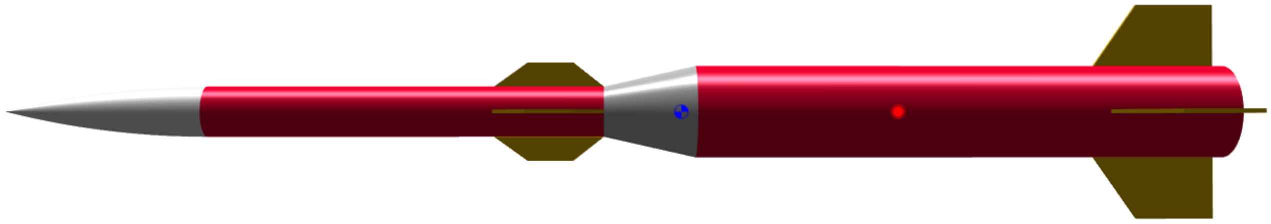

Preliminary Design Report

NASA Space Grant Midwest High-Power Rocket Competition

The Ohio State University Rocket Team

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20 March 2015

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Executive Summary

The design for the 2015 NASA Space Grant Midwest High-Power Rocket Competition is outlined in this report for The Ohio State University's Rocketry Team. The objective is to launch a boosted dart to the highest altitude possible using a Cesaroni 475-I445-16A motor and record the flight profile to compare it to predicted results. The dart will also record a looking-down video of the flight and stage separation for later viewing. The rocket design has two main stages – the booster and the dart. The booster is 17.3 inches long and will weigh between 1.24 - 1.46 pounds, and the dart is 13 inches long. Using MATLAB, an ideal dart weight for maximum apogee is calculated to be 1.9 pounds with basis of an achievable minimum weight for the booster design. The booster and dart will be wrapped in fiberglass to improve the strength of the material to prevent structural damage during flight and descent. There are three primary payload components for the booster: the electronics, the recovery system, and the air brake system. The air brake device will be used to slow down the booster quickly to increase the distance between booster and dart apogee and achieve a higher mission score. This consists of two plates that deploy from the body tube, exposing flat panels to the air flow and thus will increase pressure drag significantly. The brakes will be controlled electronically and spun on two servo motors mounted inside the rocket activated before the recovery system (a simple parachute packed in with protective wadding). The electronics on board the booster will record acceleration, velocity, and altitude, and have an Arduino controlling the air brake system's servos. The dart will have two payload components: the electronics and the recovery system. The dart's electronics will record acceleration, velocity, and altitude of the dart. They will also record the rotation in the X, Y, and Z planes. This data will be compared to the looking-down video from the dart to verify the spin rates during flight. The recovery system is also a simple parachute with protective wadding, activated via an electronic ejection charge. The construction of the rocket, mainly the fiberglass wrapping, will be done safely with the proper safety equipment such as gloves, masks, and goggles. Any flammable materials, such as any epoxies and the motor, will be stored in a fire-safe cabinet. During any test launches, common safety practices will be followed. The igniter will be placed inside the motor after the rocket is secure on the launch rails and electronics turned on. The rocket will not be armed and launched until the area is clear and any bystanders far enough way. OpenRocket and MATLAB were used for all performance simulations. Using a booster that weighs 6.32 Newtons (1.42 lbs) and a dart that weighs 8.47 Newtons (1.9 lbs), the dart was simulated to reach an apogee of 1,464 meters 16 seconds after launch. The booster was simulated to reach an apogee of 706 meters roughly 10 seconds after launch. The maximum acceleration is estimated to be maximum 26 G's; this is a rather high acceleration and is the main motivation for strengthening the booster with fiberglass. To create two versions of this rocket – a test-launch prototype and a competition version – the estimated total project cost is about $940. Total cost with competition travel expenses is $3140.00.

Design Features of Rocket

The rocket is in two stages; the booster stage and the dart (see *Diagrams of Rocket*). The booster section is 17.3 inches long and approximately 3 inches in diameter. The dart is 13 inches long and 1.65 inches in diameter. The transition section is 3 inches long, connecting the booster and dart. The nose cone atop the dart is 6.63 inches long. The overall length of the rocket is 39.93 inches. The booster is split into two sections, the motor section and the payload section. The motor section is 15 inches long and the payload section is 2.3 inches long. The booster is estimated to weigh about 1.24 – 1.46 pounds (5.5 -6.5 Newtons), and the dart about 1.9 pounds (8.47 Newtons) (see *Analysis of Anticipated Performance*). The booster and dart are cardboard tubes from Apogeerockets.com. The booster is wrapped 3 times around with fiberglass to strengthen the cardboard. The dart is wrapped as well. The dart has a boat tail which is inside the transition section while the dart and booster are connected. The boat tail and transition section will be machined out of plastic. The booster and dart have 4 fins each. The booster's fins are trapezoidal and each fin has an exposed area of 6.43 in^2. The dart's fins are also trapezoidal and have an exposed area of 1.96 in^2. Both sets of fins are wrapped in fiberglass to strengthen them to resist breaking due to impact on landing.

