2014-2015 NASA Space Grant

Midwest High-Power Rocketry Competition

University of Minnesota Senior Design Team

Team: Space Cowboys

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March 20, 2014

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1. Executive Summary

This report describes the rocket design of the University of Minnesota – Twin Cities High-Power Rocketry Senior Design team for the NASA Space Grant Midwest High-Power Rocketry Competition. The rocket for this competition is a boosted-dart of three sections: dart, booster, and transition. The lower section of the rocket is a booster with a standard 3 inch inner diameter carbon-fiber body. The upper section of the rocket is a dart with a standard 29 mm inner diameter G12 fiberglass body. The booster and dart sections join at a transition section inside the top of the booster section. The dart will have four G10 fiberglass fins and contain an avionics bay, camera, and parachute. The booster will also have four G10 fiberglass fins, contain a separate avionics bay, an airbrake system, and a 475-I445-16A Cesaroni V-max motor.

The dart will employ the use of a non-commercial avionics package and camera to satisfy the 3-axis rotational data and down-looking video footage competition requirements. The dart will use a Raven3 altimeter as the primary eject of the parachute and an Arduino Nano microcontroller as a backup. The booster will use its own avionics package to control the airbrake deploy after motor burnout. The avionics will also act as the primary eject, while the motor eject from the Cesaroni I445 motor will act as the backup.

2. Design Features of Rocket

2.1 Design Overview

The boosted-dart is made up of three main sections: booster (lower section), transition (mid-section), and dart (upper section). The dart design section will cover the avionics system, recovery system, video recording system, and structure of the dart. The transition section design will describe the mating and separation of the dart from the booster. The booster design section will cover avionics system, recovery system, airbrakes module, motor components, and structure of the booster.

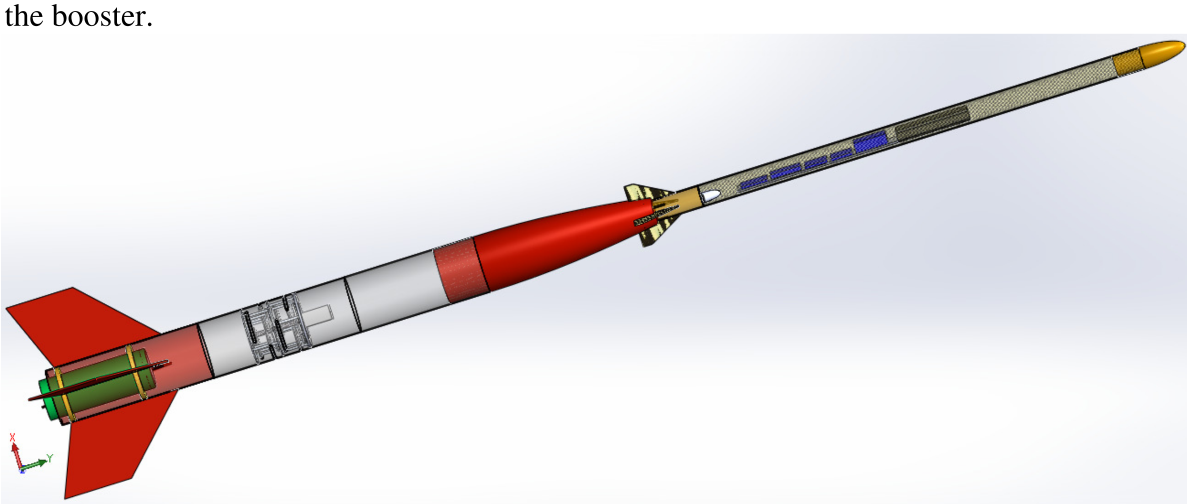

Figure 2.1 – The boosted-dart configuration. The booster and dart mate at the transition section located in the booster "nose cone."

2.2 Dart Design

The design intent of the dart was to decrease its drag relative to the booster so that the dart would be capable of separating from the booster by drag alone. This was achieved by constructing the dart airframe using a smaller diameter tube than the booster and using enough length to minimize the wetted surface area. The diameter of the dart tube is a standard 29 mm. Additionally, the weight and length of the dart is 22.96 ounces and 33.56 inches, respectively. A non-commercial avionics package was designed to satisfy the 3-axis rotation requirement of the competition. The dart contains a “down-looking” camera that is required to obtain video footage of the boosted-dart’s ascent and contains a redundant electronic recovery system needed to safely recover the dart for multiple launches. Last, the dart will carry two standard competition components: radio tracker and Altimeter Two that will function independently from the other systems.

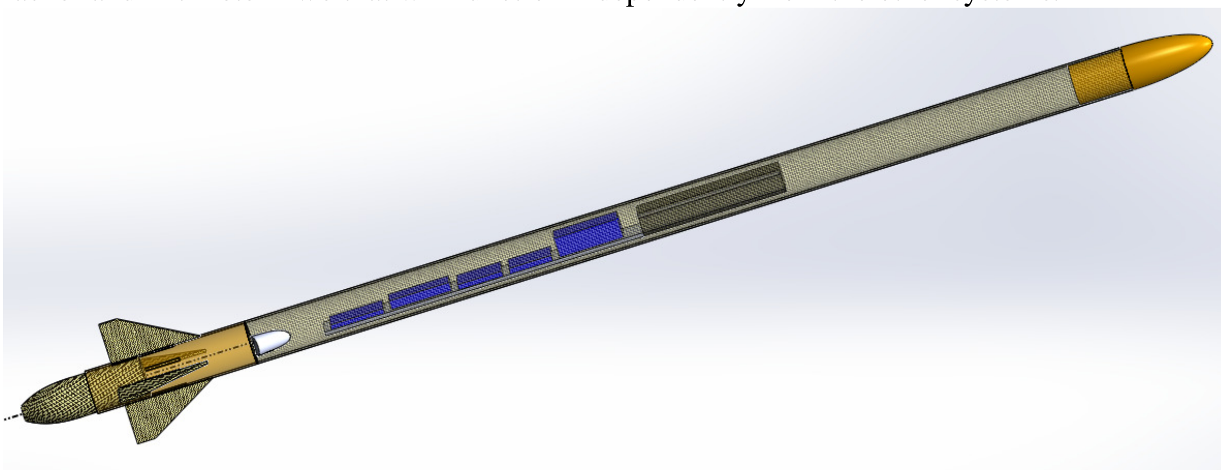

Figure 2.2 – The dart configuration has a parachute recovery system located behind the nosecone, followed by (in order), batteries (dark gray), avionics (blue), and camera with shroud (white).

2.2.1 Dart Tube

The main tube for the dart is constructed out of fiberglass with a standard inner diameter of 29 mm. Fiberglass has a high ultimate strength for its weight, making it useful for rocketry. It is less expensive than carbon fiber, allowing for more financial allocation to other aspects of the rocket. The tube will be slotted for four fins, which will be professionally machined by Orbital-ATK. Lastly, it is electrically insulating, so the avionics on board are less prone to shorting out or being interfered with by outside disturbances.

2.2.2 Nose Cone

The nose cone of the dart section is a 3:1 elliptical design constructed using Aeropoxy resin. The resin will be poured into a female mold of desired shape to harden into a solid durable nosecone with an additional cylindrical slug to be fit into the dart body tube. Drag reduction was the main factor leading to the decision of an elliptical nose cone as opposed to an ogive or conical design, as elliptical will contribute the least drag force in subsonic flight and yield a higher apogee[1].

2.2.3 Avionics

The avionics in the dart are comprised of three independent systems: the backup recovery system, the data collection package, and the camera. The backup recovery system involves one Raven3 altimeter. While the Raven3 altimeter is capable of collecting various motion data, the competition requirements restrict the use of commercial avionics for collecting 3-axis rotation data. However, using the Raven3 altimeter for primary eject does not violate the rules of the competition and it is also used to verify our competition data collection package for accuracy in test flights. The data collection package contains an Arduino Nano microcontroller, a 10 degree of freedom (DOF) breakout, an SD data storage breakout board, and a MOSFET. The Arduino

Nano has I^2C connection pins for connecting the microcontroller to the 10 DOF and connects to the SD breakout board by digital outputs. The microcontroller will be properly coded to allow the data to be recorded in real time when the microcontroller is switched on by an external switch. After a flight, an onboard SD card can be accessed for post processing of 3-axis rotational data measured by the 10 DOF breakout. The MOSFET functions as a “light switch” to allow current to flow directly to an e-match to set off a secondary recovery charge.

