inVenTs High-Power Rocketry

Virginia Polytechnic Institute
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Executive Summary

During the 2017-2018 academic year, The Minnesota Space Grant Consortium is hosting the National Aeronautics and Space Administration's Space Grant Midwest High Power Rocket Competition in North Branch, MN in May. This year's competition guidelines involve designing, constructing, and launching a single stage high power rocket to fly twice using a roll control mechanism to minimize roll and meet certain roll angle orientations. Using a non-commercial acquisition system, the teams must log data and predict the anticipated flight results in order to detect airframe detachment, chute deployment, and roll data while recording video footage. The competition also features a bonus challenge that involves the implementation of a radio-based communication system to allow for roll orientations to be reprogrammed during flight.

The inVenTs High-Power Rocketry Team is a multidisciplinary undergraduate design team based out of the inVenTs living learning communities (LLCs) of Galipata, Virginia Tech's engineering LLC, and CurVinci, the science LLC. This community serves a primary purpose to allow first year students to have a fruitful transition into university life while learning to balance the academic challenges associated with college coursework and extracurricular involvement while gaining invaluable skills. This team is unlike many other design teams as it is composed of primarily freshmen and sophomores. As a result, one of the primary purposes of this team is to allow the first year students to gain valuable design team experience while allowing them to figure out where their passions may lie within engineering and the STEM fields in general.

Although the team is divided into three sub-teams: aerospace, mechanical, and avionics, each with their own individual functions, anyone interested in joining is welcome. Since many of the members have little to no prior rocketry or engineering experience, the team began the year by teaching new members the basics of AutoDesk Inventor, OpenRocket, Computational Fluid Dynamics (CFD), Python, soldering, laser cutting, 3D printing and other necessary design tools. After these trainings, the team designed, built, and launched model rockets before beginning to design the competition rocket. Since most of the members are fairly inexperienced in the area of high power rocketry, the team will be working closely with its faculty and Tripoli advisors, Dr. Kevin Shinpaugh and Dr. Pat Artis, as well as with the New River Valley Rocketry Association and the Rocketry at Virginia Tech Design Team.

The team has designed the competition rocket by utilizing OpenRocket and AutoDesk Inventor. The 69" long, 210 oz rocket will be propelled by an Aerotech J800-16 motor. An aileron system will allow for the roll angle requirements to be met while a radio based communication system allows for the system to be reprogrammed during flight. The aileron system will be powered by a series of servo motors and connecting rods while components in the avionics bay allow for the entire system to be actuated and data to be logged.

Budget

The 2017-2018 budget for the inVenTs High-Power Rocketry Team was composed by basing the estimated costs of materials, construction, launch costs, and competition fees off of previous years and already known expenses. Based on our calculations, a total of $10,000 was requested (Figure 1). Our sincerest gratitude is extended to the Virginia Space Grant Consortium who granted us $5,000. The Center for the Enhancement of Engineering Diversity within Virginia Tech who granted us with $700 and the Virginia Tech Engineer's Forum who sponsored $500. The rest of the funding will be received through corporate sponsorships. Total expenses thus far are detailed in Figure 2.

Anticipated Expenses

Materials	*Quantity*	*Cost (estimated)*
Sub-Team Rockets		
Parachutes	6	$39.60
Shock Cord	25 ft	$9.90
Epoxy	2	$10.15
Estes D/E engine mount kit	6	$64.74
BT-80 2.6 in diameter body tube	4 pack (8 tubes total)	$35.52
NC-80b nose cone	6	$25.80
BT-80 tube coupler	3 packs (6 total)	$13.77
F-35-5W Aerotech Motors	6	$104.94
Competition Rocket		
J Class Motors	4	$500
Motor Casings	4	$500
Arduino	-	$500
Sensors	-	$500
Cameras	-	$400
G-10	-	$500
Blue Tube	-	$250
Structure Other	-	$700
Payload Other	-	$600
Travel (For 20 team members)		
Competition Fee	1	$400
Hotels	-	$2,200
Rental Cars	-	$1,000
Gas	-	$700
Tolls	-	$400
Food	-	$549
Total		**$10,000**

Figure 1: Anticipated Expenses

Current Spendings

Item	Total Cost	Category
Subteam Rocket Supplies	$293.85	All
Competition Fee	$400.00	Competition
Coupler Tube 5.5"	$55.95	Aerospace
Motor Retainer	$31.03	Aerospace
Rail Buttons	$7.14	Aerospace
Nose Cone	$54.95	Aerospace
G-10 Fiberglass	$131.52	Aerospace
Xbee Transmitter	$133.90	Electrical
SparkFun XBee Explorer USB	$49.90	Electrical
SanCloud BBE WiFi (External)	$76.00	Electrical
Adafruit Micro Lipo w/ Micro USB	$6.95	Electrical
Lithium Ion Battery Pack - 3.7V	$59.00	Electrical
Adafruit Perma-Proto Breadboard PCB	$17.70	Electrical
LewanSoul Standard Servo	$51.00	Mechanical
Total	**$1,368.89**	

