Preliminary Design Review

NUSTARS
Northwestern University

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Executive Summary

In accordance to the 2016 Space Grant Midwest High-Power Rocket Competition, NUSTARS has designed a rocket that will fly to an altitude between 3000 and 5000 feet with no drag system deployment and ¾ of the previous altitude on the second flight with active drag deployment. In addition, NUSTARS has developed a data logging package to estimate coefficient of drag over time and a video system to monitor airbrake deployment.

To accomplish an initial altitude of 4304 feet NUSTARS has built a 102 mm diameter 2.97 m long and 12.3 kg rocket, The SpacePuppy, powered by a CTI K1440 motor. This white thunder motor has a burn time of 1.64 second which accelerates the rocket to a rail exit velocity of 16.6 m/s which helps to ensure takeoff stability. To ensure a safe recovery of the rocket, a redundant set of RRC3 flight computers will deploy a 12 in drogue parachute at apogee and a 72 in main parachute at 800ft.

In order to fly a second time and achieve an altitude ¾ of the previous flight's altitude, NUSTARS has built an active airbrake drag system. The software of this system is powered by a Raspberry Pi that is constantly reading accelerometer, gyrometer, and altimeter data to ensure correct deployment times. The mechanics of this system are driven by a 150lb linear actuator that deploys four air brakes that are housed flush to the side of the rocket's exterior. In order to follow Tripoli safety code and to ensure that the extreme stresses of deployment do not cause part failures, all interior parts are made of carbon alloy steel, while the actual airbrakes are made of fiberglass.

The data logging package is run through an interiorly mounted Arduino that calculates coefficient drag from acceleration data. In addition, an 808 HD #16 Micro Keychain Rocket Camera is externally mounted to collect video of the airbrakes deployment status.

Introduction

The Space Grant Midwest High-Power Rocket Competition enables student teams to showcase their engineering and design knowledge through meeting specific performance requirements. The objective of the competition is primarily to create an active drag system to limit the drag apogee to 75% of the non-drag apogee height. Additionally, there must be a non-commercial data collection device that calculates and stores the changing coefficients of drag throughout the flights. The competition enables teams to showcase both rocket design, as well as hardware and software adaptation to collect data specific to the rocket. Our rocket, the SpacePuppy, uses a retractable airbrake system located in the avionics bay, where a Raspberry Pi determines the initialization and retraction of the air brake system. The design was drafted using OpenRocket and Rocksim as well as hand calculations in order to determine the optimal locations and sizes for the parachutes, boosters, and avionics bay. NX, MATLAB, and ANSYS were used to create and model the airbrake system. The report further explains the design of the launch vehicle, electronics, construction techniques, anticipated performances, safety, and innovation of the design.

Design Features of Launch Vehicle

Overall Dimensions and Specifications

The SpacePuppy is composed of four major sections, each with a 97.6 mm diameter (102 mm outer diameter). The nose cone (61 cm) is made of hollow fiberglass in an ogive shape with a 2 mm bulkhead and steel welded eyebolt connected to its bottom. The parachute bay (91.4 cm), avionics bay (38.1 cm), and booster (107 cm) are all constructed from fiberglass.

The parachute bay holds a 72 in parachute, 12 in square Nomex, 5 yards of shock cord, 3 quick links, fireproof wadding and 2 3 gram black powder ejection charges.

The avionics bay contains a fiberglass inner tube coupler with a 93.6 mm diameter (97.6 mm outer diameter). The coupler (61.3 cm) is broken up into three main parts. The top part (10 cm) holds the data logger mounted on a sheet of fiberglass. The middle part (38.1 cm) houses the drag system weighing 3402 g. The bottom part (13.2 cm) holds 2 Missile Works altimeters and 1 Jolly Logic altimeter mounted on a 3-D printed sled. An 808 HD #16 Micro Keychain Rocket Camera is mounted on the outside of the avionics bay.

The booster holds a 12 in drogue parachute, 9 in square Nomex, 2 quick links, 15 yards of shock cord, 2 2.5 gram black powder ejection charges, fireproof wadding, and 56.4 cm motor mount. Three fiberglass fins are fastened to the booster through slits in the booster tube.

The fins are secured with epoxy and chopper carbon fiber to the booster tube and to the motor tube inside, and then reinforced with RocketPoxy fillets. The fins have a thickness of 0.318 cm, base length of 30.5 cm, top length of 15.28 cm, and height of 16.5 cm. The fin tabs which run through the booster tube to the motor tube have a height of 1.78 cm. The sweep angle is 65°.

The overall length of the SpacePuppy is 297 cm with a weight of 12262 grams (with a loaded Cesaroni K1440WT motor). The CG with the fully loaded rocket motor is located 196 cm from the top of the nose cone, and the CP is 46 cm below the CG (242 cm from the top of the nose cone). From an OpenRocket simulation, the stability is 4.53 cal. A drawing of the SpacePuppy is shown below in Figure 1. Center of pressure is marked by the red dot, while the center of gravity is marked by the blue dot.

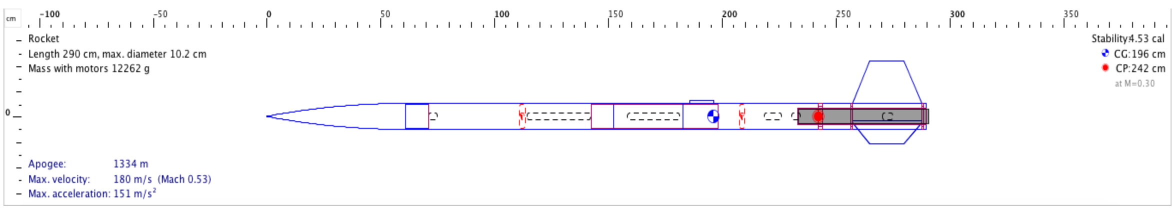

Figure 1: SpacePuppy simulation with motor

Recovery System Design Specifications

Two Fruity Chute parachutes, one main (72 in) and one drogue (12 in) will act as the SpacePuppy's recovery system. The parachutes will be deployed by ejection charges from two Missile Works altimeters. Both altimeters are placed inside the avionics bay incase one fails, each has the ability to eject the parachute. With the deployment of both parachutes, the estimated landing velocity is 5.98 m/s.

Parachute Bay: The recovery systems main parachute is an annular 72 in rip stop nylon parachute housed in the parachute bay. The Iris Ultra Standard parachute is 379.89 grams and has a 12.67 in (diameter) spill hole. It has 12 shroud lines and is rated for 28 lbs at 20 fps. The theoretical maximum drag coefficient is 2.2 for vertical descent. Five yards of tubular nylon shock cord attached to the parachute is anchored to the nose cone and the end of the avionics bay by steel welded eyebolts. The parachute will be wrapped in a 12 in square of flame-retardant Nomex to prevent charring or burning. Two ejection charges fired from a Missile Works altimeter will eject the parachute at a downward altitude of 800 m. In Figure 2 below, the parachute descent rate vs. weight is shown for the Iris Ultra 72 in Parachute.