Last, the avionics package will include two independent components: radio tracker and Altimeter Two, which are required by the competition parameters, and a FlyCamOne Eco V2 camera with dedicated storage (see Section 2.2.5).

Figure 2.3 – The Arduino Nano microcontroller is capable of collecting various flight data and setting off ejection charges.

2.2.4 Recovery

The dart recovery system employs the use of an Arduino Nano and Raven3 altimeter to actuate a piston eject system for deploying the recovery parachute. The Raven3 altimeter and Arduino Nano are redundant recovery systems for the dart, where the Raven3 altimeters acts as the primary eject and the Arduino Nano acts as the backup. The recovery parachute will be ejected where the dart nose cone and main tube are connected and will be fastened to the dart by a Kevlar cord rated to 1500 pounds. Its open diameter will be approximately 24 inches and is determined by the total weight of the dart. The descent velocity is suggested to be 22.64 ft/s with an assumed parachute drag coefficient of 0.75 [2].

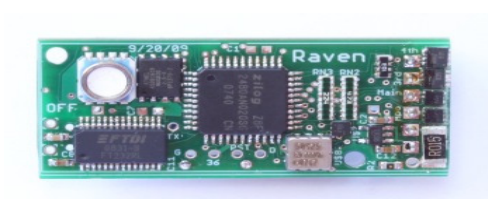

Figure 2.4 – The Raven3 altimeter is capable of collecting flight data, but will only be used as part of the recovery system.

2.2.5 Camera

The dart will be equipped with a FlyCamOne Eco V2 camera to collect visual “down-looking” footage of the launch. It will be mounted inside the dart with the lens of the camera protruding out the side of the rocket body. Video is taken in 480p at 30 frames per second with a 55 degree field of view. The main reason we chose the FlyCamOne over other options is because of the small 29 mm diameter of the dart, and the lens is attached through a cable to the battery and processor. This flexibility allows us to optimize the spatial configuration inside the dart required to capture the launch pad in the center 9th of the video footage while limiting the amount that the camera protrudes from the rocket. A shroud for the camera will be 3-D printed and be used to reduce drag caused by the camera extending out of the rocket body. The shroud will form an angle of 9 degrees relative to the tube and will be tight to the camera. The shroud will be secured with epoxy, followed by a thin layer of fiberglass. ANSYS simulation of the dart with a velocity of 400 ft/sec calculated a 7.5% reduction in drag by including the shroud, changing the coefficient of drag from 0.698 (without shrouded camera) to 0.646 (shrouded camera).

Figure 2.5 – The FlyCamOne Eco V2 is attached to a ribbon cable to allow flexibility in placement.

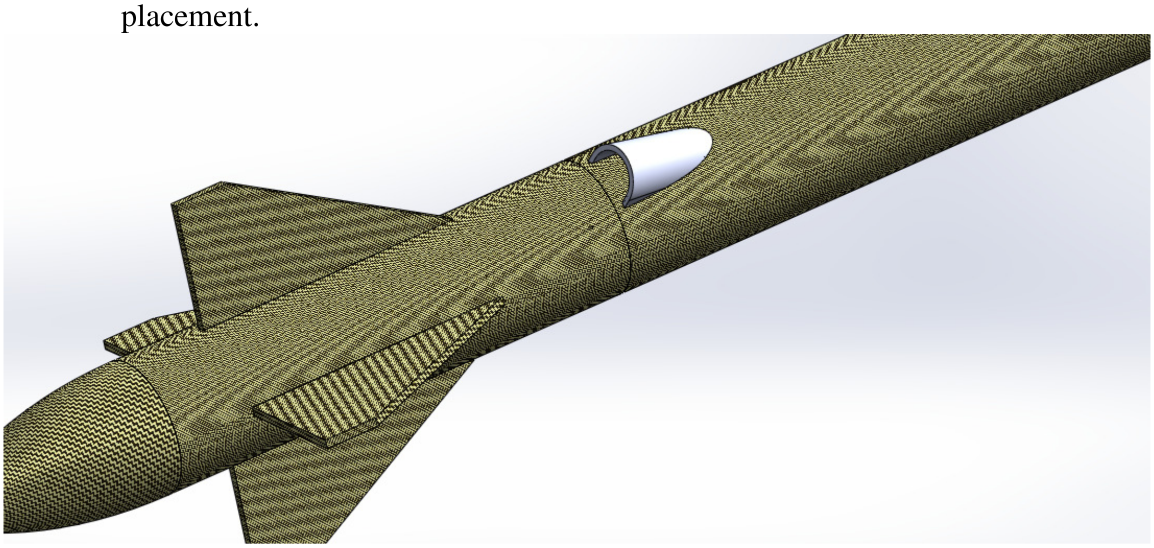

Figure 2.6 – The camera protrudes out the side of the dart airframe at the camera shroud, which is designed to reduce drag that would otherwise we be caused by the camera alone.

<u>2.2.6 Dart Fins</u>

The dart fins will be constructed out of 0.08 inch thick G-10 FR4 fiberglass because it is lightweight and designed to not deform up to 45000 psi. The fins will be epoxied on the inside of the airframe because epoxy fillets on the outside of the airframe will interfere with the mating of the booster and dart. The fins have a clipped-delta shape, with the aft corner along the root chord being 90 degrees. The root chord length is 2.5 inches, and the semi span is 1.1 inches. The leading edge will be rounded and the trailing edge will be reduced to a thickness up to 0.7% the length of the root chord to improve the aerodynamics of the rocket. Fin flutter is avoided when the dart is moving at a velocity less than 4955 feet per second [3]. Divergence is avoided when the dart is moving slower than 3642 feet per second [3]. Calculations and simulations indicate the dart will never exceed these speeds (see Section 4). As for the structural stability of the fins, the dart can travel with a velocity 90 degrees relative to the central axis at a speed of 400 feet per second and fall within a safety factor of 3 for shear forces.

2.3 Transition Design

The transition section of the rocket is the physical interface connecting the dart and booster together. The dart has a boat-tail 3:1 plastic ogive cone, and 4 fins. These four fins rest inside of slits cut into the boosters' plastic 3:1 ogive cone, of which the front portion is completely removed in order to accommodate the dart's boat-tail (slits and additional machining done by Orbital-ATK). Inside of the booster, there is an axially constrained Teflon rod secured by several centering rings which is designed to mate with a carbon fiber tube within the boat-tail.
The overall design of the transition section was primarily decided upon with consideration to the degrees of freedom of the dart during launch and upon commencement of separation. This design will minimize all other degrees of motion other than that of axial movement, allowing the dart to separate in the axial direction, and ensuring no loss of apogee height.

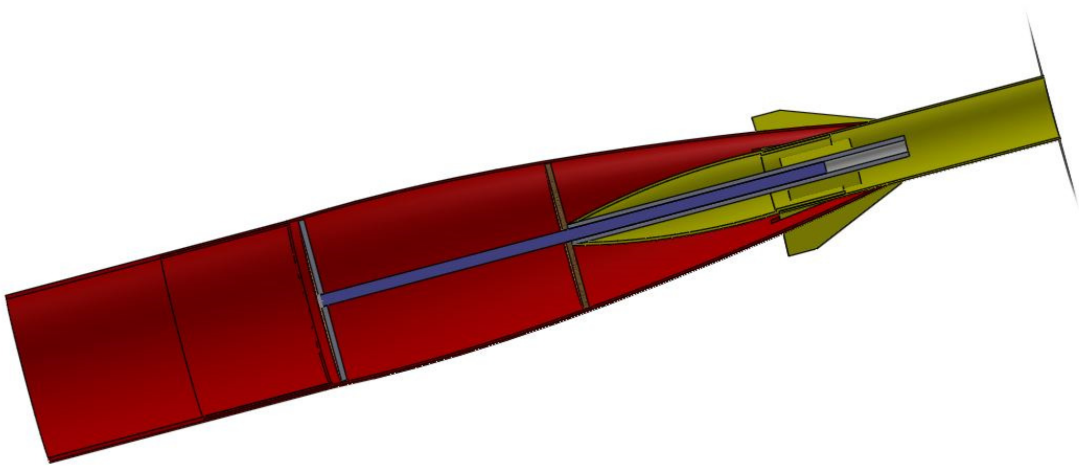

Figure 2.7 – The transition section is designed to keep the dart axially constrained during flight while allowing the dart to slide smoothly out of the transition.