Figure 2: Total spendings as of February 17, 2018

Rocket Design

Overall Design

The rocket is 69” long in total with an outer diameter of 5.5” and is divided into three primary sections. The first section is a 13” long polypropylene nose cone, which separates from the remainder of the rocket with the black powder charge that deploys the main parachute. The second and third sections are 30” and 26” long, respectively. They are constructed of blue tube with a wall thickness of .08”. The second section contains the main parachute and the upper portion of the coupler tube that joins it to the third section. The avionics bay is contained in this coupler tube, and is primarily in the upper section so as to raise the center of mass to improve stability. The coupler tube is secured to the second section using epoxy and screws, and to the third section using shear pins which break to separate the second and third sections with deployment of the drogue parachute. The third section contains the drogue parachute, aileron servo motors and hardware, motor mount, and fins. There will be a rear facing camera mounted to the external body of the rocket to record footage of the launch as well as to show when the rocket is trying to roll clockwise, counterclockwise, or trying to hold a stable orientation. The design incorporates three G10 fiberglass fins of 0.25” thickness separated by 120 degrees with each fin having an independent aileron to control roll. Each fin has a root chord of 12”, a tip chord of 3”, and a height of 5.5”. In order to optimize stability while still being able to properly mount and access the ailerons and secure the fins using fin tabs, each fin features a strake that accounts for the forward 6” of the root chord. The strake has a height of 0.5”. Once completed, the rocket weighs 189 oz with an empty motor and 210 oz with a loaded motor at launch.

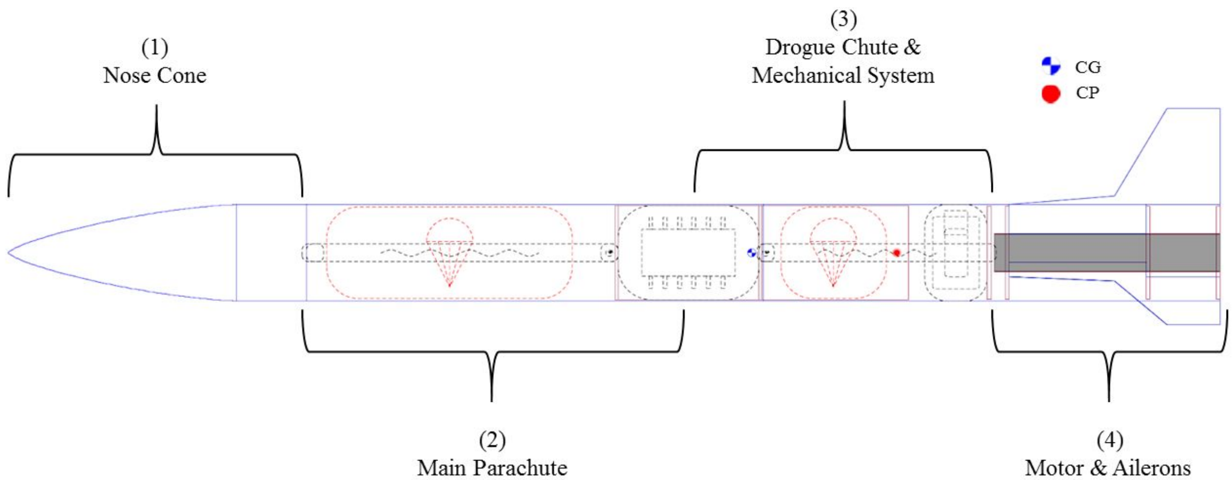

Figure 3: OpenRocket Model

Recovery System

The recovery system consists of two ripstop nylon parachutes, the drogue chute and the main chute. The drogue chute is located below the avionics bay (av-bay) and will be deployed at apogee. It has a 24” diameter with 6 shroud lines. The main parachute is located above the av-bay and will deploy at 700’ during descent. It has a diameter of 84” with 16 shroud lines. The parachutes will be deployed using black powder charges on either side of the av-bay, which are set off using an electrical signal from the av-bay. A small tracking beacon operating on a frequency between 222 MHz and 225 MHz, designated as Channel 299 will be used with a Communications Specialists, Inc. receiver/antenna model R-300A system that operates on the same frequency range and channel as the tracking beacon. This allows for the rocket to be located after landing if a line of sight visual is not available.

Motor

The rocket is powered by an Aerotech J800T-16 solid rocket motor, with an average thrust of 845 N, a burn time of 1.49 seconds, a thrust to weight ratio at launch of 14.5, and a total impulse of 1265 N*s. The motor has a diameter of 2.13” and a length of 12.8”. The motor weighs 40 oz at launch and 19 oz when empty.

Analysis of Anticipated Performance

Environmental Conditions

The weather is likely to be cloudy with temperatures between 45°F and 70°F according to weather data for North Branch, MN [1]. The wind speed will likely be 7 mph with gusts up to 15 mph. Weather related problems during the launch are not anticipated, however, the winds could cause a significant amount of drift during the descent of the rocket. The rocket has been designed to withstand adverse conditions.

