress is the hinge tape connecting the airbrake flaps to the rest of the body tube. The tape must withstand a downward force from the linear actuator, as well as that of the air pressure. In addition to this tension, the tape must be able to bend over the curved surface of the body tube. Given these factors, a reinforced material capable of withstanding a stress of 150 psi before tearing was selected. Other component materials were also carefully selected for their structural integrity. For example, Blue Tube was chosen over standard LOC tubing for the rocket body for its superior stiffness. The fins were cut from rigid plywood in order to avoid the risk of snapping midflight.

With the result of the test flight being successful and the recovery of the rocket proved to have caused little to no damage on the body of the rocket or any of its components, the choice of material was well in thought. The epoxy used and sanded down also proved to be a great addition as it provided additional support to the fins as well as the inner components such as the centering rings, etc.

A structural Finite Element Analysis (FEA) was performed on the active drag system, simulating the forces this system is likely to experience during flight. This simulation showed that under the specified loading conditions, the maximum stress experienced by the system was 130.60 psi, which is below the failure point of the material used in the hinges.

Launch Analysis

The initial launch analysis will include the analysis of both the velocity off pad as well as the velocity at deployment. Analyzing these two characteristics will yield in accurate descriptions of the vehicle as it exits the launch pad and off the launch rail. Taking these characteristics into account, a predictable assumption can be made for the flight analysis later on. Performance predictions were taken from OpenRocket, which was used to model the vehicle, piece by piece, and then simulate its flight.

Using OpenRocket’s simulations, the calculated velocity off the pad is 62.99 ft/s, which is fairly above the average off-pad velocity for a vehicle of this size and weight. The initial velocity shows that the vehicle will be fairly stable as it leaves the guide rail, which is a good sign that the vehicle will be stable throughout its flight.

Additionally, for any flight to be successful, the vehicle’s maximum velocity also factors into the performance of the vehicle. OpenRocket predicts the vehicle to have a deployment velocity of 61.8 ft/s. The recommended deployment velocity is around 131.23 ft/s so the vehicle deploying at the predicted velocity will have no trouble with stability as it leaves the launch rail.

During the test flight, the deployment of the rocket was 64.7 ft/s which was well within the range of the recommended deployment velocity. It was a little faster than what the team had originally calculated but within the realm of possibility. During the competition, the team hopes to have the deployment velocity within the same range of between 60 and 70 ft/s in order to ensure a safe deployment. The rocket also launched perfectly straight up, indicating on the quality of the rail nuts that were assembled.

Flight Analysis

The key flight characteristics made for the vehicle include the apogee, maximum velocity, and the total duration of flight. Using OpenRocket's simulation software and custom MATLAB code, the team has available a range of predictions for the flight parameters of the rocket.

A comparison the simulated apogees while not using the active drag system is shown below in **Error! Reference source not found.**. The early stages of flight are nearly identical between the simulations and scales with respect to the apogee. The OpenRocket simulation predicts the vehicle will be reaching an apogee of 4900 ft while the custom code predicts apogee at 4000 ft. This is the absolute maximum apogee this vehicle will achieve since, as stated previously, this simulation assumes that the flaps will not be deployed during launch. This decision to acquire the absolute maximum apogee is intentional as the target altitude for the competition is 3000 ft and with the addition of the drag, the approximation will be less than the predicted apogee as given by OpenRocket. Additionally, overshooting the intended the altitude allows for small changes to made to the design of the vehicle without having to alter portions of the overall design.

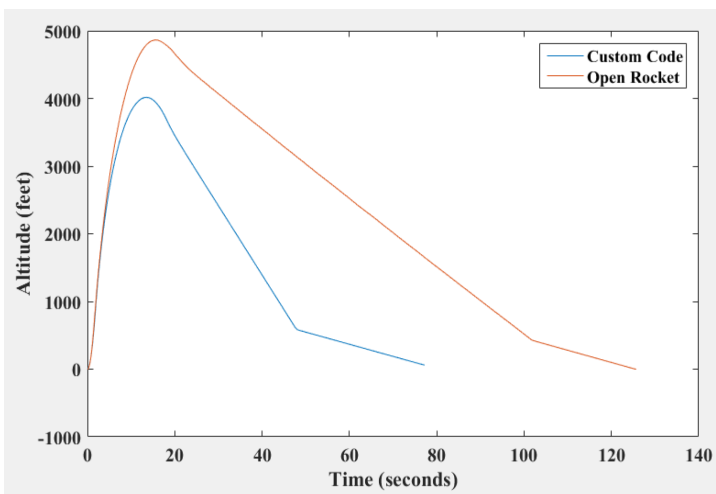


Figure 11. Predicted altitude without drag system as a function of time from both simulations.