2.4 Booster Design

The design intent of the booster section was to reduce unnecessary mass and increase drag relative to the dart section. This was achieved by selecting a lightweight carbon-fiber tube with a larger diameter of 3 inches. The weight of the booster is 45.97 ounces and its length is 35.45 inches. The purpose of the intent was to increase the velocity of the boosted-dart at motor burnout, but increase drag for larger apogee separation. The booster section contains a custom-built airbrake module to aid with apogee separation. This airbrake module is actuated by a servo that is controlled by the booster's own avionics system. This following section will provide details on these systems, as well as the recovery system, fins, and motor components.

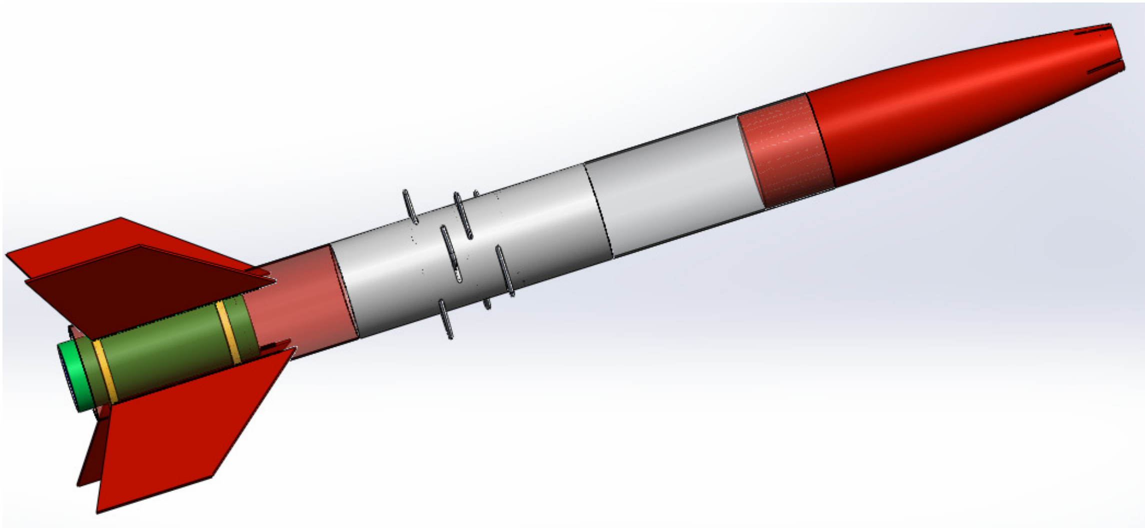

Figure 2.8 – The booster configuration begins with the transition section at the end of the red "nose cone." The avionics are located behind the transition section and are followed by (in order) a servo, airbrakes module, parachute recovery system, and motor.

2.4.1 Booster Tube

The main tube for the booster is constructed out of carbon fiber with an inner diameter of 3 inches. Carbon fiber is a low density material, useful for increasing the thrust-to-weight ratio, while still maintaining a high Young's modulus for structural safety. In addition, it provides a high heat tolerance and chemical resistance, which is needed to counter potential deformations caused by the motor igniting.

2.4.2 Avionics

The booster avionics are not required by the competition parameters, but are used to maximize rocket's performance and for improving redundancy of the booster's recovery system. The booster avionics is comprised of another Arduino Nano microcontroller, an HS-485HB servo motor, a MOSFET, an SD data storage breakout, and two sensors: a barometric pressure sensor (BMP180) and a 100G accelerometer (ADXL377). The Arduino Nano is connected to the sensors via I^2C pin connections and SD breakout via digital outputs. The purpose of the 100G accelerometer is to allow the Arduino Nano to sense motor burnout. After the motor has burned out, the Arduino Nano will detect a change in acceleration and actuate the HS-485HB servo motor. The BMP180 barometric pressure sensor will allow the Arduino Nano to sense changes in outside air pressure with the change in altitude. When the sensor detects a decrease in altitude by means of increasing air pressure, indicating that apogee has been passed, the Arduino Nano will set off the primary ejection charge by using the MOSFET to switch current directly to an e-match, similar to the backup recovery of the dart. The SD storage device will be post-processed for acceleration data to compare with predicted performance analysis.

2.4.3 Recovery

The booster recovery system employs the use of a redundant recovery system consisting of its own Arduino Nano, in addition to the built-in motor eject system from the Cesaroni I445 motor, to deploy the recovery parachute. The Arduino Nano acts as the primary eject and the motor eject acts as the backup. The recovery parachute will be ejected between the airbrakes and booster fins and will be fastened by a Kevlar cord rated to 1500 pounds. Due to a projected apogee at approximately 8 seconds (see Section 4), the motor eject delay charge will be ground down to be set off shortly after apogee if the primary eject does not go off. The parachute will be made of rip-stop nylon and will be wrapped in a Nomex parachute protector. Its open diameter will be approximately 36 inches and is determined by the estimated weight of the booster. The descent velocity is calculated to be 21.35 ft/s.

2.4.4 Airbrakes

The airbrake module to be used in the booster is a custom built device. It is designed with eight separate 1/8”6061-T6 aluminum plates, which are situated inside the device and rotate outwards through slits in the booster body tube to create a flower-like pattern as seen from above when the central axis is rotated by the servo. This will increase the total drag force on the booster by 200%, as determined through CFX simulations in ANSYS. The central rod is carbon fiber, and the additional plates and rods are aluminum. The aluminum discs and plates were constructed using a CNC Mill, and the rods were ordered and cut to length by hand.

This design was selected due to its ability to deploy and retract with ease, leading to higher assurance of reusability than other designs that were considered. The airbrakes are designed with the objective of increasing drag on the booster, causing an increase in dart-booster separation, and ultimately leading to an increase in score during the competition. As shown below in Figure 2.10 a stress analysis was performed in SolidWorks with an applied 2 pound force at the tip of each plate. This is a conservative estimate as the actual force is expected to be less than 2 pounds and will be distributed over the entire plate. The results revealed a possible failure mode at the supporting rods. However, the lowest factor of safety was determined to be 1.65.

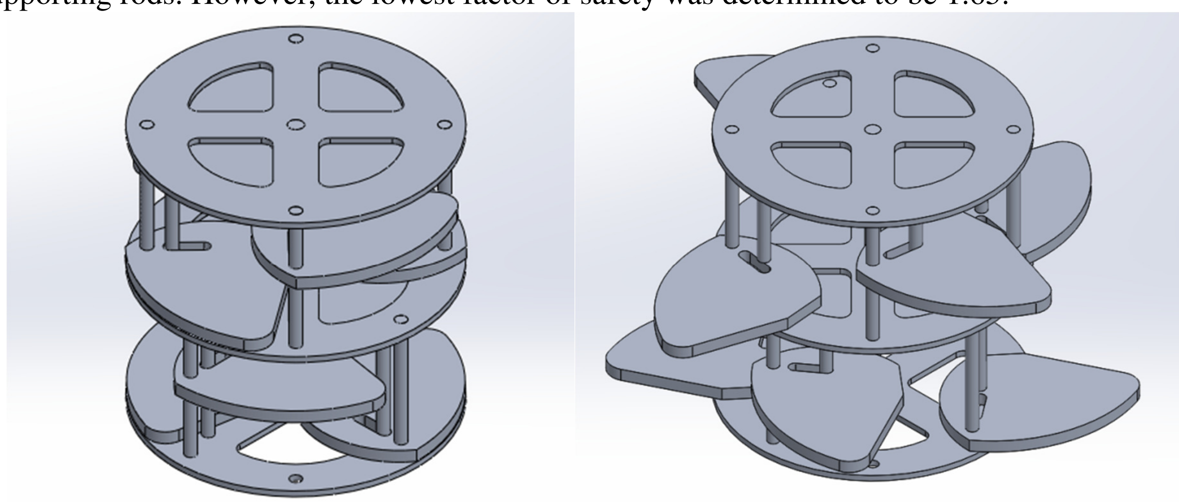

Figure 2.9 – The servo-actuated airbrake module that is used to increase the drag on the booster after motor burnout and decrease the booster’s apogee altitude.

