Design and Optimization of Carbon Fiber Composite Structures and Precision Apogee Control in Sounding Rockets

Team 150 Project Technical Report to the 2023 Spaceport America Cup

Ben Anderson*
Virginia Tech, Blacksburg, Virginia, 24061

Paul Broome†
Virginia Tech, Blacksburg, Virginia, 24061

Griffin Burd‡
Virginia Tech, Blacksburg, Virginia, 24061

Demetra Kohart§
Virginia Tech, Blacksburg, Virginia, 24061

Hanna Kruse¶
Virginia Tech, Blacksburg, Virginia, 24061

Gabe Mills‖
Virginia Tech, Blacksburg, Virginia, 24061

Ben Piper**
Virginia Tech, Blacksburg, Virginia, 24061

Binay Rijal††
Virginia Tech, Blacksburg, Virginia, 24061

Carmen White‡‡
Virginia Tech, Blacksburg, Virginia, 24061

For the 2023 Spaceport America Cup (SAC) hosted by the Experimental Sounding Rocketry Association (ESRA), Rocketry at Virginia Tech has developed a sounding rocket for the 10,000 foot apogee, Commercial-Off-The-Shelf (COTS) propulsion category of the competition. The goal for this rocket is to accurately hit 10,000 foot apogee while carrying an 8.8 minimum pound payload. The configuration of this rocket includes a 3U form-factor Cubesat payload, a Student Researched and Designed (SRAD) electronics bay, and a precision apogee control system named the Active Drag System (ADS). The airframe of the rocket is prtially composed of SRAD carbon fiber composites, including the bodytubes and fins, which are manufactured in-house. The rocket, named Valkyrie, performed three total test launches over the course of the academic year. One was a subscale recovery test launch at Blacksburg, VA and two were full-scale launches completed in Dalzell, SC.

*Avionics Lead, Department of Mechanical Engineering
†Payload Lead, Bradley Department of Electrical and Computer Engineering
‡Design Validation Lead, Kevin T. Crofton Department of Aerospace and Ocean Engineering
§Deputy Chief Engineer, Kevin T. Crofton Department of Aerospace and Ocean Engineering
¶Chief Engineer, Kevin T. Crofton Department of Aerospace and Ocean Engineering
‖Recovery Lead, Bradley Department of Electrical and Computer Engineering
**Aerostructures Lead, Kevin T. Crofton Department of Aerospace and Ocean Engineering
††Software Lead, Department of Computer Science
‡‡Treasurer and Outreach Lead, Department of Physics

Contents

List of Tables

List of Figures

Nomeclature

ADS	Active Drag System
AEDL	Advanced Engineering Design Lab
AGL	Above Ground Level
CFD	Computational Fluid Dynamics
Cg	Center of Gravity
COTS	Commervial off the shelf
Cp	Center of Pressure
ESRA	Experimental Sounding Rocketry Association
FEM	Finite Element Method
IMU	Internal Measurement Unit
IREC	Intercollegiate Rocket Engineering Competition
LCO	Launch Coordination officer
LiPo	lithium polymer
MEMS	microelectromechanical systems
NRVR	New River Valley Rocketry
PWM	pulse width modulation
RF	Radio Frequency
RSO	Range Safety Officer
SAC	Spaceport America Cup
SBB	Student Budget Board
SEC	Student Engineers Council
SISO	Single Input Single Output
SRAD	Student Research and Designed
STEM	Science Technology Engineering Mathematics
TRA	Tripoli Rocketry Association
TWR	thrust to weight ratio

I. Introduction

A. Mission Statement

Rocketry at Virginia Tech is a student led design team at Virginia Polytechnic Institute and State University in Blacksburg, Virginia. The team's goal is to promote interest in high-powered rocketry and provide hands-on engineering experience among students at Virginia Tech and members of the surrounding community. As a design team, a safe environment for rocketry enthusiasts of all backgrounds to operate high-power rockets and practice engineering design principles is provided. Annually, the team competes in the Spaceport America Cup (SAC) hosted by the Experimental Sounding Rocketry Association (ESRA) and assists students in getting their high-powered rocketry certification with the support of our regional Tripoli Rocketry Association (TRA)) chapter, New River Valley Rocketry (NRVR). This year, to compete in the $10,000$ foot apogee with Commervial off the shelf (COTS) propulsion category, Rocketry at Virginia Tech has challenged itself to develop its most complex configuration yet. Projects include a Student Research and Designed (SRAD), active flight control, and more. This report serves to summarize the progress the team has made towards achieving these goals while adhering to SAC rules and requirements.