Design Features of Payload Section

The payload is split into three main categories: the air brake system, the electronics, and the recovery systems. The air brake system is a device that will be used to separate the booster from the dart more quickly. Part of the score will be based on the distance between dart and booster apogee; therefore, it was advantageous to design a system to increase this distance. The coupler section (also referred to as payload section) of the booster houses this system. The coupler will have two slits cut into the side, where fins approximately one eighth inch thick will be able to rotate outwards; this will create a significant amount of additional drag, which will slow the booster down quickly and insure a quick separation from the dart section during ascent. There will be two servos inside the coupler that will rotate the fins. The servo motors will be controlled by an Arduino which will rotate the fins shortly after burnout as well as electronically deploy the recovery parachute. There are some risks to using this system: If a servo fails or a fin gets stuck, the other fin that does rotate outward will cause a significant moment on the booster, which will cause it to flip and become unstable. Also, these fins will take a large amount force after opening; the connections from fin to servo and servo to rocket need to be strong enough to handle this force. Due to these risks, the team plans to launch once with the system active and once without it.

There are currently three designs under consideration for the air brake system. These are pictured below:

Figure 1: Three Current Designs for the Air brake System

The design on the far left has two horizontal fins, with more exposed area than the middle design. The fins pivot around the corner where the fin meets the body tube, so when the fins are extended out the slot is open to the air. The middle design is also two horizontal fins, but there will be less exposed area. The fins pivot around the center as opposed to the corner, so the slot is never open to the air. The third design on the far right has two fins angled about 15 degrees to the horizontal. The key feature of the third design is that it will cause the booster to spin. The spinning would cause the booster to decelerate even more. Some questions need to be answered before the final design is chosen. How will a slot open to the air affect stability, if at all? Will a spinning booster be more stable than a non-spinning one? A test launch or wind-tunnel testing data can be used as basis for the final design.

The booster and dart will both have electronics on board. On the booster, the electronics will be located below the air brake system and above the recovery system (see *Diagrams of Rocket*). The booster electronics will record altitude, acceleration, velocity, and have an Arduino controlling the air brake system's servo motors. The dart's electronics will be located in the bottom of the dart, and will record altitude, acceleration, velocity, and rotation in the X, Y, and Z planes. There will also be a camera on board the dart recording look-down video. In order to capture the video, the camera will protrude out the side of the rocket. An aerodynamic cover will be machined to reduce the drag caused by the camera. There will be room saved for the competition AltimeterTwo to be placed in the dart on launch day.

The booster and dart will also have recovery systems. The booster's recovery system will be located in the motor section, below the air brake system and electronics bay. There will be an electronic ejection charge as well as the motor ejection charge for the booster. The booster will have a standard nylon parachute. The dart's recovery system will be located below the nose cone, and will have an electronic ejection charge. The dart's parachute is also standard nylon. Neither parachute size has been set yet; once the rocket is complete and exact weights are known, a parachute size will be determined.

Diagrams of Rocket

Projectile Dart

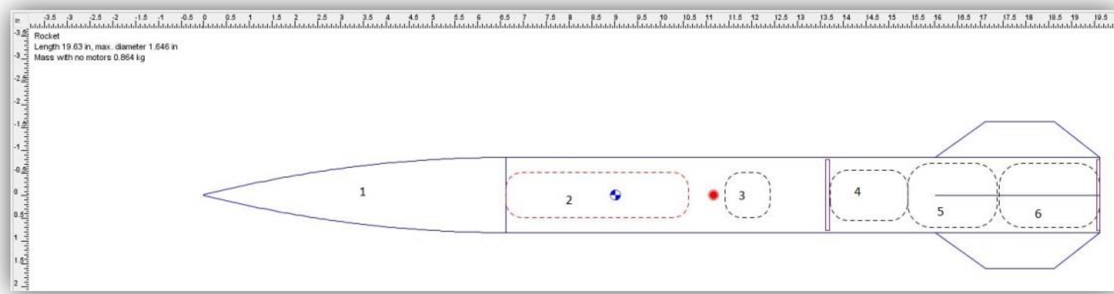

Figure 2: Diagram of Dart

The figure above shows the layout of the dart. The center of pressure is located at 11.171 inches from the tip of the nose cone. The center of gravity is located at 9.006 inches. The dart has a static margin of 1.32, therefore the dart should be stable throughout the flight after it separates from the booster. The following table indicates what each number represents in the diagram.