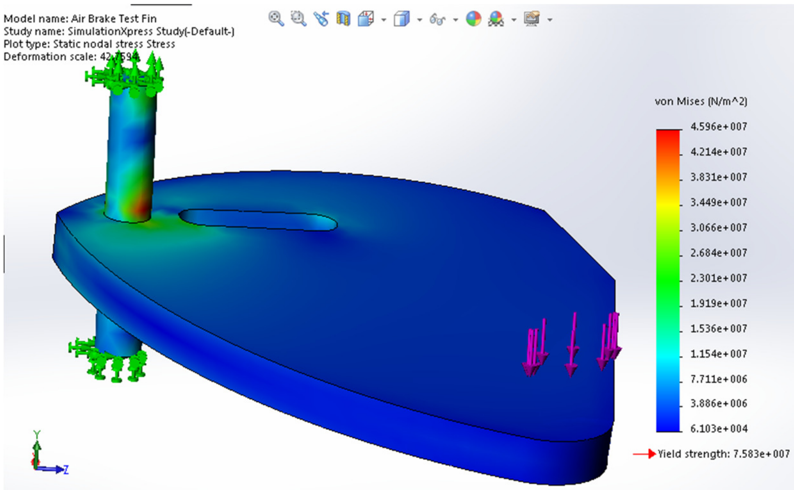

Figure 2.10 – Safety factor analysis on airbrake plate. The greatest amount of stress is seen at the pin with a safety factor of 1.65.

2.4.5 Servo

The servo to be used to deploy the airbrakes in the booster will be an HS-485 HB servo motor. By interfacing with booster avionics, it will be actuated immediately after burn-out. This specific servo model was chosen for several reasons, foremost being that its dimensions are compatible with the three inch diameter booster. This servo also supplies a torque of 83 oz-in, by which it was estimated that deployment of the airbrakes would occur in the span of 0.1 seconds. Lastly, the market price was significantly less than that of servos with slightly increased torque specifications. The servo's functionality will directly affect the dart-booster apogee separation.

Figure 2.11 – The HS-485 HB servo used to deploy and retract the airbrakes in flight.

2.4.6 Booster Fins

The booster fins will be constructed out of G-10 FR4 Fiberglass for the same reasons as the dart fins, but the thickness is increased to 0.093 inches. The fins will be slotted into the booster tube and into the centering rings of the motor mount. They will then be epoxied at the motor mount and the outer edge of the airframe. The shape of the booster fins is a swept-back clipped delta. The root chord length is 6 inches, the tip chord length is 2.2 inches, and the semi span is 4 inches. The surface area of the fins was increased in the aft to alter the center of pressure, allowing the booster to remain stable even after the dart separates and the airbrakes deploy. The leading edge of the fins will be rounded and the trailing edge will be tapered to a thickness of 0.7% the root chord length to improve the aerodynamics of the booster. Fin flutter is avoided when the booster is moving at a velocity less than 1459 feet per second [3]. Divergence is avoided when the booster is moving slower than 1072 feet per second [3]. Calculations and simulations indicate the booster will never exceed these speeds (see Section 4). As for the structural stability of the fins, the booster can travel with a velocity 90 degrees relative to the central axis at a speed of 400 feet per second and fall within a safety factor of 3 for shear forces.

2.4.7 Motor Components

To fit and secure the competition Cesaroni 475-I445-16A "V-max" motor to the rocket, a motor mount and motor retention system was designed. The motor mount utilizes two centering rings and a tube for the motor to be secured into. The tubing is phenolic, and the rings are ¼ inch plywood. Epoxy will be used to secure the rings to the tube. The importance of the motor mount is to distribute the force generated, as well as align the motor with the main axis of the booster. The rings provide more surface area to attach to the fins, allowing for more surface area to secure the fins to the booster body. The motor retainer involves a 1/16" inch aluminum plate that can be screwed into place. The purpose of the retainer is to ensure the motor does not jettison from the rocket.

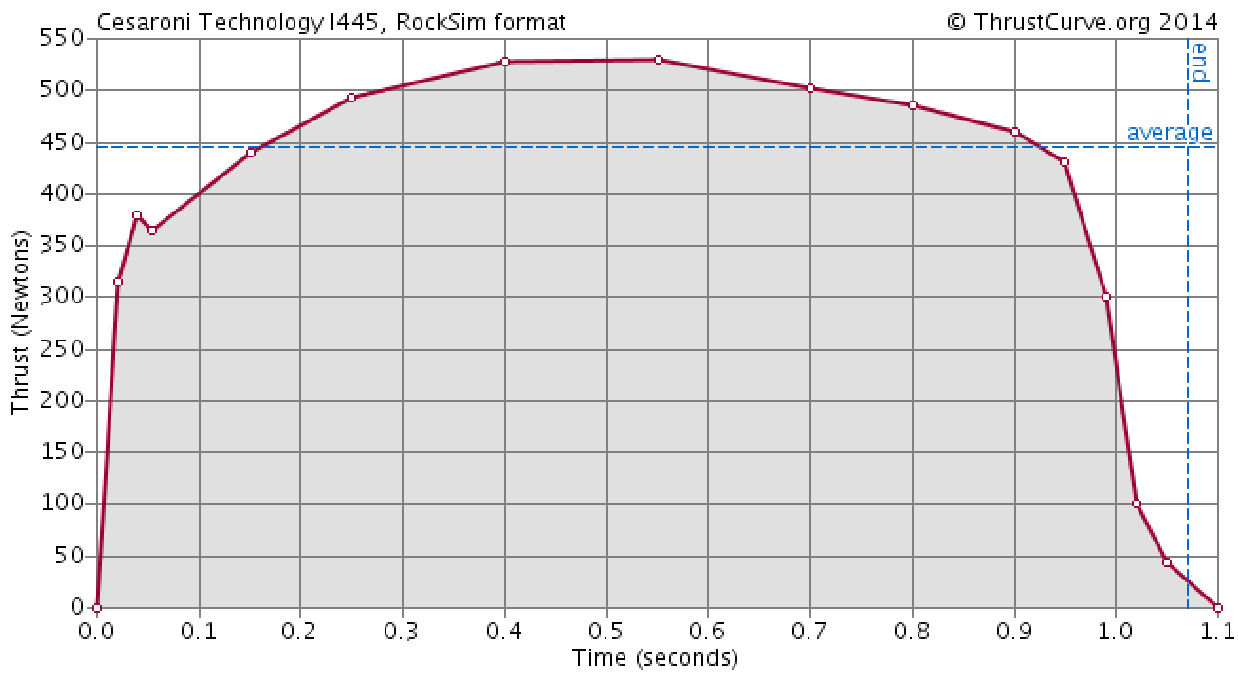

Figure 2.12 – Thrust curve for Cesaroni 475-I445-16A V-max motor. The motor has an average thrust of 445 N, but reaches maximum thrust at approximately 0.5 seconds [4].