B. Team Structure

Rocketry at Virginia Tech is composed of 75 undergraduate students and two graduate students across all years and 11 different majors in and outside of Science Technology Engineering Mathematics (STEM). The team's organizational structure consists of a chief engineer and eight subteam leads. Each subteam is responsible for a specific vehicle subsystem, and the lead engineer ensures that each subteam fulfills required tasks in pursuit of their project goals. In addition, subteam leads and the chief engineer both work to validate that all systems conform to requirements as outlined by Intercollegiate Rocket Engineering Competition (IREC) rules and requirements. Figure 1 presents the breakdown of team leadership in addition to recognizing faculty advisors who have mentored Rocketry at Virginia Tech in pursuit of our mission.

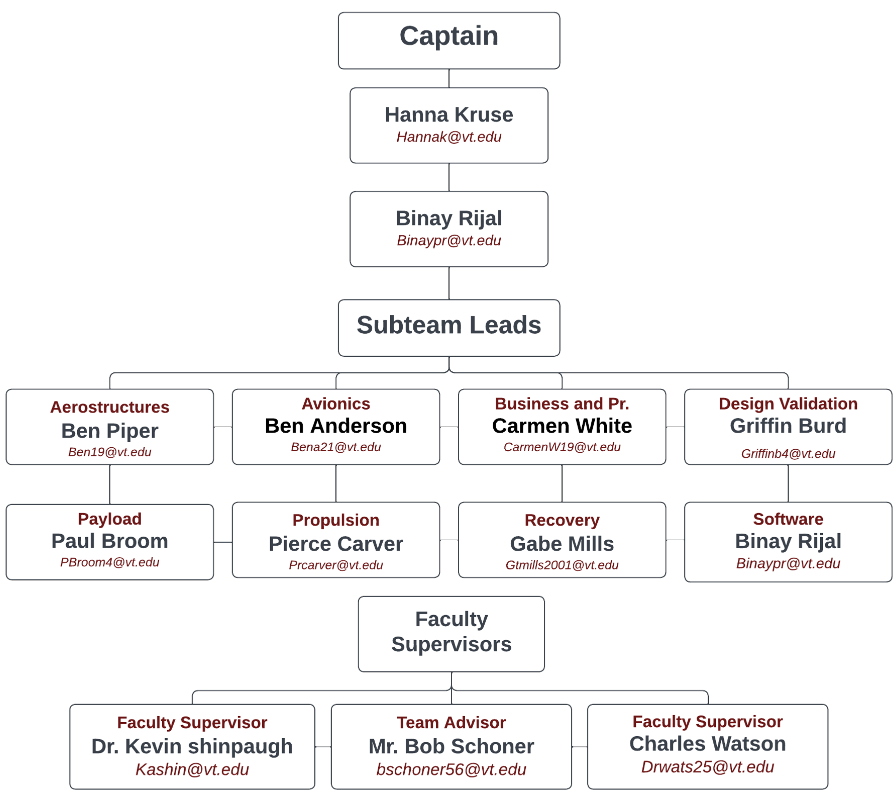


Fig. 1 Rocketry at Virginia Tech 2022-2023 leadership structure.

C. Mentors and Stakeholders

The team's mentor and Flyer of Record (FOR) is Bob Schoner, a level 3 certified TRA member, prefect for the TRA prefecture #143 in Christiansburg, VA and head of the local New River Valley Rocketry association. Bob Schoner attended the team's first test launch in Culpeper, VA and provides Range Safety Officer (RSO) support to the team at certification launches, performed locally in Blacksburg, VA at Kentland Farms. Rocketry at Virginia Tech's faculty advisor is Dr. Kevin Shinpaugh. Dr. Shinpaugh is collegiate professor of the Kevin T. Crofton Department of Aerospace and Ocean Engineering who works with a variety of university design teams, including NASA SLI, NASA Robotic Mining Competition, RASC-AL RoboOps, RockSat-X, and others. He is a level 2 certified TRA member and provides additional support at team certification launches as the Launch Coordination officer (LCO).

The team received financial support from Virginia Tech's Kevin T. Crofton Department of Aerospace and Ocean Engineering, Student Engineers Council (SEC), and Student Budget Board (SBB). Additional financial support was provided by corporate sponsors, such as Northrop Grumman, Leidos, Siemens, Truesdell Engineering, and Newton Engineering and Product Development. Rocketry at Virginia Tech was able to manufacture the team's 2023 launch vehicle through the use of the Advanced Engineering Design Lab (AEDL), a lab space owned and operated by the Kevin T. Crofton Department of Aerospace and Ocean Engineering, and its equipment. Lastly, the team received mentoring regarding current and past projects from its extensive alumni network now employed at various companies including Lockheed Martin, SpaceX, Northtrop Grumman, Aerojet Rocketdyne, TORC Robotics, and others.