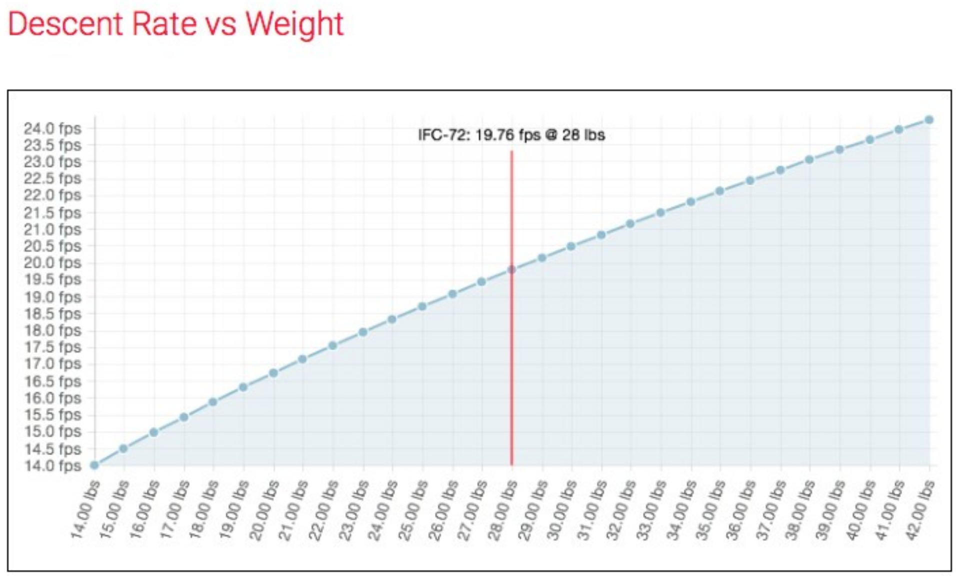

Figure 2: Descent Rate vs. Weight of 72 in parachute

Booster: The recovery systems drogue parachute is an elliptical 12 in rip stop nylon parachute housed in the booster. The Classical Elliptical parachute is 37.14 grams and has a 2.4 in (diameter) spill hole. It has 8 shroud lines and is rated for 0.5 lbs at 20 fps. The theoretical maximum drag coefficient is 1.5 for vertical descent. Fifteen yards of tubular nylon shock cord attached to the parachute is anchored to the end of the avionics bay and the motor mount by steel welded eyebolts. The parachute will be wrapped in a 9 in square of flame-retardant Nomex to prevent charring or burning. Two ejection charges fired from a Missile Works altimeter will eject the parachute at apogee. In Figure 3 below, the parachute descent rate vs. weight is shown for the 12 in Elliptical Parachute.

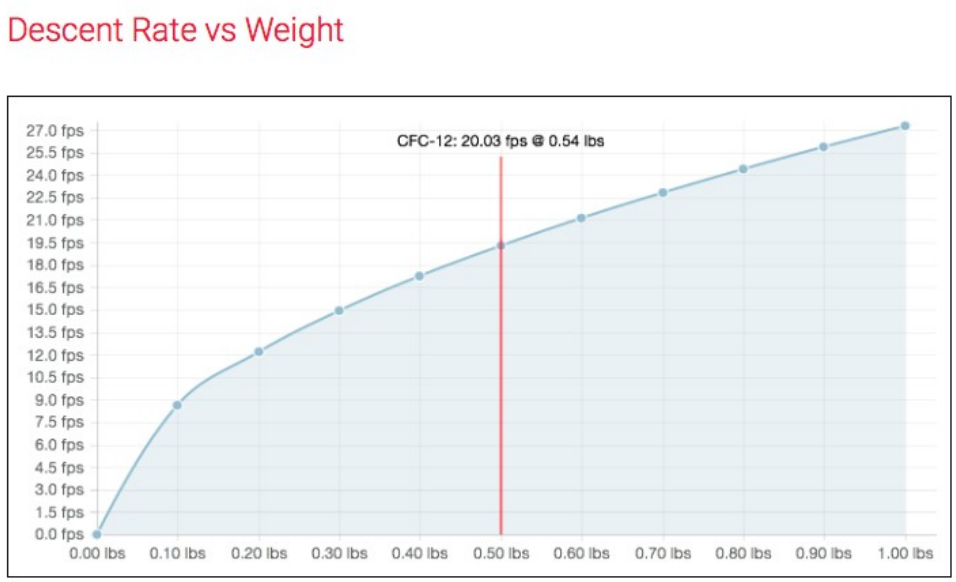

Figure 3: Descent Rate vs. Weight of 12 in parachute

Propulsion System

The Cesaroni K1440WT has an average thrust of 1444 newtons and a maximum thrust of 2168 newtons. A total impulse of 2368 newton-seconds is provided by the burn time of 1.64 seconds. The total launch weight of the motor is 1893 grams with dimensions of a 54 mm diameter and 572 mm length. The propellant weight is 1129 grams, making the empty weight 764 grams. The unadjusted delay grain is 17 seconds. To safely use the motor, a minimal diameter of cleared area of 75 ft, a minimal personal distance of 200 ft, and a minimal personal distance of 300 ft for a complex rocket is required. The thrust curve for the Cesaroni K1440WT is shown below in Figure 4.

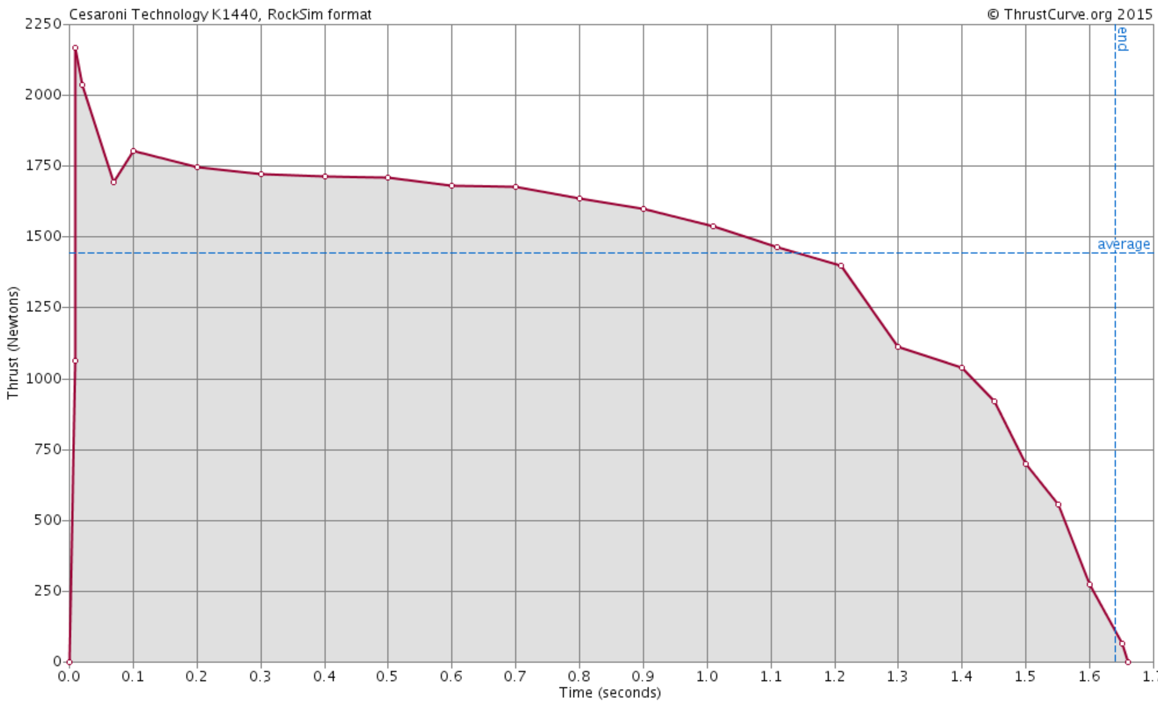

Figure 4: Thrust curve vs. time for the Cesaroni K1440WT

Design Features of Payload

Data Logger

A requirement of the design is an onboard data collection package that will record the coefficient of drag over time. The coefficient of drag is calculated through the equation:

$$C_d = \frac{2m(a \;\; - g)}{\varrho V^2 A}$$

Where C_d is the coefficient of drag, m is mass, a is the acceleration of the rocket, g is the acceleration due to gravity on earth, ρ is the density of air, V is the speed of the rocket and A is the frontal area of the rocket.

In order to calculate the coefficient throughout the flight an Arduino Uno is used in combination with an Adafruit High-G accelerometer and an eeprom storage chip, as seen in Figure 5. Throughout the flight the accelerometer sends acceleration data to the Arduino, which uses the values to estimate velocity, and then calculates the coefficient of drag. The Arduino then sends the values to the eeprom chip to be stored for the rest of the flight. After the flight the Arduino is connected to a computer and the data is downloaded and processed.