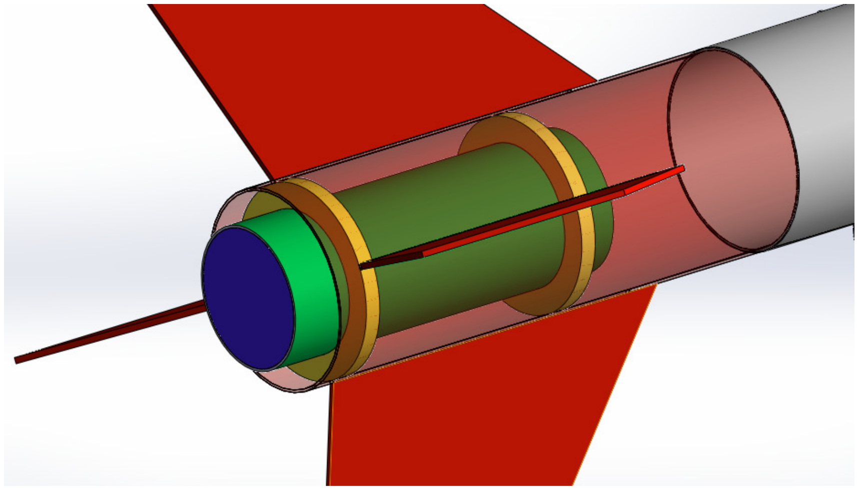

Figure 2.13 – The motor mount design used to distribute thrust forces from the Cesaroni motor and to provide more surface area for the fins to bond with.

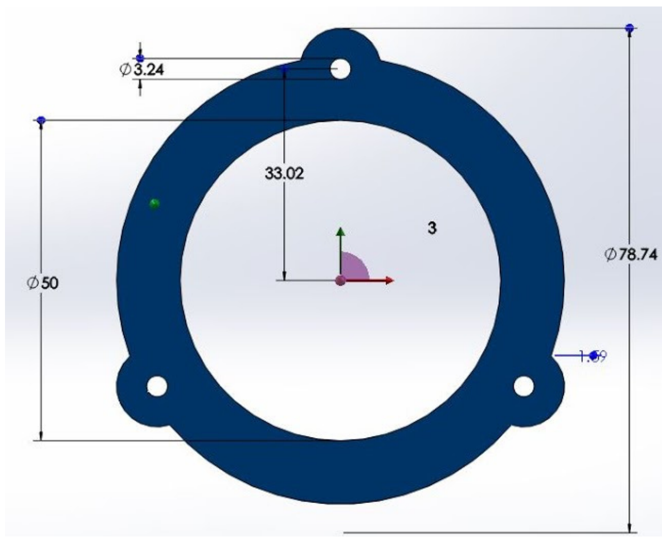

Figure 2.14 – The motor retention design for preventing the ejection of the Cesaroni motor.

3. Stability Locations

The following table shows the locations of the center of pressure, center of gravity, and the static margin for all boosted-dart configurations relevant to the competition requirements. The stability locations were determined using CFX in ANSYS and RockSim. As shown below, all configurations satisfy the safety requirements of maintaining a static margin greater than 1.

	BOOSTER & DART	BOOSTER	DART
Length	63.13"	35.35"	33.56"
C_P - Center of Pressure	55.98" from tip	29.17" (Pre-Airbrakes) 25.38" (Post-Airbrakes)	19.70"
C_g - Center of Gravity	41.02(Pre-Launch)	21.94"(Post-Burn)	17.74"
Static Margin	4.98	2.41 (Pre-Airbrakes) 1.15 (Post-Airbrakes)	1.92

Table 3.1 – Stability locations of all configurations of the boosted-dart.

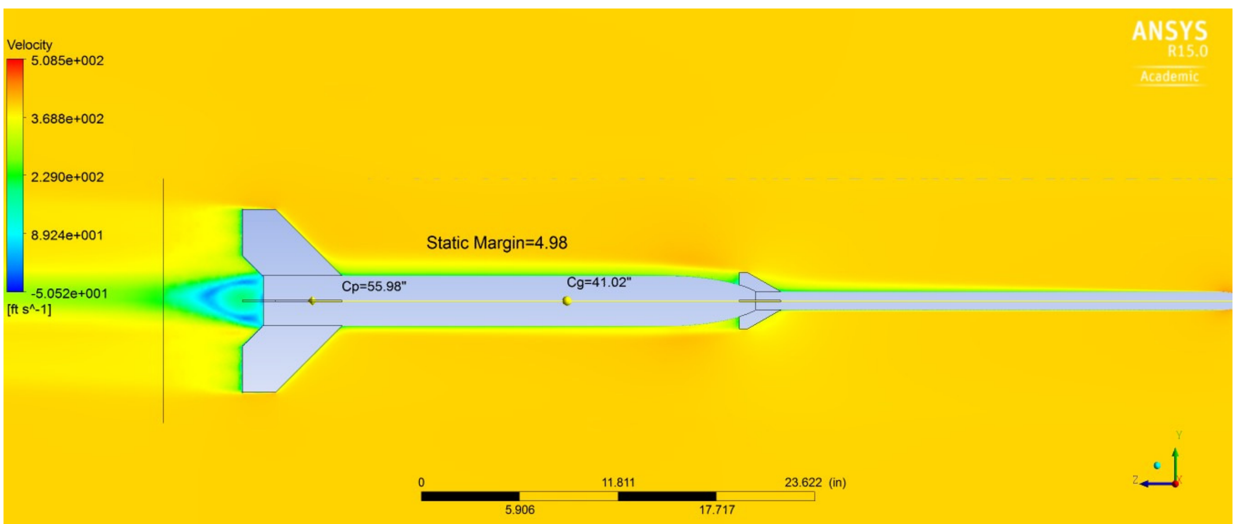

Figure 3.1 – ANSYS generated fluid flow results of the boosted-dart composite configuration.

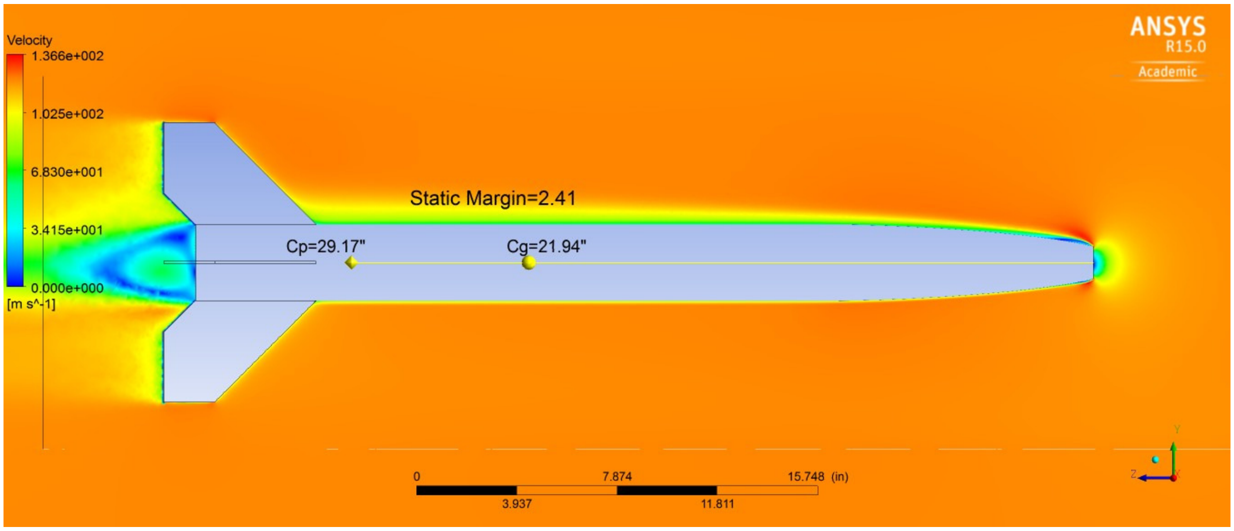

Figure 3.2 – ANSYS generated fluid flow results of booster section with retracted airbrakes.