Launch and Flight

The anticipated flight performance was simulated in OpenRocket. Through this simulation, the determined apogee is expected to reach 4,200'. This maximum height should surpass the required 3,000' apogee by a safe margin. The initial thrust of 1265 N*s will provide a velocity of 72.3 ft/s off the launch rail and continue to accelerate to the maximum velocity of 770 ft/s. During this time, the ailerons will remain flush with the fin until the rocket needs to execute specific commands in order to roll in the desired compass direction based on instructions provided prior to the launch. These commands will signal to the rocket when and how much to actuate the ailerons in order to perform the desired roll. The rocket will maintain stable flight throughout its ascent with a stability of 1.5 calipers. The fins will provide stability and a vertical ascent. Aerodynamic aspects of the rocket were considered to minimize drag during flight. The rocket will reach a maximum velocity and acceleration of 770 ft/s and 810 ft/s^2, respectively. Once at apogee, the rocket will enter the recovery stage of performance.

Recovery

At a decent speed of 45 ft/s, the flight recovery system first deploys the drogue parachute at apogee (about 14 seconds after launch) and the main parachute at 700' above the ground (about 91 seconds after launch). The recovery systems will be deployed using black powder charges placed on either side of the avionics bay and actuated with an electric charge sent through a wire. The drogue chute slows the rocket down to 45 ft/s before the main parachute deploys, slowing the rocket down to 15 ft/s before the rockets hits the ground. The total flight time is 140s.

Roll Control System

Aileron Mechanics

The aileron is fastened to a 3/16" diameter steel shaft that runs parallel to the fins and perpendicular to the rocket body. Three servo motors, one for each aileron, are mounted above the lowest bulkhead, just above the rocket motor. The servos' rotating arm is positioned outside of the rocket, flush with the body tube. Attached to each servo arm is a 1/8" steel rod that runs down the length of the rocket and attaches to the aileron. The avionics system controls the rotation of the servo, and the servo arm rotation is translated down to the aileron with the rod. The system is designed to allow the aileron to rotate 30 degrees in either direction.

Aileron Prototype

A CAD model of the aileron system was created using AutoDesk Inventor. It was then tested using AutoDesk CFD to calculate the torque requirements. The CAD assembly was also used to test and confirm that the rotation of the servo would translate correctly to the rotation of the ailerons. A physical prototype made from wood, 3D printed parts, steel rods, nylon clamps, and a servo will be constructed. It will model a single servo/aileron system to ensure that all movable joints function as predicted.

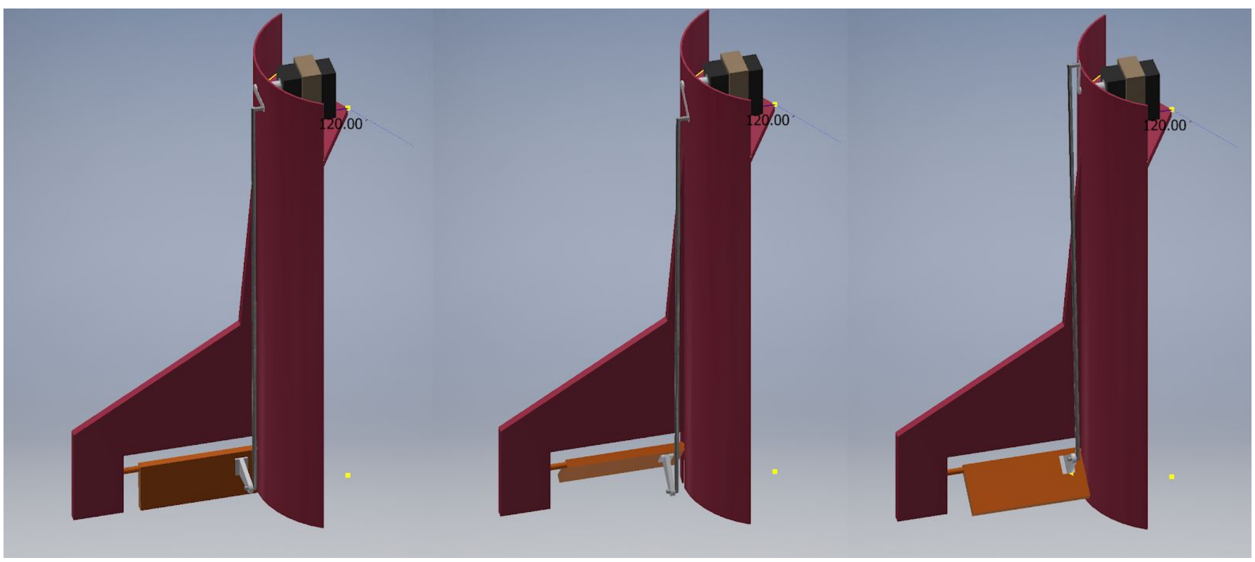

Figure 4: CAD model of the aileron system demonstrates the translation of motion from the servo to the aileron