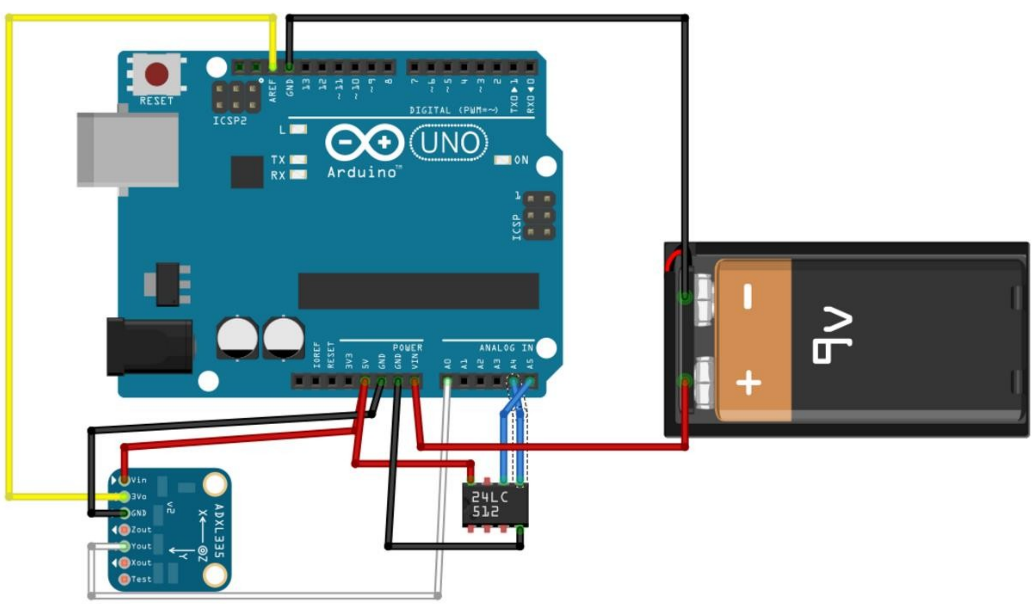

Figure 5: Arduino Uno, Adafruit High-G accelerometer, and eeprom storage chip

Note: The actual accelerometer is the ADXL 326 and the actual EEPROM chip is the 24LC256I

Avionics Bay

The avionics bay holds two Missileworks RRC3 flight computers to control the deployment of the drogue and main parachutes, as seen physically in Figure 6 and electrically in Figure 7. In addition, there is a Jolly Logic Altimeter Two to record flight data for competition data. This will be mounted in the avionics bay and is internally powered. Equipped with a pressure based altimeter, the RRC3 delivers current to black powder charges in both the drogue and main parachute bays at the desired altitudes to initiate deployment as well as collecting flight altitude data.

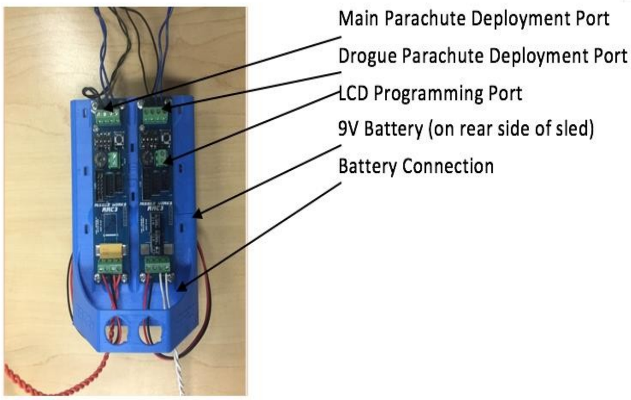

Figure 6: RRC3 Housing

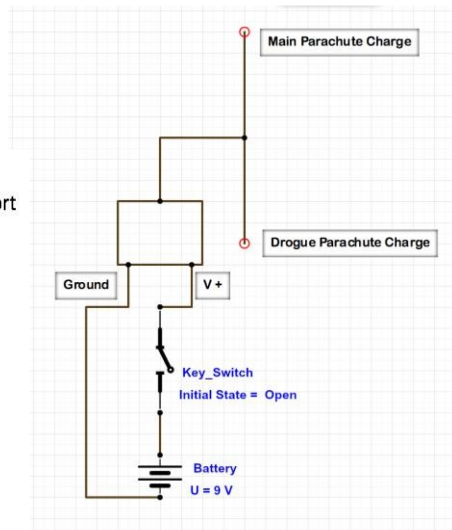

Figure 7. Wire Schematic of RRC3

To ensure functionality two flight computers are used, creating a redundant system. The first RRC3 model is programmed to deploy the drogue at apogee and then the main parachute at 800 feet. The second computer is programmed to detonate additional charges on a one second delay after apogee and 750 feet. The delay prevents simultaneous charge detonation, while still accounting for primary altimeter malfunction. Two Key switches are placed interrupting wires coming from the batteries for each respective computer. These are used to turn the computers on and off.

The avionics bay is located in between the two parachute bays. The main parachute is stored above the active drag system, so the wiring for the drogue moves up the rocket through a hole in the bulkhead, through heat shrink wrapped conduit in the active drag system bay, and finally through another bulkhead hole to the drogue charges. The drogue parachute wiring moves down the rocket through a similar bulkhead hole to the booster bay.

To hold the computers within the bay a fiberglass sled is positioned using two parallel threaded rods. The rods run through cylindrical channels on both sides of the rear of the sled. These rods are then anchored into bulkheads above and below the bay. Nuts are used to prevent vertical movement of the sled within the bay. On the rear side of the sled two 9 V batteries supply the flight computers respectively.

Additionally, the RRC3 will collect data on flight altitudes. This will be stored in the 8 MB flash memory card on board the flight computer. Using the LCD port this data can be displayed following rocket recovery.

Camera

Attached to the avionics bay is an 808 HD #16 Micro Keychain Rocket Camera with an installed 8 GB class 4 microSD card, as seen in Figure 8 below. It is 50 mm (L) by 32 mm (W) by 13 mm (H) and 17 grams. The camera is secured to the outside of the avionics bay by a 3D printed mount. It has an internal battery which can record movie clip lengths of 5 minutes, 20 minutes, 40 minutes, or 70 minutes. A full battery life requires 2.5 hours of charging. The camera can connect to any PC or MAC through an external USB port.

Figure 8: 808 HD #16 Micro Keychain Rocket Camera

Active Drag System

To provide additional drag onto the launch vehicle we have designed an active airbrake system, as seen with and without its body tube in Figure 9 and Figure 10, that can turn the coefficient of drag from the rocket's non-deployed value of approximately 1 to over 150 when deployed, per RockSim simulation.

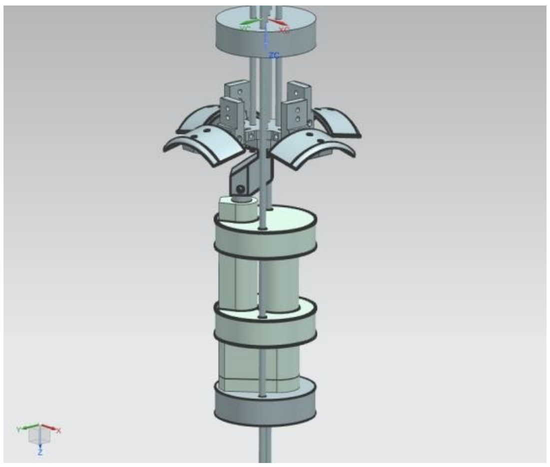

Figure 9: Airbrake system without body tube

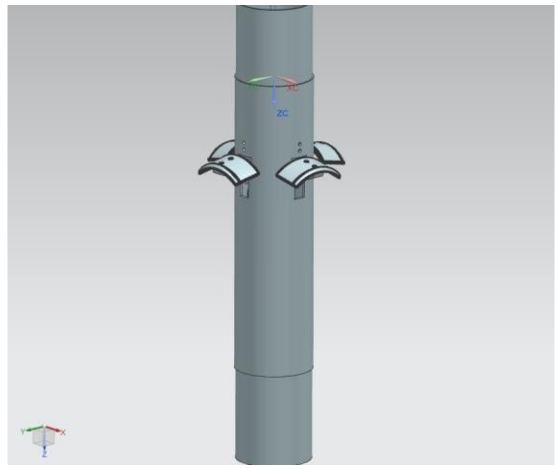

Figure 10: Airbrake system with body tube

In order to assure stability, simulations were run in RockSim utilizing worst-case scenario of treating the brakes as flat plates. This proved that the airbrakes deployment would only change the stability margin by 2%, an insignificant amount.