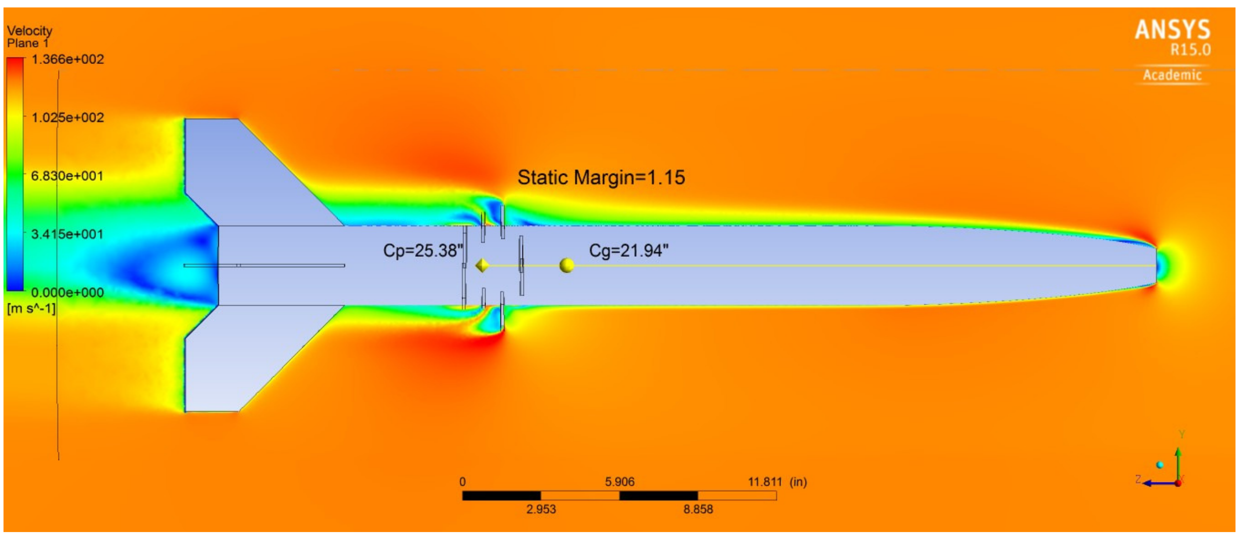

Figure 3.3 – ANSYS generated fluid flow results of booster section with deployed airbrakes.

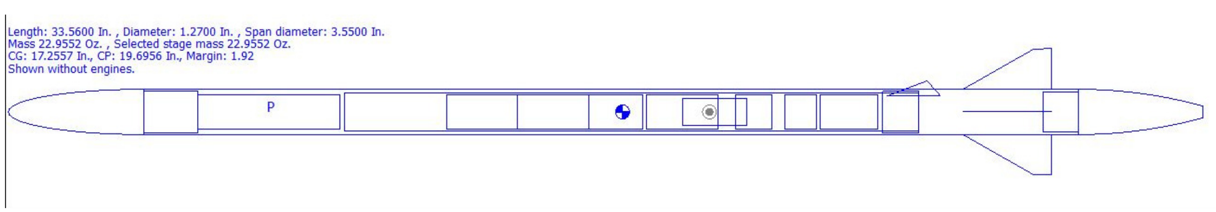

Figure 3.4 – RockSim generated stability results of the dart section.

4. Analysis of Anticipated Performance

4.1 Analysis Overview

The boosted dart's trajectory was simulated using kinematic equations in MATLAB. The following data shows the trajectory of the boosted dart during the boosting phase. Then, the trajectories of the booster and dart are analyzed individually during the coasting phase. The data shows an estimated maximum dart and booster altitude of 4233ft and 1758ft, respectively. The data also shows an estimated peak acceleration of 24.16gs. All kinematic values are represented in a North-East-Down inertial reference frame.

4.2 Estimated Max Altitude

The altitude of the booster and dart were plotted against time using MATLAB software. Using kinematics equations, an ideal situation of no crosswind conditions was determined in MATLAB. For moderate crosswind conditions, we simulated our rocket in RockSim and found our solution to be an 85% correction from the ideal case. Taking note of the flight durations, the time duration would be shorter in a less than ideal case.

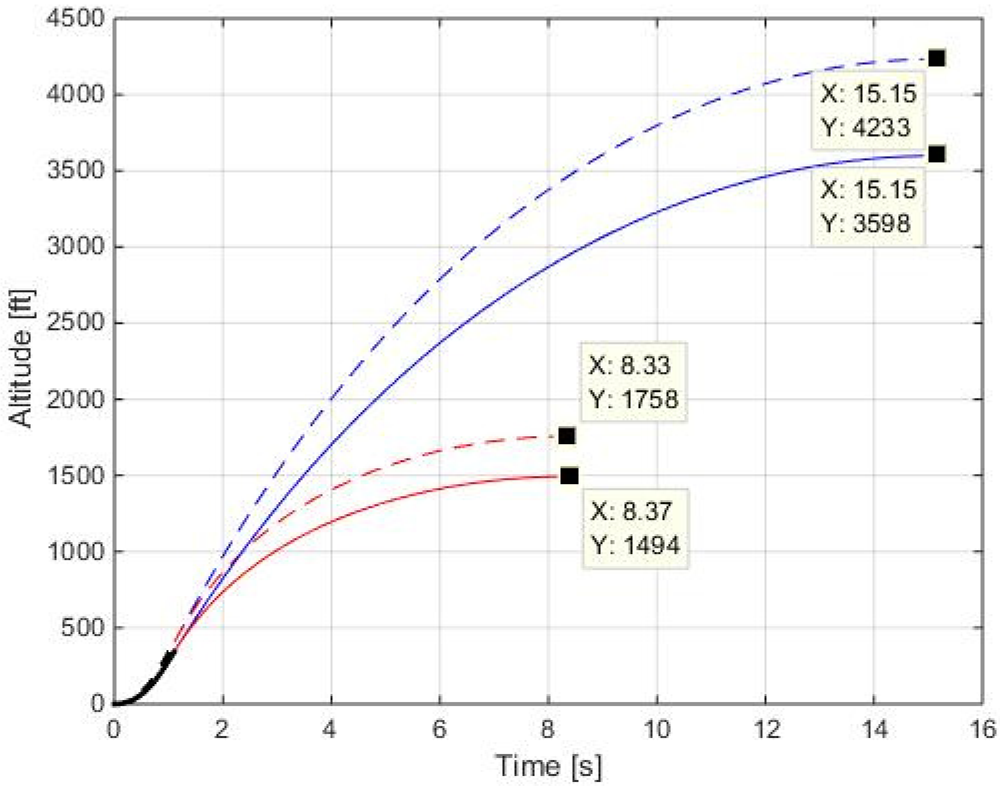

Figure 4.1 – The black line represents the boosting phase of the booster-dart composite configuration from 0 to 1.1 seconds. The blue and red lines represent the dart and booster altitudes in the coasting phase, respectively. The dashed line variants represent an ideal trajectory and the solid line variants represent a moderate crosswind condition.

4.3 Estimated Peak Acceleration

The peak acceleration for the rocket's flight was determined using MATLAB software and provided thrust-curve data [4]. The curve was determined using kinematics equations in an ideal case of no weather conditions and no weather-cocking. From RockSim, a moderate weather condition was simulated to be an approximate 85% correction of the ideal case. The absolute maximum acceleration, of 24.16 g's, occurs about halfway through the motor burn under no-wind conditions.