Table 1: Dart Components

Part Number	Description
1	Ogive Nose Cone
2	Parachute
3	Mass Representing Ejection Charge
4	Camera Electronics
5	AltimeterTwo
6	Battery/Custom Electronics

The electronics housing can easily take the place of traditional motor placement due to the separate booster design. This allows for the dart to have a lighter and more weight-versatile design so it may be ballasted easily to achieve a maximum apogee. Calculations for weight-based optimization are included in *Analysis of Anticipated Performance*.

Booster (Single Stage)

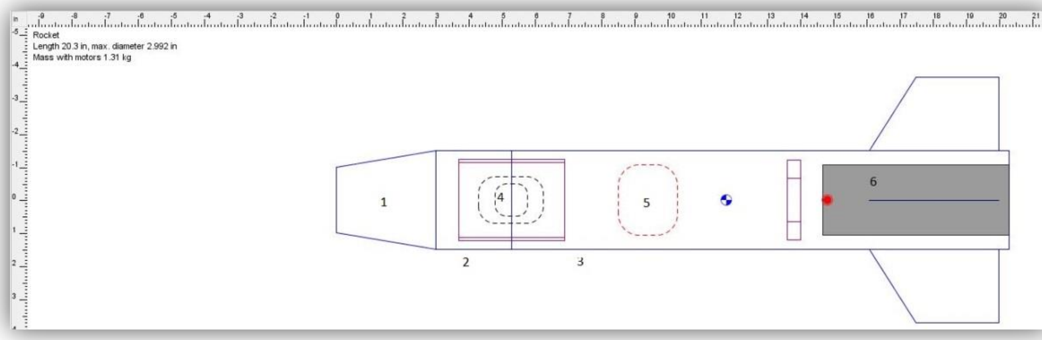

Figure 3: Diagram of Booster

The figure above shows the layout of the booster stage. The center of pressure is located at 14.815 inches; the center of gravity is located at 11.768 inches. These are measured from the leading edge of the transition section. The static margin of the booster is 1.02 with a loaded motor. Once the booster is flying separately from the dart, the motor will be empty and the center of gravity will be closer towards the transition section, giving more stability to the booster. The following table shows what each number represents in the diagram.

Table 2: Booster Components

Part Number	Description
1	Transition Section
2	Payload Section
3	Motor Section
4	Electronics Bay/Air brake System
5	Parachute
6	Cesaroni 475-I445-16A Motor

Assembled Launch System

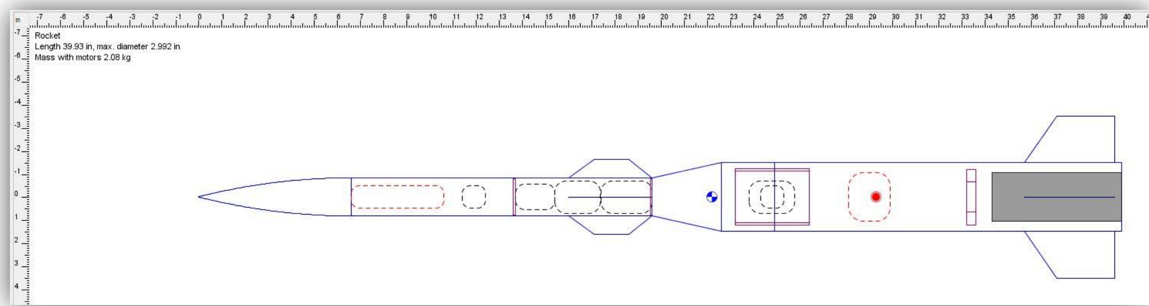

Figure 4: Assembled Rocket System

The figure above shows the layout of the entire rocket before separation. The center of pressure is located at 29.301 inches and the center of gravity is located at 22.174 inches. These are measured from the tip of the dart nose cone. The static margin of the entire rocket is 2.38. This is a relatively high static margin. During design, it was found that lowering the stability of the overall rocket was making the booster stage unstable by itself. Therefore, because separation will occur early on during the flight, the team decided that having a high stability on the overall rocket will not be a significant issue for the overall performance. This static margin is as low as the team could make it while keeping the booster stage stable.

All schematic drawings are created in *OpenRocket*.