When the flight algorithm, explained in in the following section, detects the optimal time for deployment, a Firgelli 150lb Feedback Linear Actuator pushes upward onto a connection piece that centers the off centered load provided by the actuator. From this connection piece, a centered mount is pushed upward. This centered mount has four steel rods that run through the airframe ensuring again that mount moves parallel to the body tube, as seen in Figure 11 below. Connected to this centered mount are four arms that push four brackets out of the rocket airframe when moved upward. These brackets have fiberglass brakes bolted onto them, as seen in Figure 12. Because of this temporary joining, alternative brake designs can be switched into the system if the current brakes are providing too much or too little drag.

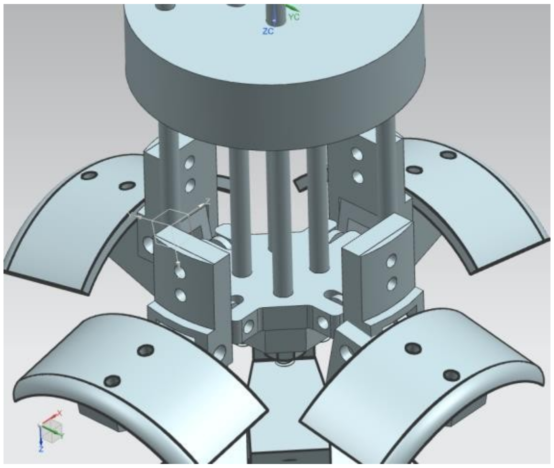

Figure 11: Centered mount of airframe

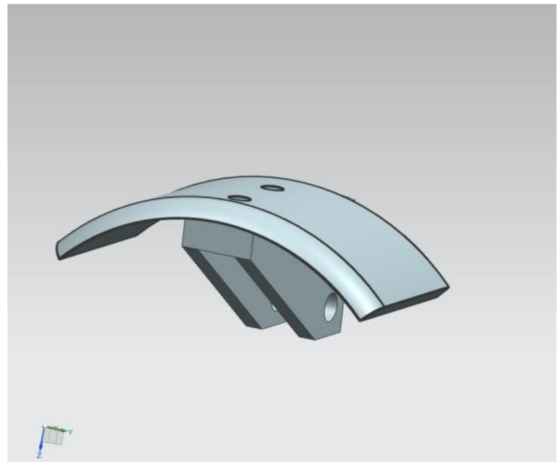

Figure 12: Brakes Attachment

Because of the extreme stress experienced by this system, all main components are made out of carbon alloy steel that allows for easy machining while also retaining a high yield strength.in addition, all pins are made of titanium to prevent shearing. The most extreme of these stresses will be explored in the stress analysis section.

Electrical Design

The electronics for the active drag can be separated into two main sections: hardware and software.

Hardware

The active drag system is set into motion by a Firgelli Feedback Rod Linear Actuator. This actuator has a dynamic force capability of 150lbs and speed of .5 inches per second. The movement is controlled through a Pololu G2 High-Power Motor Driver and Raspberry Pi. The Raspberry Pi and linear actuator are powered respectively by a USB Battery Pack (5V @ 2A) and a 23.4V LiPo battery. Additionally the Raspberry Pi is taking data through an AltiMU-10 Gyro, Accelerometer, Compass, and Altimeter. The wiring diagram can be found in Figure 13 below.

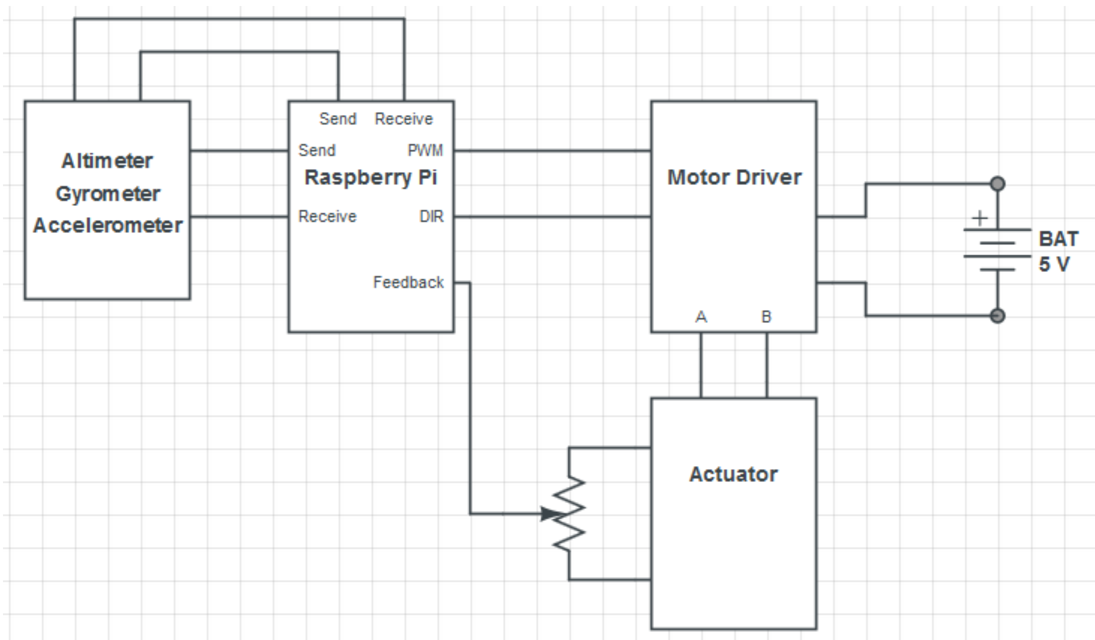

Figure 13: Wiring diagram

Software

Sensor System: The raspberry Pi will continuously read and store the accelerometer and altimeter data to create a numerical position and acceleration profile as function of time. The primary objective is to acquire the maximum height of the launch vehicle. The secondary objective is to acquire the details of the entire flight path to use to adjust the control system. This Sensor system will be active on all launches, even when the airbrake system is disabled to effectively compare the both the airbrake system profile with the normal rocket flight path.

Control System: The following three methods will be implemented to control the air brake system. Each method builds on the first and potentially increases the accuracy of desired elevation. They are described in the order in which they will be implemented and tested.

Passive System with Disabled Airbrakes: Raspberry Pi passively records flight path data. Actuator is never enabled, and air brakes never deploy.

Fixed Deploy Method: The Raspberry Pi is preprogrammed to begin air brake deployment at a fixed elevation. When the controller reads that appropriate elevation from the altimeter, it sends a PWM signal to the motor driver which then powers the linear actuator to push the airbrakes out. A feedback potentiometer tells the controller how much the actuator has extended. After extending 1” the controller turns the PWM signal off to cut power to the actuator. The actuator can withstand 300lbs of force while not moving so no power is necessary to maintain the air brakes at full deployment position. The full deployment of the air brakes takes between .25 and .5 seconds, the time it takes the actuator to fully extend 1”.