The MATLAB code is also used to estimate the effects of the active drag system. With the system engaged, the rocket reaches an apogee of 3250 ft. This is 18.75% less than without the drag system. The code used to predict the coefficient of drag for a given velocity. This is calculated through the manipulation of the drag equation as well as the equation used to calculate the Reynold's number. By solving for the density, thereby minimizing the effects of altitude change, the team was able to equate the two otherwise dissimilar equations with one another. The resultant of this manipulation yields an equation which relates the coefficient of drag to the velocity. Figure 14 shows the results of this calculations during the simulation.

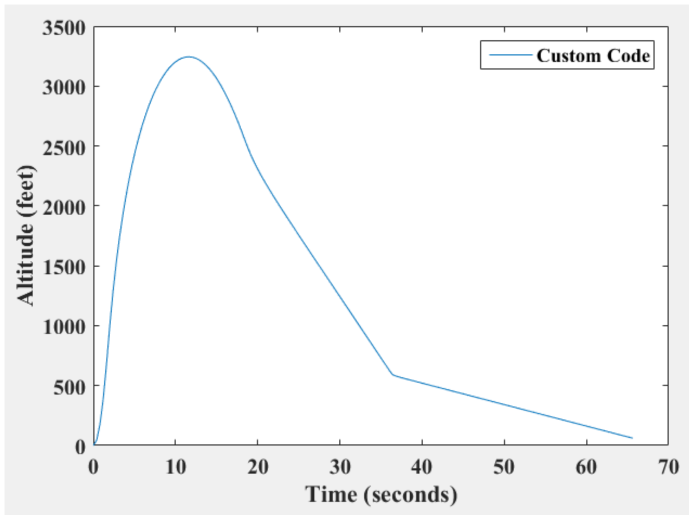


Figure 1. Altitude as a function of time with the drag system engaged.

In addition to the predicted apogee, the vehicle's maximum velocity is simulated at 850 ft/s by OpenRocket, approximately Mach 0.76, and at 800 ft/s by the MATLAB code. The velocity curves, shown in Figure 2, match up nicely in both simulations, suggesting a high degree of accuracy in this estimate. A Mach number of 0.76 will not be close to transonic speeds, so structural integrity will not be compromised and there will be evaluation of the effects of supersonic or transonic airflow on the vehicle required. Knowing that this maximum velocity is well below the transonic range, the team is confident that performance will not be impeded.

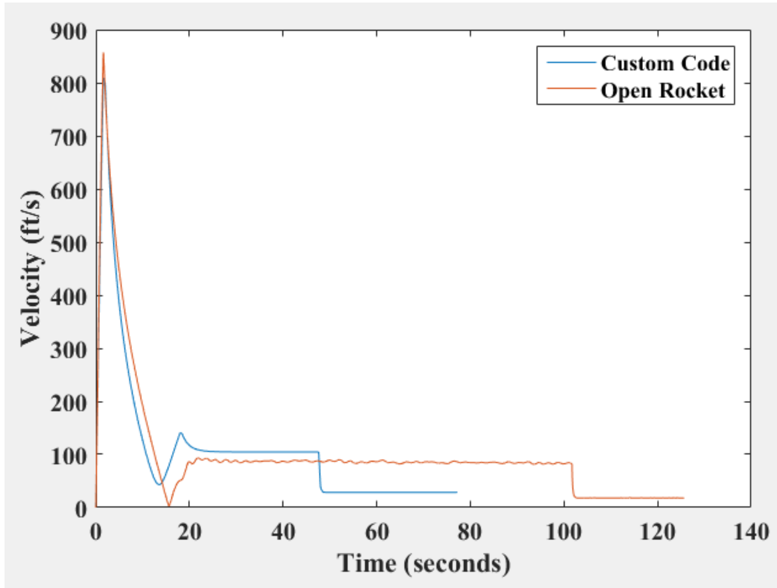


Figure 2. Predicted total velocity without drag system from both simulations.