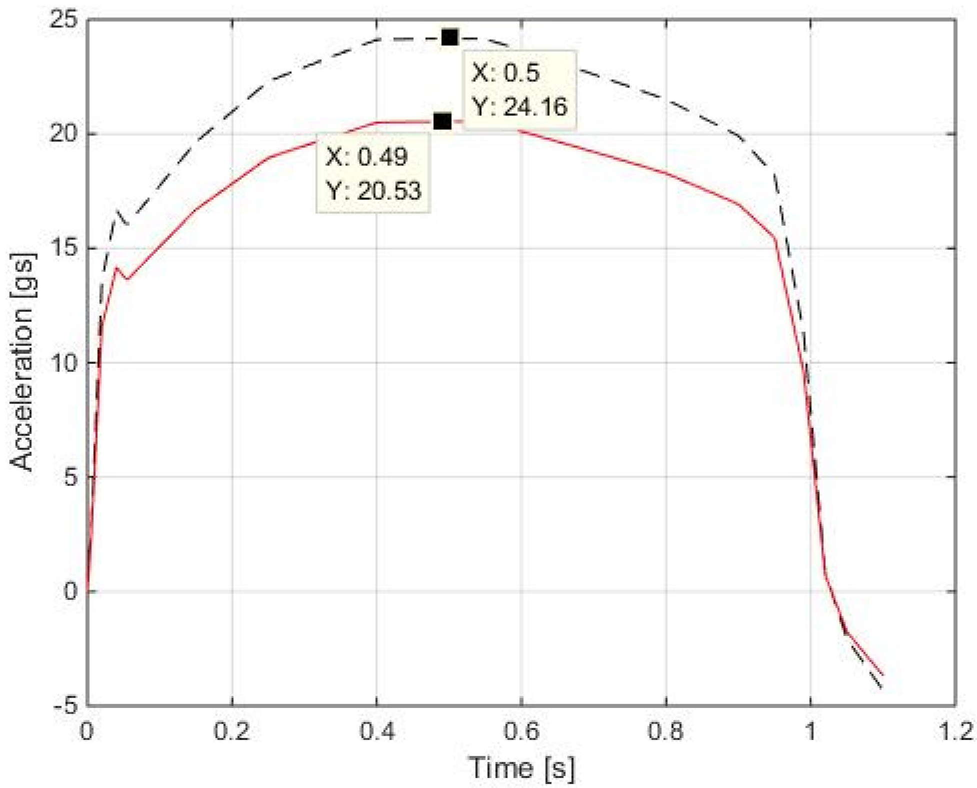

Figure 4.2 – The dashed black line represents an ideal case under no weather conditions and no weather cocking. The solid red line represents a solution similar to our results simulated in RockSim for moderate weather conditions.

4.4 Estimated Acceleration vs. Time

The acceleration of the composite rocket, booster (separately), and dart (separately) were plotted against time for the entire duration of the ascent. There is a discontinuity at the end of the boosting phase because of the piecewise function used to calculate acceleration for the booster and dart before and after motor burnout. We assume that their accelerations are equal until motor burnout, at which point we assume that drag forces them out of contact and their individual drag forces are determined by their respective dimensional parameters. Also, the drag on the booster has a discontinuity when the airbrakes deploy, right at motor burnout.

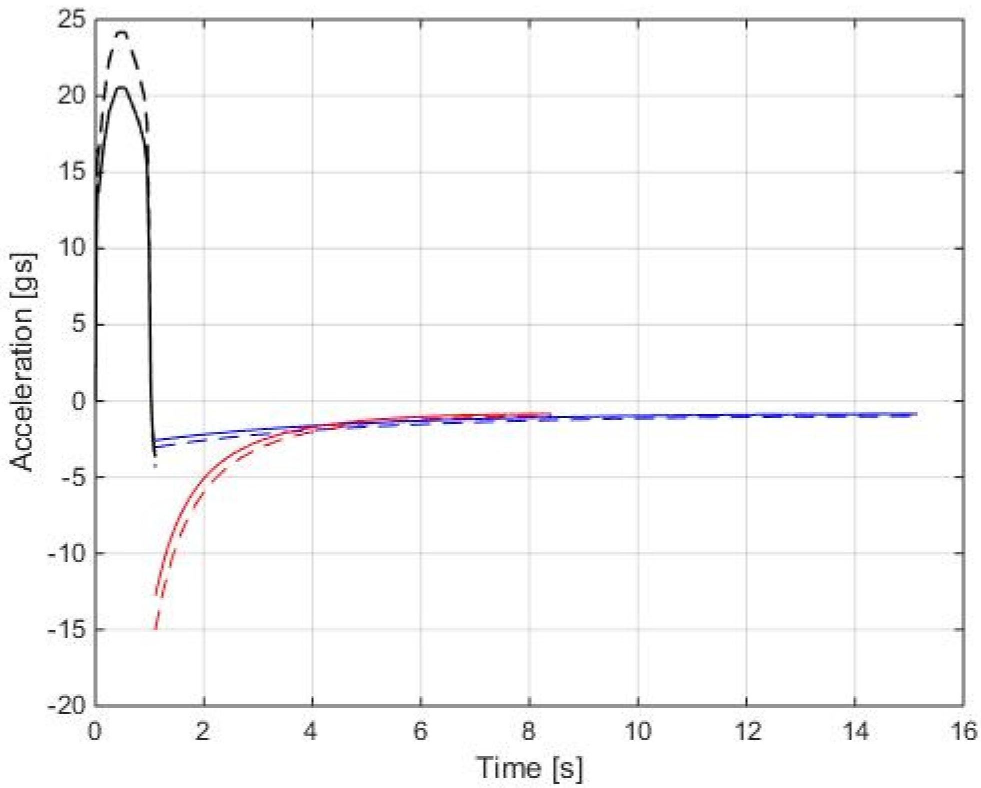

Figure 4.3 – The black line represents the acceleration of the composite rocket during the boosting phase (see Fig. 4.2). The blue and red lines represent the acceleration of the dart and booster, respectively, up to the point of their respective apogees. The dashed line variants represent an ideal case of no weather conditions and no weather cocking. The solid line variants apply the 85% correction seen in previous analyses.

4.5 Estimated Velocity vs. Time

The velocity curve of the composite boosted-dart, booster (with deployed airbrakes), and dart configurations were simulated in MATLAB with kinematic equations. For the ideal case of no wind conditions or weather-cocking, the boosted-dart was simulated to a peak velocity of 678.5 m/s. Under an 85% from ideal case, the peak velocity was simulated to 576.5 m/s. The peak velocities were necessary to investigate the possibility of fin flutter.

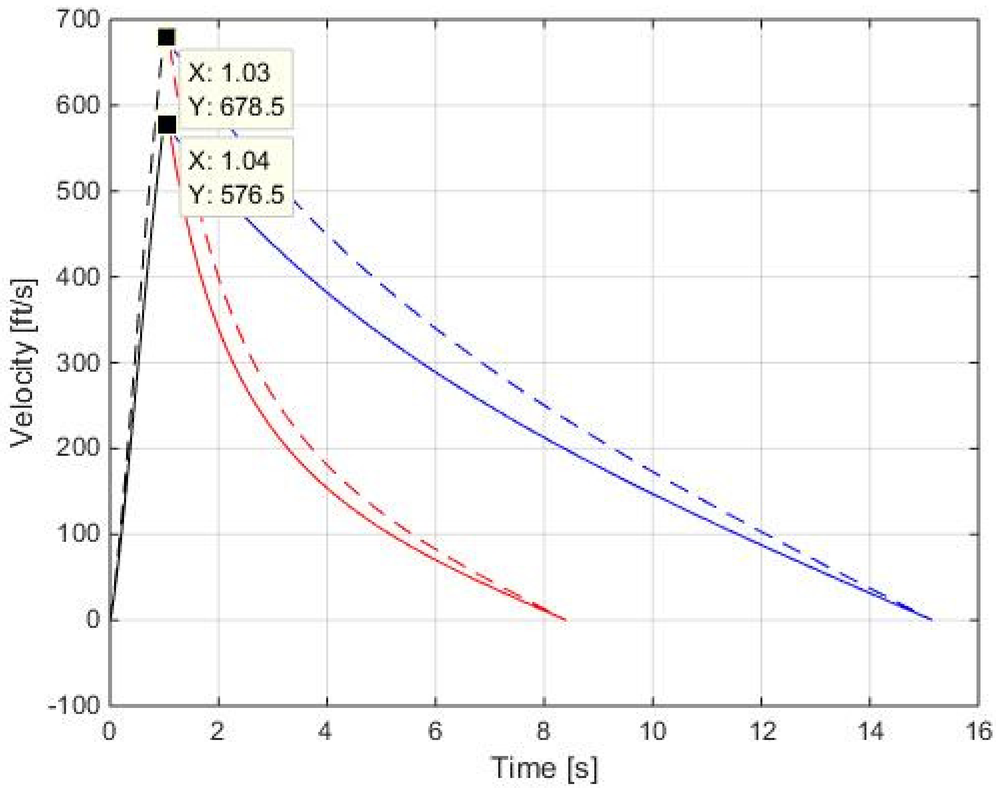

Figure 4.4 – The black line represents the velocity of the composite boosted-dart configuration in the boosting phase. The blue and red lines represent the coasting velocity of the dart and booster, respectively. The dashed line variants represent an ideal, no weather condition, and no weather-cocking case. The solid line variants represent 85% less than ideal case for moderate wind conditions.