The fixed elevation at which the air brakes deploy is approximated by simulations run on RockSim and will be validated with potential wind tunnel testing as well as actual flight data. This fixed elevation will be calculated by taking a percentage of the first launches altitude so that when the brakes are actuated to fully deployed position the increase in coefficient of drag increases deceleration such that the maximum height reached is ¾ that of the original height. To safeguard against early deployment, the elevation must be higher than the predicted elevation at which the motor burns.

After the controller receives data from the altimeter that the launch vehicle has reached a max elevation, the controller reverses the motor driver direction and it enables the motor driver until the actuator returns to its original position and the air brakes return to closed position.

The limitation in this scenario is the accuracy of the predetermined elevation to deploy. If not sufficiently satisfactory, the next method will be attempted.

Fixed Acceleration Curve with Adaptable Air Brake Deploy: The data from the passive launch creates an original acceleration curve. The acceleration curve after motor burnout is offset with an increase in deceleration to create a second acceleration curve (A2). The offset and increase in deceleration is calculated such that the corresponding maximum elevation is ¾ that of the original launch.

The Raspberry Pi uses data from the accelerometer to match curve A2 through a PID control system in a feedback loop. If the launch vehicle is not decelerating fast enough, the controller computes an error, and powers the actuator to extend, deploying the air brakes. If the launch vehicle is decelerating too quickly, the controller computes a negative error, and powers actuator to retract, storing the airbrakes. If the acceleration of the launch vehicle matches curve A2, the airbrakes are at the correct position and the actuator will not be powered to move. The controller can recalculate error at thousands of times per second.

After the controller receives data from the altimeter that the launch vehicle has reached a max elevation, the controller reverses the motor driver direction and it enables the motor driver until the actuator returns to its original position and the air brakes return to closed position.

The limitation in this scenario is the slow speed at which the actuator moves. If the actuator is not able to adjust the angle of deployment of the air brakes fast enough, then it is possible that the error accumulated by the controller grows disproportionately large such that attempting to match A2 proves inefficient. At this time it is unclear as to whether this limitation will become relevant because even though the actuator is slow, the drag created by the airbrakes is so large that even a slight change in angle of the air brakes might prove to be extraordinarily effective at adjusting the acceleration. If this limitation becomes an issue, the following method will be implemented to try to increase accuracy.

Variable Acceleration Curve and Adaptable Air Brake Deploy: If a fixed acceleration curve proves to be too inaccurate due to the slow nature of the actuator or external factors, the program will be adjusted to continuously recalculate a flight path that results with a maximum elevation that is ¾ of the original max elevation. This method would be using two PID controllers with one inside of the other.

The error created from not matching the acceleration profile adds up and adjusts the elevation profile. In this method, local elevation and local acceleration would be used by reading both the data from the altimeter and the accelerometer at all times. The controller reads the local elevation, it projects the acceleration profile by integrating it to represent future elevation, it determines whether following the acceleration profile would result in the desired maximum elevation, and then it adjusts the acceleration profile slightly. The controller then proceeds to attempt to match the new acceleration profile. This process would be repeated continuously until a maximum elevation is reached.

The controller would adjust the acceleration profile only a few times a second, but it will work to attempt to match the profile thousands of times a second. One possible limitation of this method is computer speed. The Raspberry Pi 2 has a clock cycle of 900MHz, however it is unclear at this time as to whether projecting the acceleration profile would require more time than the controller is able to provide.

Which Method? Each new method builds on the last. Each method will apply the airbrakes and decrease the maximum elevation with some degree of accuracy. If a method is found to be sufficiently accurate, the controller will not be adapted to a higher-level controller because the goal is to make the system as simple as it needs to be.

Structural Analysis

In building the SpacePuppy, many nonstandard parts were created to fit our design specifications. These pieces include fins, active drag components, flight electronics, and centering rings. Of these pieces, the electronics and fins have already flown and proved their structural integrity, while the centering rings were tested by shear testing, which can be seen in the shear testing section.

To ensure the active drag components are of sufficient strength, the following parts of highest endured loading and risk were analyzed using ANSYS:

Bracket

This bracket was analyzed under two different scenarios. The first scenario is the bracket experiencing acceleration from the motor burning. In this case the bracket is in the stowed position, flush to the body tube. As seen in Figure 14, the bracket endures a maximum stress of 108.4psi. This load has a safety margin of approximately 470, well below the 51,000psi threshold of yielding for this steel component.

The second scenario this bracket was analyzed under was when the brakes are fully deployed at 90 degrees with max possible acceleration, a worst case condition that is extremely unlikely due the deceleration caused by their gradual deployment. In this case, seen in Figure 15, the bracket experiences a maximum stress of 450.8psi, thus sustaining the load with a safety margin of 113.

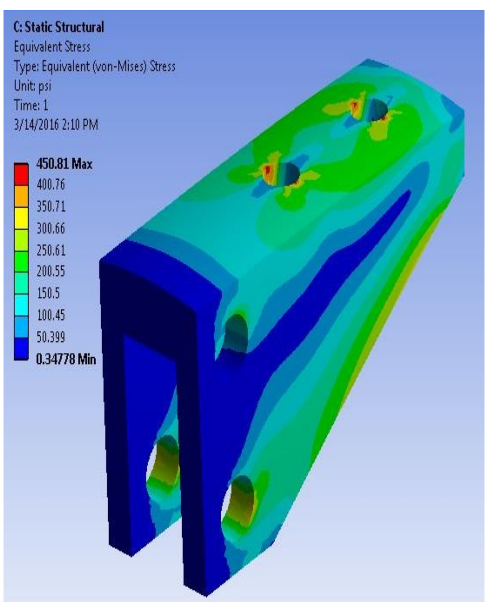

Figure 14: Stress on bracket in stowed position

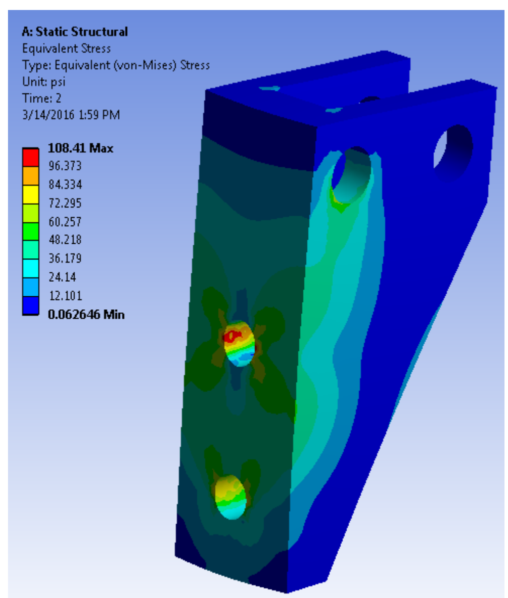

Figure 15: Stress on bracket fully employed

Load Centering Connection

This piece is responsible for centering the load of the linear actuator, ensuring all force is transmitted alongside the center of the airframe. The stress exerted on this piece was taken for a worst case scenario of the linear actuator delivering its maximum full 150lbs of force. In this event, the max stress endured is 23,890psi, as seen in Figure 16. Because this is also a steel component with a yield strength of 51,000, this load has a 2.1 margin of safety.