Safety

The demanding stresses that the rocket design will be subject to during flight require strong structural materials to prevent deformations and fractures. Fiberglass composites will be used to reinforce the exterior of the body tube and can be dangerous to work with. Before being coated in the hardening epoxy solutions, glass fibers are strong skin and eye irritants; safety gloves and glasses must be worn during the coating processes and respirators must be used post-hardening sanding to prevent inhaling the airborne glass fiber particles. The I-445 Rocket Motor is a highly flammable solid rocket fuel that can be ignited with high temperature sparks. The motor must be stored in fire-safe cabinets when not in use and must be handled with care during transportation to the field and during launch procedures.

Preparing the rocket for launch will include the packing of the parachutes into the body tube sections with protective wadding. Once assembled, the rocket motor will be slid into the aluminum motor housing and secured into the motor tube. After the rocket is secured to the launch rails, the electronics devices will be armed to prepare for data collecting. Only after the rocket has been secured to the launch rails will the rocket ignitor be placed inside the motor and discharge leads connected to the launch station. The custom IMU recorder will be set to record data following the thrust of the motor start up and will record until they have sensed that the rocket has returned to the ground. Upon completion of the launch, the rocket will be recovered and the saved data log file will be recorded to a computer for analysis and comparison to estimated results. The motor tube will be extracted from the booster upon cooling down and will be cleaned with rubbing alcohol in preparation of the next anticipated launch as the electronics batteries are recharged and memory reset.

Analysis of Anticipated Performance

The preliminary rocket design is constructed using *OpenRocket* projectile simulation software. This software has the capability of mathematically modeling a constructed three-dimensional rocket profile and computing rough drag characteristics, mass centers, pressure centers and stability margins through empirical estimate methods. Uploading the projected design and adjusting mass placements for a suitable stability margin (between 1 and 2 diameter lengths), drag characteristics can be extrapolated. Drag coefficient values vary with flight Mach number and are difficult to predict without computational software such as *OpenRocket*, where they can be exported to display the Cd values of the two stages combined as well as after separation. These values will be used in an original MATLAB-based program to predict flight performance of the two stages through Runge-Kutta iterative methods of solving systems of differential equations which are needed to project the height of the rocket as a function of time.

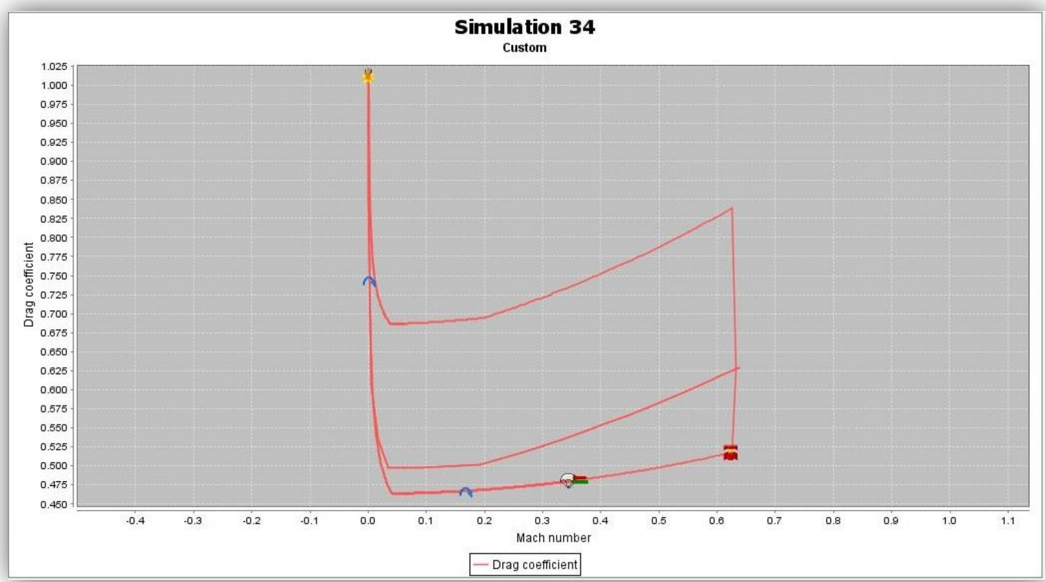

Figure 5: Cd vs. Mach Number for Booster and Dart

The following governing physics equations of projectile motion will be the basis of setting up the ODE system. These differential equations can be solved using inputted initial conditions of the initial y displacement (0 meters) as well as the initial y velocity (0 m/s). Given a regime of time intervals, the program will step through a time vector iteratively solving these equations to determine the displacement and velocity profiles.

$$F_{drag} = \frac{1}{2}\rho V (\frac{dy}{dt})^2 S * C_d \qquad \frac{d^2y}{dt^2} = \frac{F_{thrust}}{m} - \frac{F_{drag}}{m} - g$$

M is the mass of the rocket component, Cd is the Drag Coefficient extrapolated from OpenRocket, and S is the reference area (largest body cross sectional area). All of these variables are inputted specific for the case being run, such as the initial combined system, or the separated dart stage. The coding is run with combined stages to collect values of maximum velocity (this is best separation moment for max dart altitude) and then will be run again for both separated stages using the initial conditions of the rocket at separation. To further the accuracy of a rocket launch, variance to air density with altitude has been included based of values of a Standard Atmosphere assumption. Mach Number values are based from a sea level speed of sound of 343 meters per second.