5. Safety Procedures & Risk Mitigation Analysis

5.1 Material Handling Procedures

The team will be working primarily with fiberglass, carbon fiber, and epoxies. According to MSDS sheets on these materials [5-7], the team will use safety glasses, disposable gloves, and applicators to avoid contact with these materials and prevent debris from making eye contact.

5.2 Risk Mitigation Analysis

The boosted-dart may encounter any number of failure modes in flight. The following table is an abbreviated list of the most severe failure modes that could occur and what could be done to mitigate those failure modes.

Feature	Failure Type	Potential Impact	Severity	Potential Causes	Occurrence	Detection Mode	Detection	Risk Priority
Dart	Parachute fails to deploy	Dart crashes	10	Deployment avionics failure	3	Test avionics, parachute ejection, and test fly the entire rocket	5	150
Transition slits	Forces cause fins to rip through material	Instability in flight and rocket is non-recoverable	10	Structural flaws	2	Check crack propagation before launch, have back up nose cone, round edges of dart fins	7	140
Booster Body Tube	Crack Propogation	Instability in flight, loss of material, or splitting	10	Machining, manufacturing error, or tightening screws too tight	1	Professional Machining	7	70
Avionics	Voltage Spike, wrecking electronics	All avionics components lost to damage	10	Bad batteries	1	Test batteries, purchase fresh batteries prior to launch	5	50

Table 5.1 – Abbreviated list of failure modes for the boosted-dart. Most severe modes result in a non-recoverable rocket.

5.3 Pre-Flight & Post-Flight Procedures

In pre-flight procedures, the team will install fresh batteries and use external switches to turn on the avionics systems to check that they are functional (either by checking LEDs or beeps). While the avionics are off, the team will make sure the e-matches are properly wired to the ejection charges. They will pack the parachutes as necessary for each section of the rocket. If needed, the transition section will be lubricated to reduce friction at drag separation. Last, the team will confirm that each section of the rocket is securely in place and ready for launch.

In post-flight procedures, the team will track the dart by a radio beeper and the booster by sight. They will then retrieve the avionics bays to access the flight data needed for processing.

6. Budget

	Vendor	Cost/Unit	Quantity	Total Cost
Kit Build	[Various Vendors]	$ 491.72	1	$ 491.72
Arduino Nano	Gravitech	$ 34.99	2	$ 69.98
10DOF Chip	AdaFruit	$ 29.95	1	$ 29.95
Micro SD Break Out	AdaFruit	$ 14.95	3	$ 44.85
BMP180	AdaFruit	$ 9.95	2	$ 19.90
FlyCam One Eco V2	SparkFun	$ 39.95	1	$ 39.95
FlyCam One Eco V2 - Battery	All-Battery	$ 30.00	1	$ 30.00
Ultra Light Carbon Fiber 3" Length = 45" thickness = .040"	Public Missles	$ 134.95	1	$ 134.95
FiberGlass 29mm x .0555" for 48" length	ApogeeComponents	$ 48.31	1	$ 48.31
24x24 G10 FR-4 Natural Fiberglass sheet thickness = .093	ePlastics	$ 49.01	1	$ 49.01
3/8" PTFE Virgin Rod	MSC Direct	$ 4.93	1	$ 4.93
3/8" PTFE Glass-Filled Rod	MSC Direct	$ 7.89	1	$ 7.89
3/8" PTFE Tubing	MSC Direct	$ 6.56	1	$ 6.56
1/16" 6061-T6 Aluminum Sheet 8"X8"	McMaster	$ 8.85	1	$ 8.85
1/8" 6061-T6 Aluminum Sheet 6"X6"	McMaster	$ 9.52	1	$ 9.52
HS-485HB Servo Motor	Robotshop	$ 16.99	2	$ 33.98
1/8" 2024 Aluminum Rod 3 ft	McMaster	$ 8.37	2	$ 16.74
Pr2032 Resin w/ Ph3660 Hardener Qt. Kit	PTM&W	$ 40.85	1	$ 40.85
Arduino Nano 3.0 - No Pin	Gravitech	$ 32.99	2	$ 65.98
High-G Accelerometer	Adafruit	$ 24.95	2	$ 49.90
Kevlar Cord 1500#	Apogee Components	$ 0.92	32	$ 29.44
Plastic 3" Ogive	MadcowRocketry	$ 17.95	1	$ 17.95
Carbon Fiber Rod .125"OD, 48" length	ACP Composites	$ 3.75	3	$ 11.25
Servo Gear .688" OD	Servo City	$ 4.20	2	$ 8.40
Rod Mounted Gear .375"OD	Servo City	$ 1.71	2	$ 3.42
PNC 29mm Boat Tail	Apogee Components	$ 8.63	1	$ 8.63
Pro54-1G Motor Casing	Offwegorocketry	$ 39.75	1	$ 39.75
Pro54-1G Motor Casing Closure	Offwegorocketry	$ 39.95	1	$ 39.95
475-I445-16A Vmax 54mm motor	Offwegorocketry	$ 52.99	2	$ 105.98
PTFE 1/4" ID Virgin Tube	MSC Direct	$ 3.16	2	$ 6.32
29mm x 6" G12 FW Fiberglass Coupler	Apogee Components	$ 11.33	2	$ 22.66
Phenolic Coupler 2.88" ID 5" length	PML Missles	$ 3.15	2	$ 6.30
Carbon Fiber Tube .196" OD	CST Composites	$ 2.95	1	$ 2.95
Washers #8	HomeDepot	$ 1.18	1	$ 1.18
JBWeld	HomeDepot	$ 5.67	1	$ 5.67

PTFE Spray	Amazon	$ 9.69	1	$ 9.69
E-matches	OffWeGoRocketry	$ 2.00	10	$ 20.00
MicroSD cards 8GB	Amazon	$ 4.97	3	$ 14.91
Loctite 770 Primer for Glues	Amazon	$ 23.30	1	$ 23.30
1/8" ID Washers	Amazon	$ 2.47	1	$ 2.47
Loctite 770 Primer for Glues	Amazon	$ 23.30	1	$ 23.30
Loctite Prism 480	Amazon	$ 25.17	1	$ 25.17
Molex 51021 2 Pin Connector	All-Battery.com	$ 1.50	6	$ 9.00
MOSFET N-CH 60V	Digi-key.com	$ 0.80	10	$ 7.95
Total Cost	---	---	---	$ 1,649.46

Table 6.1 – Budget to date (including kit rocket expenses).

7. References

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4. Cesaroni 475-I445-16A V-max motor thrust curve. http://www.thrustcurve.org/simfilesearch.jsp?id=1609

5. Fiberglass MSDS. http://web.mit.edu/rocketteam/www/usli/MSDS/Fiberglass%20%28differnt%20supplier%29.pdf

6. Carbon-Fiber MSDS. https://www.tapplastics.com/uploads/pdf/MSDS%20Carbon%20Fiber%20Sheet.pdf

7. Epoxy MSDS. http://www.westsystem.com/ss/assets/MSDS/MSDS105.pdf