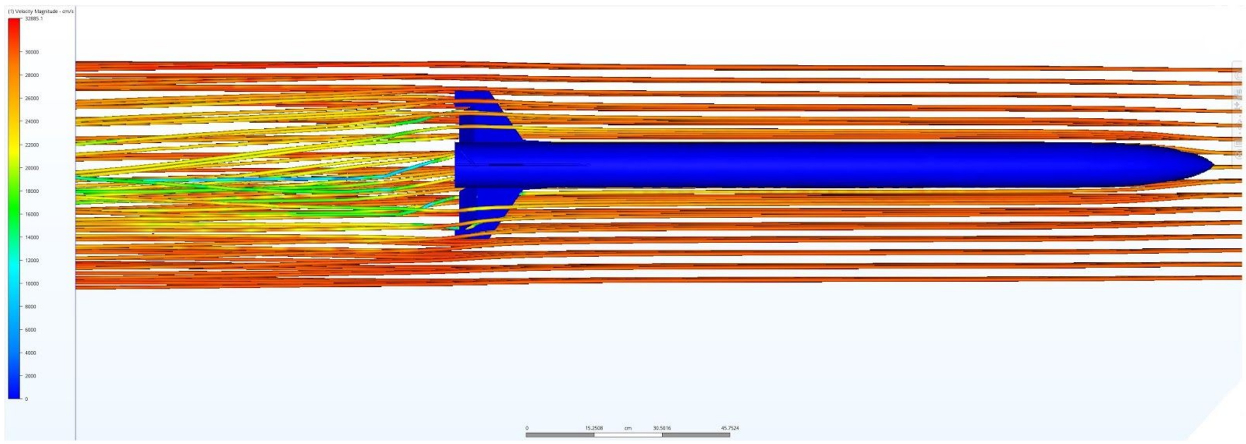

Figure 5: CFD with ailerons at a 45° angle relative to the fins

Construction

The ailerons are 2” by 4” and are constructed from G10 using a laser cutter to etch the design and a bandsaw to cut the aileron out. The trailing edge of each fin is sanded into an airfoil. The slot for the aileron is then cut out from each fin and the pieces removed are cut into the proper aileron dimensions using a bandsaw. The aileron is attached to a 3/16” steel rod with epoxy. This steel rod holds the aileron in place and allows it to rotate. The steel rod is attached to the fin with a bearing epoxied in place and to the body of the rocket with another bearing epoxied to a bulkhead just inside of the body tube.

For each of the three fins, a servo motor is fastened onto a bulkhead immediately above the rocket motor mount by screwing in a removable 3D printed servo motor casing. The servo’s arm protrudes from the rocket body and is fastened to an 1/8” steel rod with a nylon clamp rotational joint (Figure 6). This steel rod extends down the length of the body tube and is fastened to a 3D printed tab by the same nylon clamp mechanism. The 3D printed tab is epoxied in the middle of the stretch of aileron bordering the body tube. Three of these systems will be made to accommodate each aileron. Three additional ailerons with tabs will also be constructed and brought to the launches in the event any of the mounted ailerons break during flight. In order to access the components that are inside the rocket body, the bottom bulkhead is removable. This bulkhead is fastened to the rocket with screws through the blue tube along with two threaded rods that run through the centering rings.

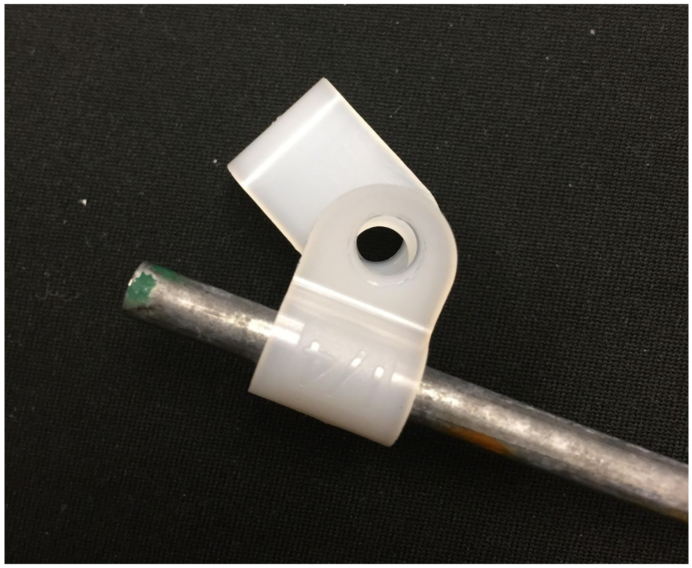

Figure 6: The nylon clamp that attaches the 1/4” rod which runs down the outside of the rocket body from the servo to the aileron. This mechanism shows the joint concept without the bolt and nut that will complete the joint.

Avionics System

Data Logging Code

The data logging code will take input from the various sensors included on the BeagleBone, as well as external sensors for additional measurements. Since the challenge involves adjusting the orientation of the rocket, the gyroscope will be used to determine the orientation of the rocket. The magnetometer will serve as additional confirmation of the readings from the gyroscope. The logging of this data will serve as confirmation that the rocket held its required orientation.