Being able to mathematically model the rocket launch allows for the optimization of the weight of the booster and dart sections to maximize both dart apogee and booster-dart separation distance. With governing factors such as the motor casing weight and the weight of required electronics, a minimum booster weight can be predicted and included into the created MATLAB program with a range of dart weights to create a three-dimensional visualization of dart apogees for different dart and booster weights. This will easily allow the correct target dart weight to be achieved in the prototyping process to acquire the maximum score at the competition.

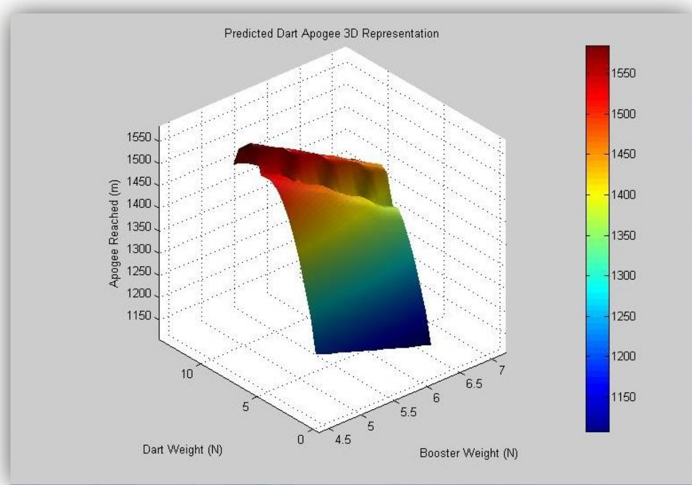

Figure 6: Predicted Dart Apogee 3D Representation

Having a heavier dart than booster is desired where the drag force of the freestream velocity can quickly slow down a lighter object due to its smaller momentum. A heavy dart has more inertia allowing it to travel higher before gravity and drag forces can stop it; however, it is still desired to create the lightest rocket system possible in order to achieve a high velocity via the motor's thrust. This is where mathematical optimization assists in the design process. The mathematical results confirm these conceptual ideas and creating a prototype with an adjustable dart weight can experimentally verify these results. Running the program with an estimated booster weight of 6.32 Newtons yields a maximum dart altitude at a dart weight of 7.8 Newtons.

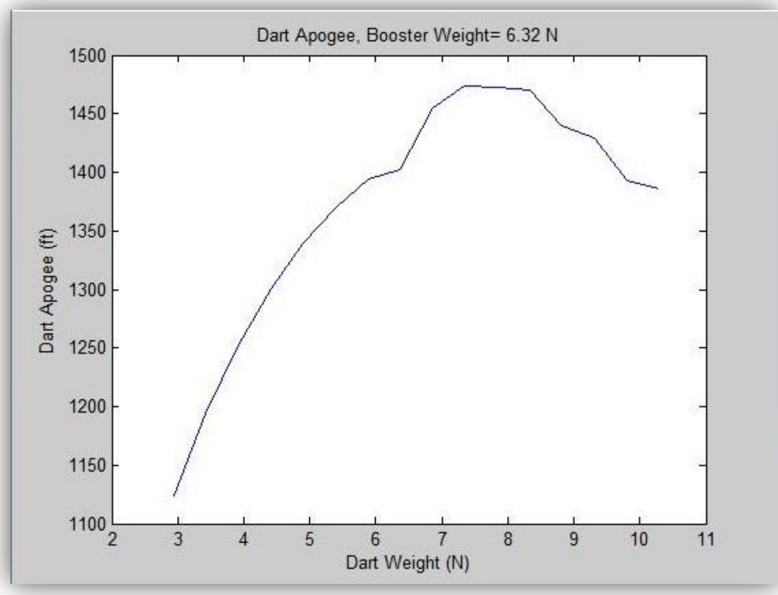

Figure 7: Dart Apogee using Booster Weight of 6.32 Newtons

After an appropriate dart weight is chosen that satisfies flight stability conditions, the results of the second-order numerical ODE process are plotted with respect to time to analyze the peak altitudes as well as the vertical accelerations of the dart and boosters. Below are the results of the rocket design using a booster weight of 6.32 Newtons (1.42 lbs) and a dart of 8.47 Newtons (1.9 lbs). The results were then compared to that of OpenRocket using the same motor characteristics which relies on a different itterative solving method for the ODE system. This provides a slight source of variance. OpenRocket relies on pressure and drag estimations as well as projectile equations derived by James S. Barrowman which are commonly used for rocket design analysis programs.