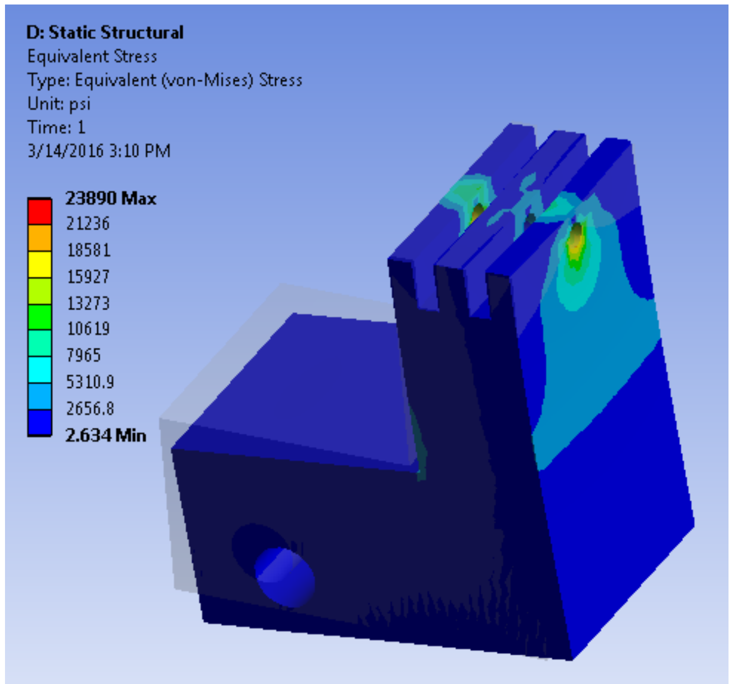

Figure 16: Maximum stress on load centering connection piece

Arm Connection

This piece transmits the load supplied by the linear actuator onto the fins, as well as receives load from the fins deployment. If worst-case scenario is taken with full 90 degree deployment and max deceleration from the fins, the stress propagates as seen in Figure 17. This arm connection undergoes a maximum load 33,406psi. This too is a steel component with a yield strength of 51,000, thus the piece has a 1.5 margin of safety in worst case conditions.

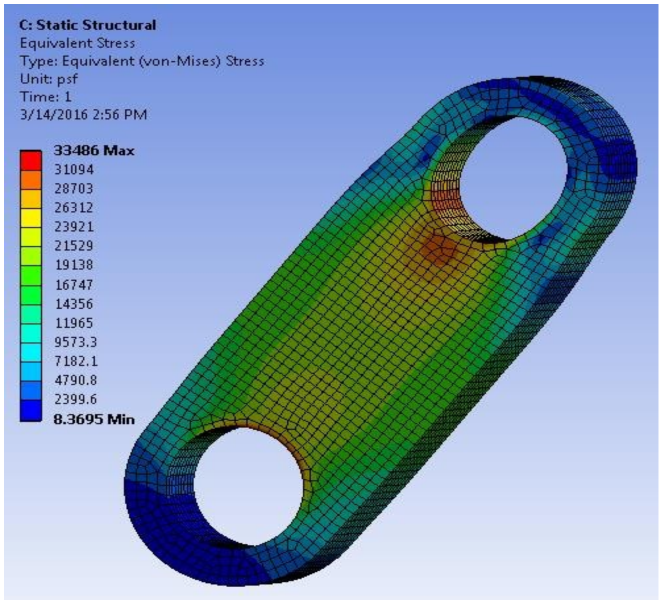

Figure 17: Maximum stress on arm connection piece

Construction Methods

In constructing this launch vehicle extreme care was put into material selection and build processes to ensure a safe and stable flight. In addition to following common high power rocketry guidelines such as using closed eye bolts and fiberglass for airframe, we utilized three main ways of joining in order to maximize strength in stressed areas, and reduce weight in non stressed areas. As a prerequisite for all three joining methods, the affected areas were sanded to promote better adhesion.

For nonmajor stressed joints, such as bulkheads and couplers within the rocket, West Systems 105 Epoxy and 205 Hardener was used.

To ensure strength of fins, we implemented through-the-wall fin design. On the interior joint of the fin and motor tube, chopped carbon fiber was combined with West Systems Epoxy and 205 Hardener. On the exterior joints between the fin and the body tube, large fillets were created with RocketPoxy.

The avionics bay is held together by wing nuts mounted on two steel rods that are running parallel through the bay. The wingnuts are tightened to provide compressive strength, ensuring that the avionics bay stays together. These wingnuts, as well as all nut connections are strengthened with Loctite Blue 242.

Shear testing

In order to build and maintain the active drag system the centerings rings that support the linear actuator were made to be removable. Made out of one inch thick PVC, the rings are mounted inside the tubes and then held in place by four equally spaced bolts running through the body tube.

Because the SpacePuppy will experience 16g of acceleration at takeoff, it was deemed necessary to make sure that the walls of the airframe or the centering rings would not shear.

To test the strength of this setup we installed a centering ring into an extra piece of tube and mounted a downward facing eyebolt through the center. From this eye bolt we tied a piece of nylon shock cord and mounting bar so that we could add weight. 340 pounds were added before we ran out of weights to add to the bar. This setup can be seen in Figure 18 and Figure 19. Although we were not able to shear any of the parts, the weight added shows that the centering ring assembly can withstand the 16g acceleration on a 2.7lb linear actuator at a minimum safety margin of 1.75.

Figure 18: Unweighted shear testing setup

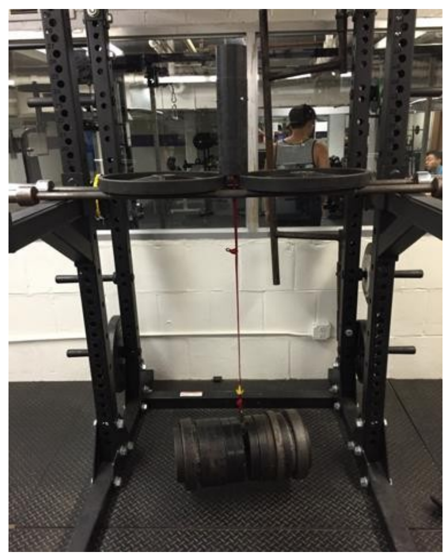

Figure 19: Weighted shear testing setup

Analysis of the Anticipated Performance

The primary analysis of the SpacePuppy's performance was obtained through simulations conducted in the OpenRocket. In the software a model of the rocket was constructed and loaded with a Cesaroni K1440WT motor. The simulation was set to have the drogue parachute deploy at apogee and a main parachute at 800ft and was given ideal flying conditions with minimal wind. This simulation yielded an apogee of 1312 meters (4304 feet) and a peak velocity of 178 meters per second (398mph). These numbers reflect the rockets simulated flight without the drag system deployed. Simulations of anticipated performance for flights with active drag activated are left of this report, as they will vary wildly by software technique used, as mentioned in section XX. Additionally, each flight with a slightly differently powered motor would garner largely different reactions from the airbrakes as they attempt to match flight and acceleration curves.

As shown in Figure 20, the velocity increases with the burning of the motor and deceases after motor burn out. Once the velocity reaches zero the drogue parachute deploys and the vertical velocity stabilizes until the main parachute deploys at 800 feet. At this point the velocity travels asymptotically to its final descent rate of under 10 m/s.

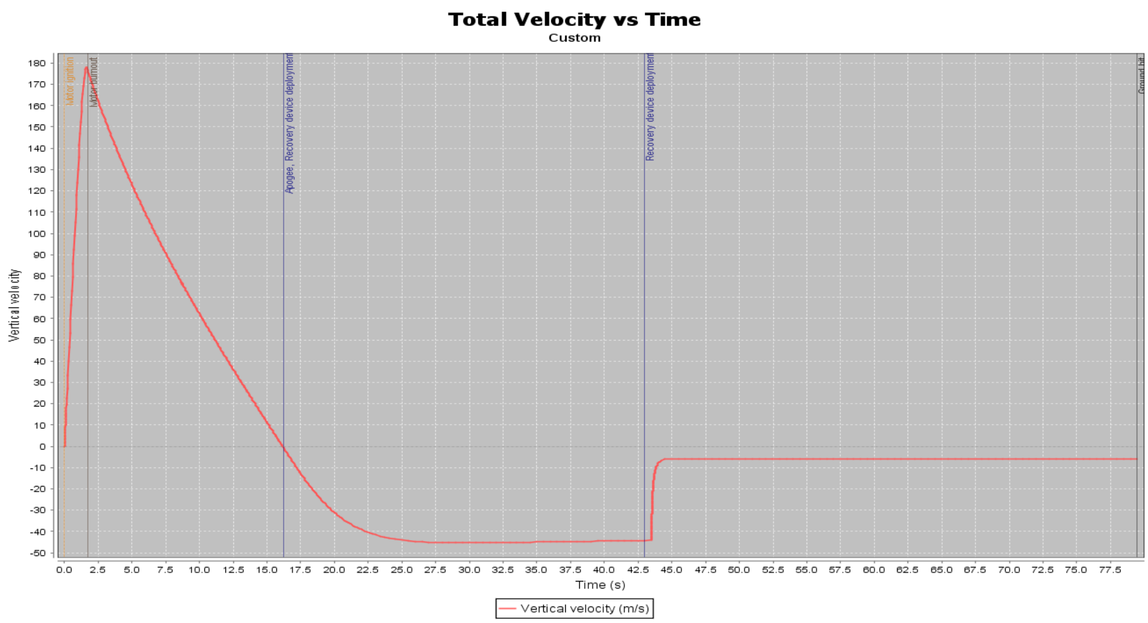

Figure 20: Graph of the velocity vs. time during a simulated flight without drag system deployed.