The role of the rocket will be determined by the onboard accelerometer as well as an external magnetometer. This data will be used to determine what adjustments need to be made to the ailerons during flight to hold the rocket’s orientation. The data will also be used to determine whether the rocket is rolling clockwise or counterclockwise. The data gathered from the test flight will be used to make adjustments to simulations in order to more accurately predict future flights.

Lastly, the onboard pressure sensor will be used to determine the altitude. Using equations and the data read from the pressure sensor, the altitude will be calculated. The changes in pressure will be used to determine when to deploy the ejection charges for the parachute. After the flight, the data will also be used to calculate the maximum altitude, acceleration (in both vertical and roll), reached during the flight. After the flight is over the data will be sorted and compiled into a table that contains the maximus, commands, and primary data, as well as after the landing but before retrieval.

Data Acquisition Code

To collect the data, an algorithm in Python will be developed. The team has chosen to go with Python as the programming language mainly due to many of the team members being new to programming. Data will be taken at about 15 Hz with the downwards facing camera mounted on the airframe to navigate specified directions using the ground markers. The program will start when the microcontroller is activated. Once started, it will start recording altitude, orientation, etc., but the active flight system will start three seconds after burnout on the first flight. The data that is collected will be saved onto the internal onboard storage available. After this, a couple of models of the flight based on the actual data recorded will be retrievable. From that data, it will be possible to closely extrapolate what should be occuring during the flight. This becomes important when sending signals to the system. The signals that are sent must be analyzed to properly predict the amount of rotation that will occur on the rocket.

Hardware

The rocket will be using a SanCloud BeagleBone Enhanced WiFi as its microcontroller to connect the various electronics. It was chosen for its onboard sensors, including an accelerometer, gyroscope, and a barometer. As an additional sensor, the Adafruit 9-DOF IMU Breakout will be utilized for its magnetometer to verify data gathered by the accelerometer and gyroscope. The processor on the BeagleBone and its memory should have sufficient specifications to handle any functions it needs to serve. This includes logging data, communicating with a ground station through the Xbee transmitter, and adjusting the servos that control the ailerons. Last year’s design used a SD card to store and manage data, but this year the avionics bay contains the SanCloud BeagleBone Enhanced WiFi due to its onboard storage which allows for no interruption of data flow throughout the flight of the rocket. Each of the sensors in the rocket have been carefully chosen due to the factors of ease of use, durability, and previous knowledge of sensors by members of the team.

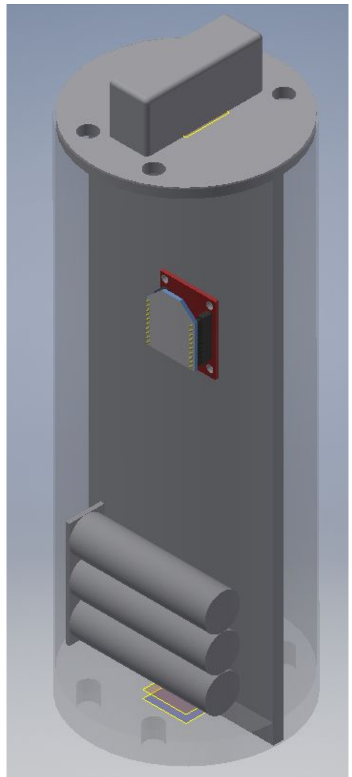

Figure 7: av-bay Construction

In Figure 7, the design of a custom wooden avionics bay is shown, and in Figure 8, the avionics bay with parts expanded is show.. The outer shell will be placed inside of the body tube. It is threaded so that the sled is securely held inside of the tube, as opposed to being on metal rods held by nuts. All of the parts will be bolted to the center of the avionics bay as seen in Figure 8. The body tube will enclose the inner section of the avionics bay. The SanCloud BeagleBone (C) and the microcontroller (D) used to connect the various electronics are bolted to the center wooden piece to insure a secure installation.