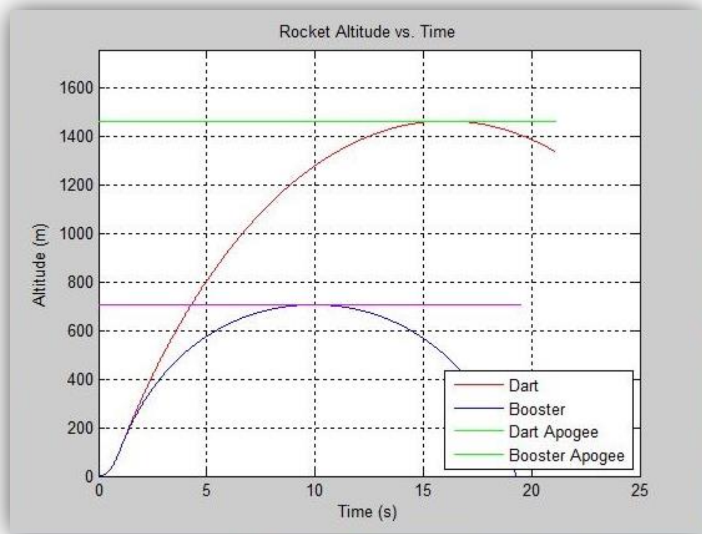

Figure 8: Computed Altitude vs. Time

A dart apogee of 1,464 meters is calculated to occur nearly 16 seconds after launch as well as an estimated booster apogee of 706 meters at around 10 seconds after launch. Knowing these values will assist in determining the ejection charge delays to be set in the electronics coding of the rocket's two stages so recovery systems can deploy after apogee.

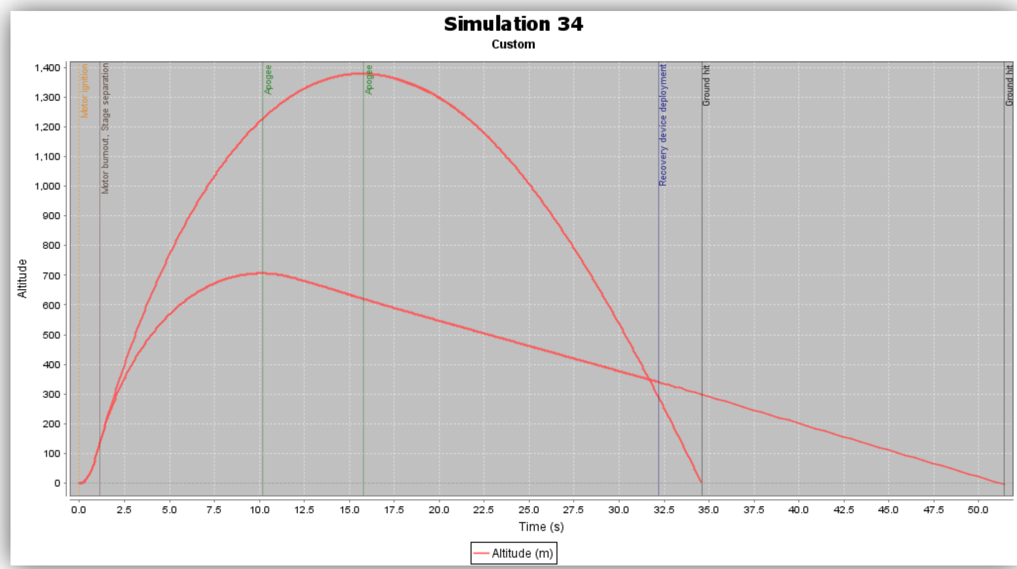

Figure 9: OpenRocket Altitude vs. Time (for comparison)