II. Mission Concept of Operations Overview

An overview of the launch vehicle concept of operations is shown in Figure 2. Following pre-launch operations, the team will conduct a final checklist review and sign-off, then proceed to secure the vehicle upon its launch-pad and begin the arming sequence. After all personnel are ensured to be a safe distance from the vehicle, ignition will occur. The solid motor will provide thrust until burn-out at approximately $4,049\ ft$ Above Ground Level (AGL). This begins the coast phase of the ascent. During the coast-phase, on-board telemetry systems will use a 3 DOF model to determine the expected vehicle apogee. It is from this time onward, during the coast phase, that the Active Drag System (ADS) will deploy and will remain as such until apogee. This system will help to add drag to the system and get us as close to the $10,000\ ft$ AGL as per competition guidelines. If that does not occur, the ADS will be active until apogee.

At apogee, the vehicle will attempt to begin the recovery sequence. At approximately $T_{apogee}\ s$ the vehicle will use black powder charges to separate at its midsection and deploy its drogue chute. Both nose-cone and midsection separation will be armed with main, and backup black powder charges for redundancy. With the drogue chute deployed, vehicle descent rate will decrease to approximately $61.9\ ^{ft}/_{s}$.

At approximately 800 feet AGL, the launch vehicle will deploy its main chute using black powder charges from the break between the nosecone and the rest of the launch vehicle body. Under main, vehicle descent rates are further decreased to $17.7\ ^{ft}/_{s}$.

Once the vehicle and payload have touched down, on-board GPS on both systems will broadcast landing zone coordinates back to a ground-station. The launch operations team will proceed to recover the vehicle once it is safe to do so. Following this, on-board data including in-flight footage will be off-boarded from the vehicle and the team will debrief on the flight.

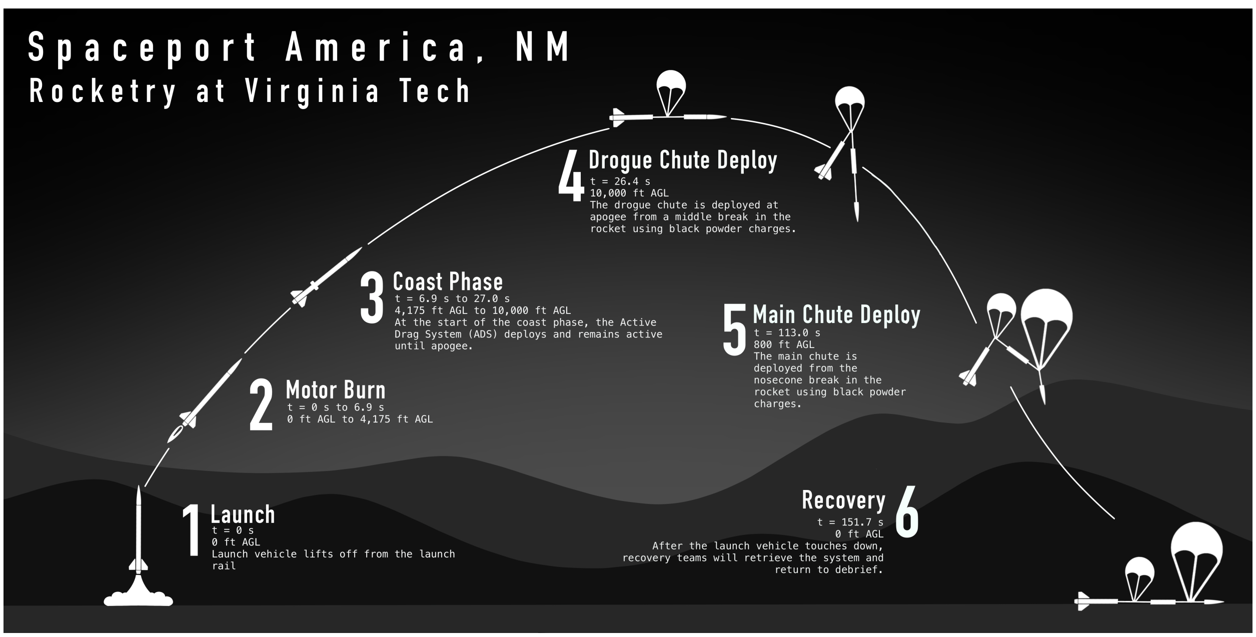


Fig. 2 Rocketry at Virginia Tech 2023 concept of operations.