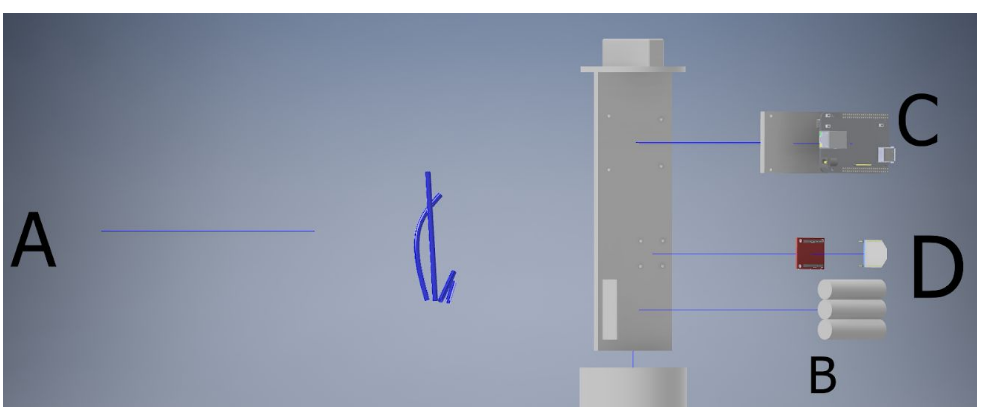

Figure 8: av-bay Construction Label and Disassembled

The battery cells (B) are connected to the same plane as the wooden center plane. They are also connected to the bottom of the avionics bay. This will insure that the battery as well as the backup battery are securely connected to the rocket. There will be a power switch on the top of the avionics bay beside the sled handle used to insert the bay. There will also be a set of signaling LEDs that are posted on the outside of the shell of the rocket. This will be used during the signal sending portion of the bonus challenge. A camera will be posted outside of the avionics bay to allow for the LEDs to be recorded to test and see the different states. Due to the placement of the handle and switch on top as well as the easy removal of bolts and the placement of parts, the avionics bay will be well constructed and easy to use, arm, and test.

Dealing with wire management was the largest issue during this iteration of the design. Dealing with the small wires going to place to place was a hassle so, therefore cables are used to manage the wiring of each system to each other. There will also be a main cable that will hold power and ground, this can be seen in figure 8 (A). In conjunction with this, each of the wire colors are referring to the different uses of each wire. For example red is power and black is ground. With this, the management of each of the cables will be easy and there will be a ledger of which cables are referring to each part of the avionics system. Each of these cables will also be zip tied down to the sled bed of the avionics bay meaning that the wires coming from the cables will not be ripped from the reciprocal ends. On top of this, all of the pins shall be soldered directly to the boards, and they all will be inspected for cold solder joints, distributed joints, and so forth to prevent the interruption of data flow.

Bonus Challenge

For the bonus challenge, the team has obtained a XBee Pro 60mW Wire to communicate with the rocket before and during the flight. A 128 bit encryption with a 2 character code shall be used to ensure that the connection is from our system. The team has been writing code to send 8-10 Hz worth of data from the avionics bay, and each transmission of data will be preceded by a size_t counter that will go from zero to number of transmission. For each transmission, there will also be a response which will be from the rocket sending back what the call was and stating whether the transmission was properly received. The avionics team has been considering adding a md5 checksum with each of the commands to confirm that the received command and the transmitted command match. This feature will only be enabled after extensive testing due to the amount of time it may take to check each command.

Model Rocket Flight

Construction Description

The team constructed two model rockets from a combination of common store bought components and custom made parts to launch on November 11th, 2017. To begin, the team was divided into two smaller teams and each designed a rocket using OpenRocket. The fins, centering rings, and bulkheads were modeled in AutoDesk Inventor and then laser cut. This enabled new members to learn crucial skills before beginning work on the competition rocket. The construction process also included cutting body tube, attaching shock cord and parachutes, and epoxying the motor mount as well as other components. After the bulkheads, fins, and centering rings were laser cut, they were sanded down to the desired dimensions before being epoxied in place. All of the parts were thoroughly inspected before the final assembled began. The launch occurred the following weekend.

Launch Description

The launch took place at Kentland Farms, Virginia Tech's 2,600 acre farm and the site of many engineering and science projects. The field where the rocket was launched was large and relatively flat providing a safe area for launch. On the day of the launch, the weather was slightly overcast with a temperature of around 40°F with a fair amount of wind. The launch was hosted and supervised by the New River Valley Rocketry Association. All rockets were inspected and approved by the Registered Safety Officer prior to launch. Despite a few minor setbacks, the launch was successful and both rockets performed as expected.

Launch Results

Due to a few construction issues as well as misinterpreted calculations, a few major changes had to be made at the launch site in order to reach an appropriate level of stability and weight. One of the teams took the fins off of their rocket and turned them around in order to reach a better stability. The other team added a considerable amount of weight to their nose cone to raise the center of pressure. Despite the significant changes that were made, both rockets still performed successfully. The first rocket reached an apogee of 254 m, a maximum velocity of 112 m/s, and a maximum acceleration of 192 m/s^2. The parachute successfully deployed shortly after apogee and the rocket was recovered. The flight time was 43 seconds and the rocket reached apogee at 6 seconds. Unfortunately, the altimeter was unable to be used in the second flight resulting in the team being unable to retrieve data from the second rocket. Although several mistakes were made, this certainly served as a strong learning experience for all team members enabling us to be more aware of issues before launching the competition rocket.

Figure 9: The inVenTs Rocketry Team assembled before launching the rockets.

Safety

Material Handling Procedures

To ensure the safety of all team members and bystanders, the team has implemented certain handling procedures while constructing and handling the rocket. All blue tube and G10 fiberglass will be handled whilst wearing dust-masks to ensure that toxic particles are not inhaled. All team members understand that inhaling these materials can cause respiratory issues and appropriate safety precautions will be taken.