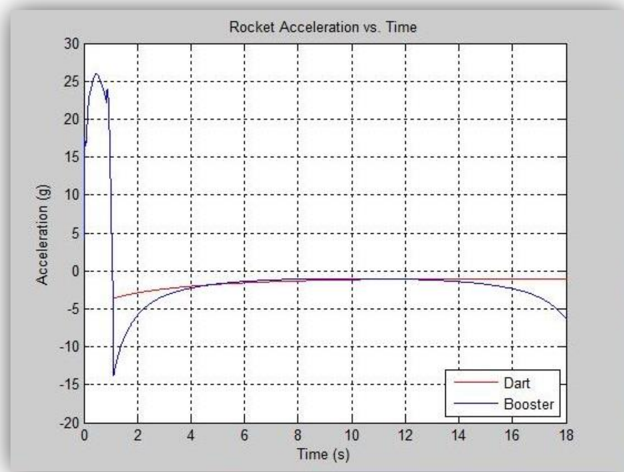

Figure 10: Rocket Acceleration vs. Time

Peak acceleration of the dart and booster will theoretically occur before burnout (within the regime of 0 to 1.1 seconds of flight time using the I-445 motor). The booster stage will still be in contact with the dart at this point in the flight, where separation will occur close to motor burnout time. The results of the MATLAB simulation coding displayed maximum acceleration values of nearly 26 G to be achieved during flight after 0.48 seconds of flight time. As the motor fuel decreases, the acceleration of the rocket becomes dominated by gravity force and drag force which cause the plot reach negative acceleration values. These results compare to that of OpenRocket's.

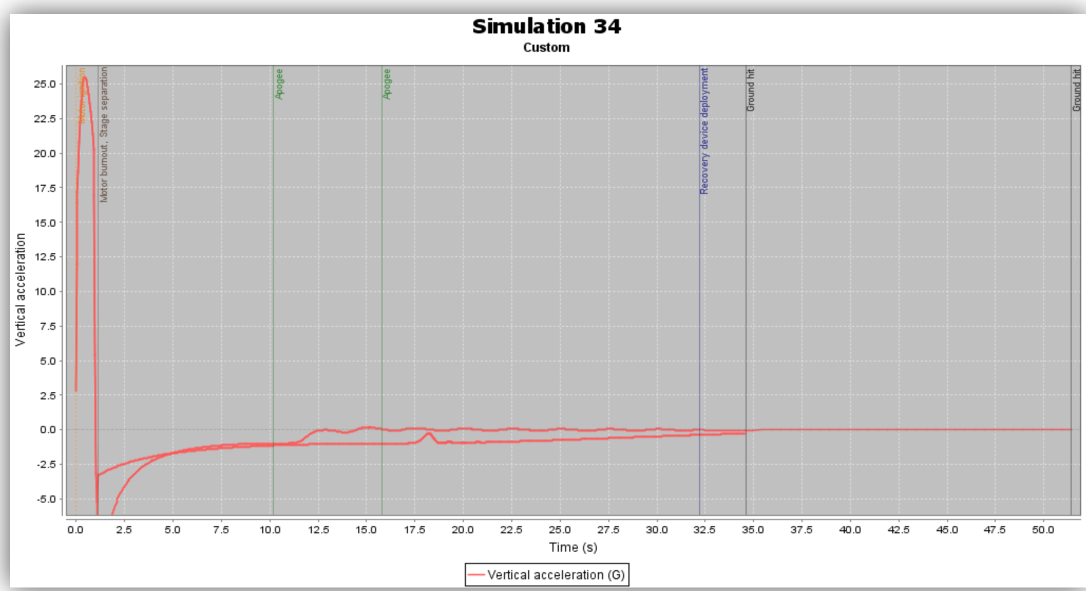

Figure 11: OpenRocket Acceleration vs. Time

Recovery systems of the current design include the same equations of motion used before but will be using the design drag coefficient of the included parachutes chosen. During descent, the rocket must achieve a safe landing speed that will not damage components of the rocket so it may be reused in another launch. The dart and booster parachute design holds a Cd value of 0.8 and a reference area of 0.2831 square meters. Computing the descent of the rockets components with their respected masses at apogee (where initial conditions for the ODE system are at apogee and zero velocity) will result in the computation of the darts velocity at zero altitude. Below are figures produced by *OpenRocket*. Displayed on the plot below are the estimated altitude and vertical velocity profiles for the launch through time. As the rocket approaches zero altitude (relatively), the velocity magnitude should be low enough so the rocket will not sustain damage upon hitting the ground. The rocket system must be able to be reusable after a launch.