In Figure 21 below, coefficient of drag is plotted versus velocity. Motor ignition is pictured on the left by the explosion, the parachute symbol represents the apogee parachute deployment, and the symbol on the far right denotes motor burnout. It is apparent that the Cd starts high and lowers as the motor burn and the rocket coasts to apogee, only to spike when the drogue parachute is deployed. Although it is not shown here, when the main parachute is deployed the Cd will greatly increase.

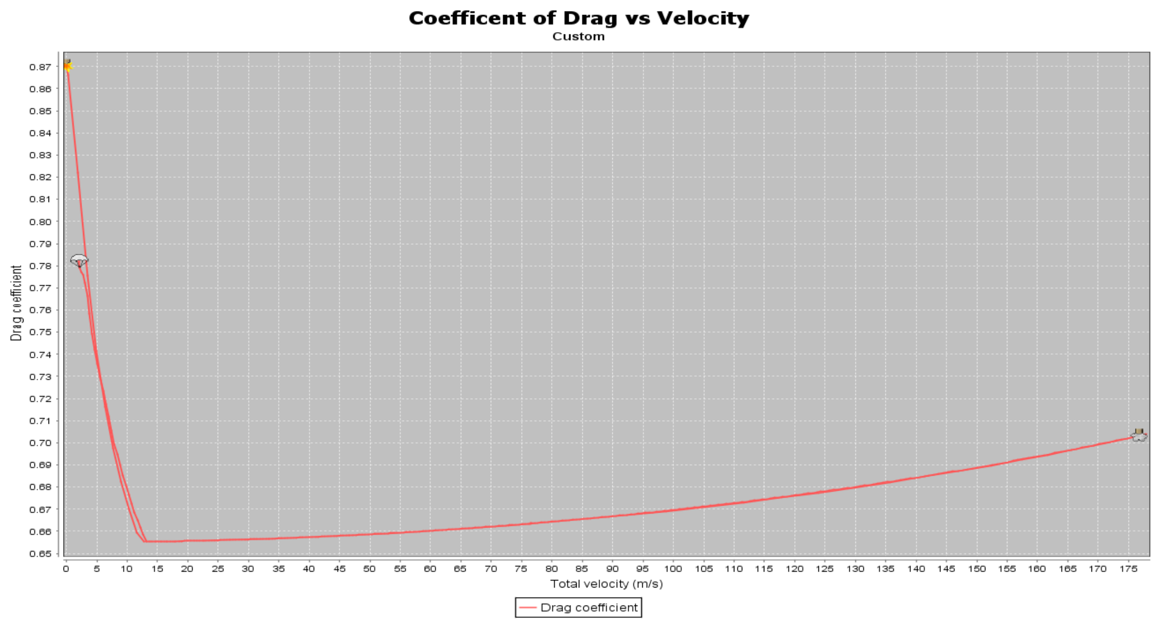

Figure 21: Simulation of the coefficient of drag vs. vertical velocity.

In Figure 22 below, coefficient of drag is plotted versus time. It is clear that the coefficient of drag starts high and lowers as the motor burns until it jumps again at burnout, the coefficient lowers again as the rocket coasts to apogee, only to spike when the drogue parachute is deployed. Although it is not shown here, the drag coefficient will roughly flatline until the main parachute is deployed, and then the coefficient will spike again to an even larger value.

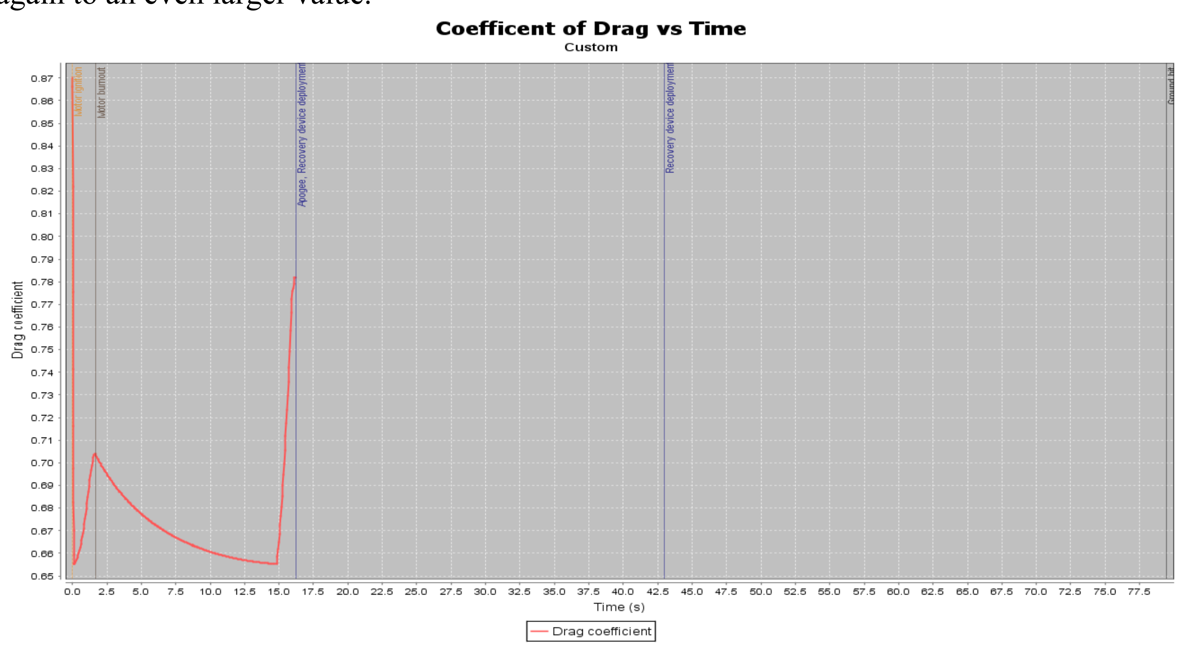

Figure 22: Graph of the coefficient of drag vs. time during a simulated flight without drag system deployed.

Innovation

A couple unique systems were designed for the implementation of the linear actuator. Given the speed of the SpacePuppy's ascension, the linear actuator used was large enough such that it is not possible to align the actuator with the center of the airframe. A piece was specially manufactured to transfer the load on the fins to the linear actuator. This piece enables us to use such a linear actuator in our launch vehicle without encountering large amounts of shear force. Another unique technique we are utilizing are removable centering rings. These allow for the linear actuator to be removed to maintain the drag system. The three removable centering rings are made of PVC, and are held in place by bolts threaded through the exterior of the body tube that lock into the rings.