Due to the explosive nature of rocket motors and the black powder charges used to separate the rocket, extreme care will be taken to ensure safety. All team members understand that if these materials are not handled properly, fire and/or injury can occur. As a result, the charges will be prepared before the launch and only handled again immediately prior to the time the rocket is setup on the launchpad in order to ensure the safety of the team, launch personnel, and bystanders. All materials will be transported with caution in order to prevent accidental detonation.

Assembly Procedures

Prior to leaving for the launch, the rocket will be disassembled into two subsections with the av-bay and parachute removed. The servos and other mechanical components will remain attached to the lower part of the rocket. Once at the site of the launch, the black powder ejection charges will be added to the av-bay. The av-bay will be re-inserted into the body tube and the two sections will then be joined together with shear pins.

Pre-Launch Procedure

1. Follow the appropriate packing instructions for the parachute and drogue chute.
2. Secure the parachute and drogue chute inside the rocket and attach the shock cord to the appropriate connections on the rocket.
3. Activate the avionic system and secure the avionics bay in the rocket.
    a. Turn on and test tracking beacon.
    b. Set delay.
    c. Turn on and secure the altimeter.
    d. Secure the camera to the side of the rocket and turn it on.
    e. Download the flight program to the microcontroller, ensuring everything is connected and working properly.
    f. Secure the microcontroller system inside the avionics bay.
    g. Connect the quick disconnect wires to the servos and LEDs
4. Verify aileron connections.
5. Test aileron system for functionality.
6. Ensure motor is secure in the rocket.
7. Verify that the correct amount of black powder is placed in the ejection canisters and that the canisters are properly sealed.
8. Place flame resistant wadding inside the rocket subsections to separate the ejection charge devices from the payload components.
9. Inspect the nose cone to ensure it is properly secured to top of the rocket.
10. Align and properly secure all sections of the rocket.
11. Check that the rocket motor has been installed properly inside the rocket.
12. Have the Range Safety Officer, inspect and approve the rocket for flight.
13. Properly mount the rocket on the designated launchpad.
14. Activate the microcontroller and the transmitter.
15. Ensure that the recovery devices are activated.
16. Insert the electronic match for ignition.
17. Follow the appropriate safety procedures.
18. Launch the rocket.

Post-Launch Procedure

1. Wait for Range Safety Officer to declare that the area clear.
2. Recover the rocket using the tracking beacon if necessary.
3. Verify that all components have been recovered.
4. Take a photo and a video of the landing site.
5. Ensure that the rocket has not been damaged.
6. Download the video from the camera.
7. Download the flight data from the microcontroller.
8. Deactivate the camera, microcontroller, and beacon.
9. Charge components prior to next flight.
10. Provided the rocket is in flyable condition, prepare for the next flight.

Appendix

Anticipated Flight Performance Graphs

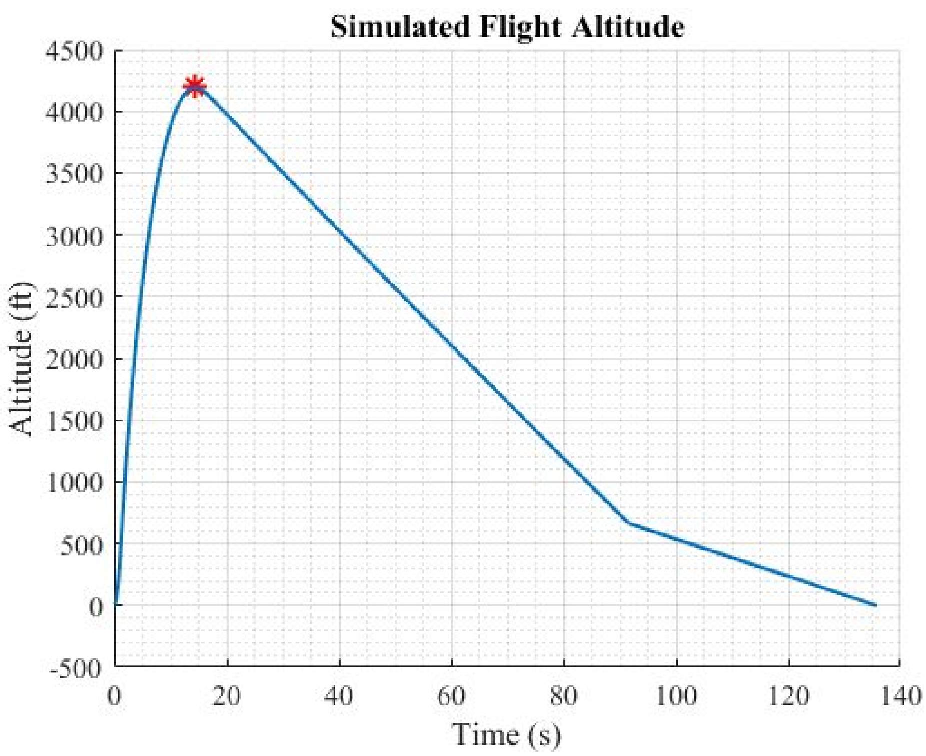

Figure 10: OpenRocket Plot simulating anticipated flight altitude. The red star represents the maximum altitude (4,193') obtained and time of occurrence (14.37 seconds after launch) in the simulation.