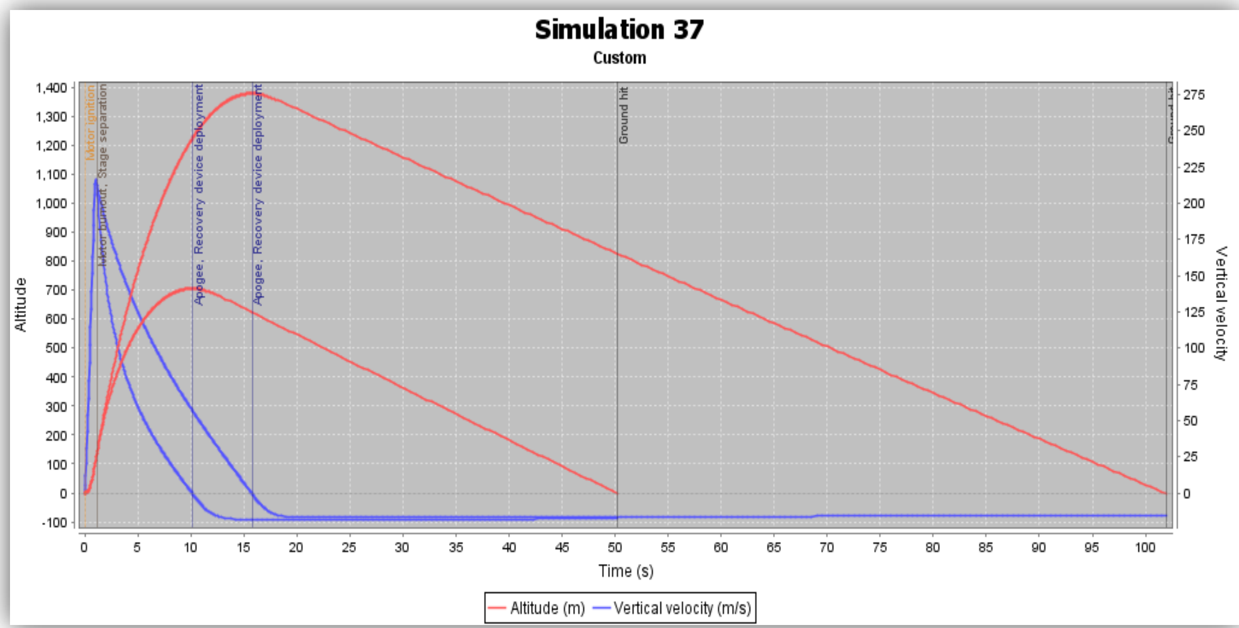

Figure 12: Flight Profile with Recovery Deployment at Apogee

Both the booster and the dart landing velocities fall within 15 to 18 feet per second which are considerably safe velocities in regards to the structural integrity of the rocket. The scheduled test launch will determine if a larger parachute or that of a larger drag coefficient is necessary for the design. If damage to the rocket occurs after the prototype's launch, changes will be made to the recovery systems.

Budget

Current budgeting estimates are projected to cover only the costs of materials to create two versions of the current rocket design, the flight-test prototype and the competition rocket. Price estimates of individual components have been based off of past material costs for past projects of The Ohio State University's Rocketry Team as well as maximum pricings for necessary electronic components to be included in dart and booster sections. Travel expenses for the team as well as overlapping budgeting for tools and equipment are not included in the below tables.

Table 3: Minnesota Competition Budget Projections

Minnesota Competition Budget Projections			
	Unit Price	Units	Total Price
1 Fiberglass Sheets Fins	$120.00	1	$120.00
Custom electronics	$150.00	1	$150.00
Hobby Grade Altimeters	$150.00	1	$150.00
Fiberglass Body Tubes costs	$200.00	1	$200.00
Parachute Modules	$120.00	2	$240.00
Composite Nose Cone	$80.00	1	$80.00
Camera System	$65.00	1	$65.00
Motor Casing	$54.00	1	$54.00
Motors for Test Launches	$53.00	2	$106.00
Hotel 3 Nights (2 rooms)	$200.00	3	$600.00
Van Rental Fees			$1,600.00
Total Cost			**$3140.00**

Table 4: In-Kind Costs of Operation

In Kind Costs			
Sources	Rate	Estimated Cost	Reasoning
OSU Campus Lab 1 (Bolz 112)	$10/hr	$1,500	25 weeks, 6 hours a week
OSU Campus Lab 1 (Bolz 114)	$10/hr	$1,500	25 weeks, 6 hours a week
Faculty Advisor (Time support)	$40/hr	$1,000	25 hours at $40/hr
Lab Tool use/Maintenance	$50/Semester	$100	2 semesters
	Total	$4,100	

Sources

Technical information sourced from a Master's Thesis of Sampo Niskanen, creator of the software *OpenRocket*.

Niskanen, Samp. *Development of an Open Source Model Rocket Simulation Software*. Thesis. HELSINKI UNIVERSITY OF TECHNOLOGY, 2009. N.p.: n.p., n.d. Print.

Anderson, J. (2012). *Introduction to flight* (7th ed.). New York: McGraw Hill.