Finally, the duration of the flight is also taken into account when analyzing the characteristics of the simulated flight. The reason in doing so is so that the team is able to have an estimation for the total launch time, accounting later on for recovery and set up as well. The duration of the flight as simulated by OpenRocket is 244 s which is a fairly average length in time for a flight of this size of vehicles. With the flight of the duration taken into account, the team is confident in making sure that the time spent during the competition is dedicated to the launch characteristics of the vehicle.

Over the time of flight, the coefficient of drag changes. Figure 3 and Figure compare the coefficient of drag to both the time, and velocity of flight. It is clear from Figure 3 that coefficient of drift is reliant on velocity of the rocket. These values were generated by the OpenRocket software.

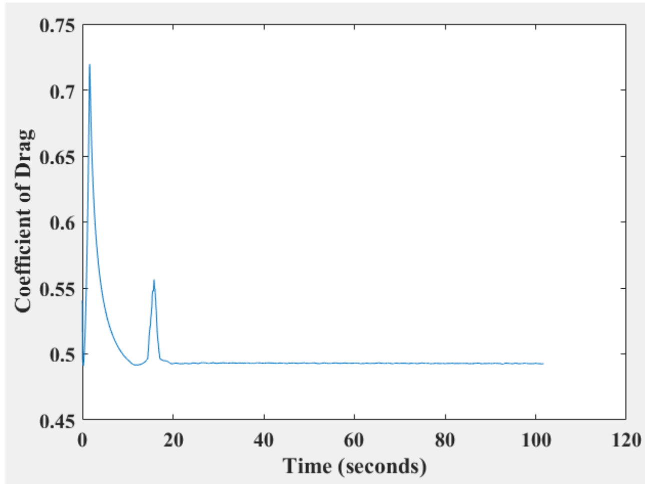


Figure 14. Coefficient of drag without drag system as a function of time predicted by OpenRocket.

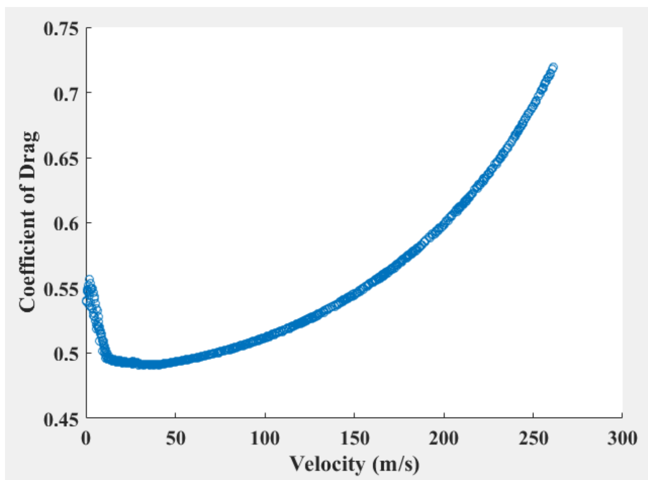


Figure 3. Coefficient of drag without drag system as a function of velocity predicted by OpenRocket

Findings and Future Work

Key Findings

The success of the test flight is a good indicator of possible successes in competition. There are some improvements to be made regarding the code needed to manipulate the active drag system and the amount of unintended drag made by the rocket; however, most of the probable errors during flight were anticipated and corrected during construction.

Potential Design Improvements

Despite an overall successful test flight, adjustments must be made to improve the rocket's performance at competition. These adjustments include the aesthetics of the rocket for easier recover and the reduction in weight for reduced induced drag force.

Additional measures must be taken to minimize unintended drag on the rocket. Extra epoxy and jutting edges will be sanded down, and the leading edges of the fins will be further sharpened. The addition of torsion springs will also keep the wedges from protruding from the rocket during the initial flight. These measures will further reduce the rocket's drag, increasing its apogee and yielding results closer to the predicted performance of the rocket.

Another adjustment is to find as many components that are not necessary to the performance of the rocket and reduce the weight of those components if possible. This includes removing excess wires, removing unnecessary screws, and all other contingencies. By doing so, this will reduce the overall weight of the rocket and therefore reduce the unintended drag that the rocket experiences.

In terms of aesthetics, the whole rocket will be painted and a brightly colored streamer will be attached to the parachute. Both of these changes will increase the rocket's contrast against the open sky, allowing for faster recovery and a quicker turn-around for the second launch.