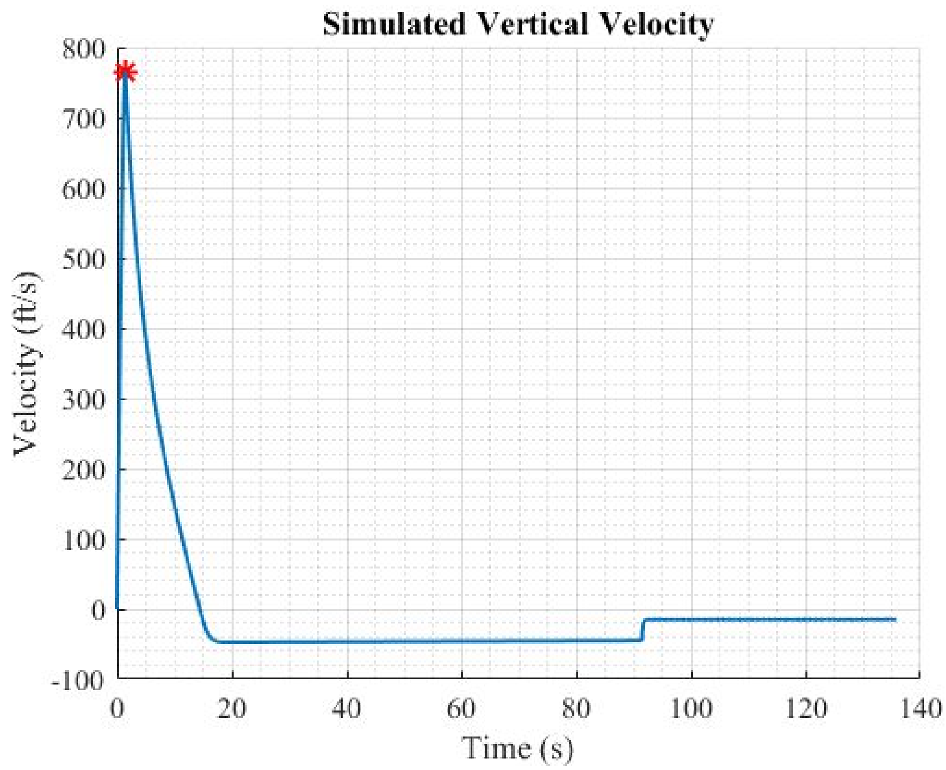

Figure 11: OpenRocket Plot simulating anticipated vertical velocity. The red star represents the maximum velocity (765 ft/s) obtained and time of occurrence (1.37seconds after launch) in the simulation.

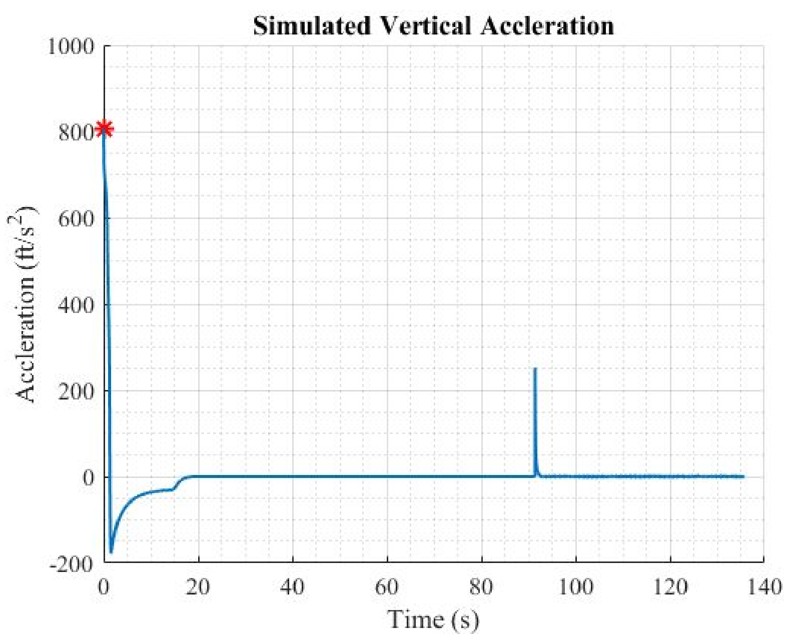

Figure 12: OpenRocket Plot simulating anticipated vertical acceleration. The red star represents the maximum acceleration (805 ft/s^2) reached during flight and time of occurrence (0.01 seconds after launch) during the simulation. Note the second peak in acceleration around 90 seconds; this corresponds to main parachute deployment in the simulation.

Citations

1. AccuWeather. (2018). *Weather in North Branch - AccuWeather Forecast for MN 55056*. [online] Available at: https://www.accuweather.com/en/us/north-branch-mn/55056/daily-weather-forecast/338871?day=82 [Accessed 28 Feb. 2018].