Risk Mitigation

The following guidelines were followed as a minimum to ensure a safe flight and recovery:

- Calculate Center of Gravity for Full Assembly.
- Calculate Center of Pressure for Full Assembly.
- Calculate Stability for Full Assembly.
- Ensure at least one body diameter and less than five body diameter distance between Center of Gravity and Center of Pressure throughout the entire flight.
- Align the center of thrust with the center of gravity along the central axis.
- Mount fins utilizing through-the-wall attachment technique employing generous amounts of injected epoxy and fillets.
- Drogue parachute deployed by a delayed charge in motor as well as redundant flight computers triggering black powder deployment charges.
- Main parachute deployed by redundant flight computers triggering black powder deployment charges.
- Fireproof wadding is used to protect parachute from deployment charges.
- Nomex is used to further protect parachute from deployment charges.
- Closed eye bolts securely epoxied to centering rings as well as being tightened with a nut.
- Parachute is securely attached to the shock cord using a quick link carabiner

- Numerous flight simulations conducted using OpenRocket and RockSim ensuring stability in various weather and flight conditions.

Material Handling Safety Procedures

Many of the materials used in the construction of our launch vehicle could be potentially hazardous to our health. For this reason, precautions were put into place to minimize the risk of harm occurring during the construction and launch of the SpacePuppy. Materials like epoxy, fiberglass, and paint have potentially hazardous effects on our respiratory systems. To minimize this risk, we constructed our launch vehicle in a well-ventilated area, wearing respiratory masks when necessary. The launch vehicle also is stored in a dry, cool place when not being worked on. When handling the motor and the black powder charges, extreme care was and will be given to ensure that no potential ignition source is in the vicinity of either material. Also, eye protection was utilized at all times when there is potential for flying debris from building processes.

Assembly Safety Procedures

Care was given to ensure that the individual parts constructed have parity with those in our model. All parts were weighed and measured at build times, and if discrepancies existed between actuality and the model, the model was updated.

If ballast is deemed necessary we will ensure that the center of thrust aligns with the center of gravity inside the SpacePuppy. Additionally, the model will be updated to ensure that the margin of stability is greater than one and less than five.

The main components of the launch vehicle will be constructed out of fiberglass. These are cut down to approximate size and sanded down to the precise dimensions required. A few of the pieces, mostly belonging to the active drag system, will be milled from steel. These are pre-dimensioned and modeled thoroughly before fabrication. Finite element analysis has been used to ensure no part of the SpacePuppy fails during any stage of flight.

The internal parts, including the linear actuator, data collection apparatus, and the components of the active drag system, will be securely mounted in place along the inside of the body tube utilizing bolt and epoxy connections.

Planned Launch Procedures

Pre Flight Procedures

1. Inspect shock cords for damage
2. Inspect shock cord connections to nose cone and parachute tube
3. Inspect shock cord connections to avionics bay and booster tube
4. Inspect wiring in Altimeter bay
5. Inspect wiring in Data Collection bay
6. Ensure fresh batteries are connected to altimeters in Altimeter bay
7. Ensure camera has sufficient charge
8. Ensure all electronics in avionics bay are securely attached
9. Ensure all electronics in the data collection bay are securely attached
10. Inspect rail guides, ensure rail guides are securely attached and aligned vertically
11. Inspect motor for damage
12. Ensure motor is properly assembled
13. Install motor
14. Inspect motor retainer for damage, ensure it is securely attached
15. Record mass and type of motor before launch
16. Install black powder charges in booster bay
17. Inspect connections to black powder charges in booster bay
18. Add fireproof wadding to booster section
19. Inspect booster bay parachute
20. Properly fold booster bay parachute
21. Inspect booster bay Nomex
22. Wrap booster bay parachute in aforementioned Nomex
23. Attach parachute package to shock cord using quick link. Ensure secure connection.
24. Insert parachute into booster bay
25. Inspect active drag system
26. Inspect active drag fins
27. Visually inspect fins and fillets
28. Attach avionics bay to booster section
29. Ensure avionics bay is securely attached to booster section by sheer pins
30. Connect nosecone to parachute tube by shear pins
31. Inspect black powder charges in parachute bay
32. Inspect connections to black powder charges in parachute bay
33. Inspect parachute bay parachute
34. Properly fold parachute bay parachute
35. Inspect parachute bay Nomex
36. Wrap parachute bay parachute in aforementioned Nomex
37. Attach parachute to shock cord using quick link. Ensure secure connection
38. Ensure radio transmitter has a fresh battery
39. Ensure radio transmitter is properly secured shut
40. Attach radio transmitter to parachute bay shock cord
41. Insert parachute into parachute bay
42. Add fireproof wadding to parachute bay

43. Rivet parachute tube to avionics bay
44. Have RSO inspect rocket
45. Place rocket on launch rail
46. Turn on camera
47. Arm the three altimeters in altimeter bay
48. Turn on data tracking system
49. Insert igniter into motor, ensure it is fully inserted and secure using motor cap
50. Attach igniter to trigger, ensure no short circuit is present
51. Visually inspect rocket one last time
52. Document rocket on pad
53. Clear launch area
54. Launch
55. Maintain Visual on rocket

Post Flight Checklist

1. Locate rocket using radio receiver
2. Inspect rocket for damage
3. Document rocket landing area
4. Bring rocket to competition official to inspect
5. Disarm Altimeters
6. Disarm Flight Controller
7. Turn off Camera
8. Disconnect batteries from electronics
9. Retrieve flight data
10. Record empty motor mass
11. Clean out motor tube

Budget

Fullscale budget

Item	#	Total Cost
4 inch fiberglass coupler 2 feet	1	64
4 inch fiberglass tube 4 feet	2	186.76
Nosecone	1	62.1
2' x 3' Fiberglass sheet for fins & sleds	2	51.3
Bulkheads	6	32.4
Eye bolts + Nuts	4	7.96
West Systems Epoxy	1	58.21
RocketPoxy	1	33.25
Spreading sticks	10	2
Jar of Carbon Fibers	1	7.95
Syringes pack	1	4.45
54 mm Motor tube	1	13.68
54 mm Retainer	1	38
30 yards Nylon shock cord	1	37.5
5 feet Kevlar	1	5.4
Quick links	6	5.95
72 inch Fruitychute	1	171
12 inch Fruitychute	1	47
6 feet threaded rod	2	39.54
Titanium pins	20	214.68
Fiberglass centering rings	3	18.9
Raspberry Pi	1	39.95
Motor Driver	1	29.95
Accelerometer/Gyro	1	22.95
Arduino Uno	1	24.95
Accelerometer	1	17.95
Storage Chip	1	1.95
Actuator Battery	1	26.5
9V battery	4	4.6
Stranded wires, Spool	2	30.9
Wingnuts	6	2.7
Terminal blocks	4	7.9
Steel for air brakes, various sizes	5	319.21
PVC centering rings	4	16.8
Nomex 9 inch	1	6.95
Nomex 12 inch	1	8.95
Rail buttons	2	5
Linear actuator	1	139.99
RRC3 Altimeter	2	Grant
Subscale motor	1	59
fullscale motor	2	Grant
education kit	72	282.68
registration	1	Grant
Hotel	n/a	1200
Food	n/a	500
Car	n/a	460
Gas	n/a	200
Jolly Logic altimeter	1	69.95
Total		**4580.86**

Subscale Budget

Item	#	Total Cost
2inch fiberglass tube 3 feet	1	41.89
2 inch fiberglass coupler 1 foot	1	24
Nosecone	1	22.49
2' x 3' Fiberglass sheet for fins & sleds	1	51.3
Bulkheads	2	7.2
Eye bolts + Nuts	3	5.97
West Systems Epoxy	1	58.21
RocketPoxy	1	33.25
Spreading sticks	5	1
Jar of Carbon Fibers	1	7.95
Syringes pack	1	4.45
29 mm Motor tube	1	9.95
29 mm Retainer	1	23
10 yards Nylon shock cord	1	13.5
3.7V battery	2	4.5
Quick links	3	2.97
48 inch Fruitychute	1	119
Fiberglass centering rings	2	5.4
2 feet threaded rod	1	19.77
Stranded wires, Spool	1	15.45
Wingnuts	2	0.9
Terminal blocks	2	3.95
Nomex 9 in	1	6.95
Rail buttons	2	5
Total		**488.05**