A flowchart of the mission's CONOPS can be seen below in Figure 3, with more detail regarding the order to events during the launch vehicle's flight. Further information about each phase of flight can be found in the vehicle subsystems' respective sections.

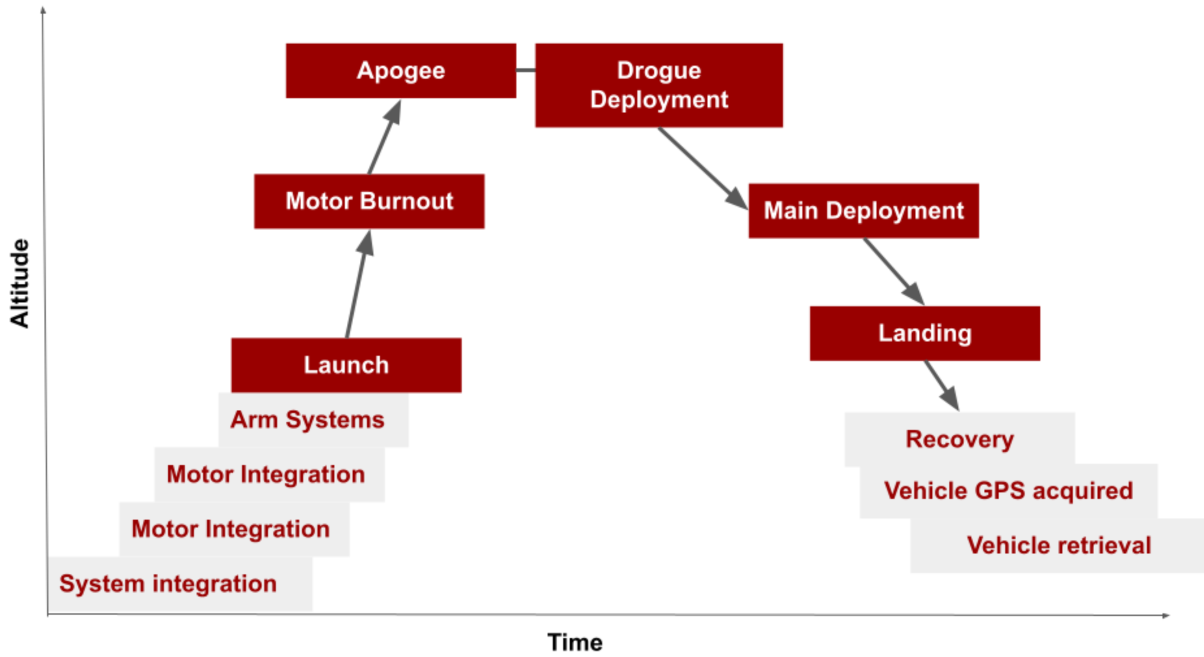


Fig. 3 Concept of Operations flowchart.

III. System Architecture

A. Overview

Rocketry at Virginia Tech's 2023 launch vehicle is a COTS solid motor-powered launch vehicle measuring $128 inches$ in length with a $6.17\ inch$ body diameter. The vehicle structure is designed to carry propulsion, avionics, recovery, payload, and telemetry systems to an apogee of $10,000\ ft$ AGL.

The vehicle's airframe is designed to allow for replacement of damaged parts and reuse for year-over-year optimization. In its current configuration, Rocketry at Virginia Tech's 2022 launch vehicle is designed to fly on an AeroTech N1939 constrained by the motor casing in the thrust structure. The thrust structure provides motor retention, and transfers thrust loads into the airframe during flight. The airframe is made of an SRAD carbon fiber body tube, a COTS fiberglass body tube, and a COTS 5.5 : 1 Von Karman nose cone.

The avionics bay provides space for the primary electronics stack and ADS. The ADS is placed as far aft in the vehicle as possible to reduce the destabilizing effect of control surface deployment into the free stream which shifts center of pressure closer to the center of mass, decreasing overall stability margin. The electronics stack contains a BeagleBone for ADS control, altimeters, and associated batteries.

The aft bay contains the drogue chute, shock chord, and redundant ejection charges. The forward bay contains the main chute, shock chord and redundant ejection charges. By placing the relatively heavy payload up in the nosecone, vehicle stability is increased by roughly 0.3 calibers. The nose cone contains electronics for live telemetry and GPS tracking as well as an altimeter to activate a nose cone ejection charges prior.

B. Vehicle Trajectory and Flight Characteristics

The vehicle is estimated to have a mass of $65.7\ lbm$ at liftoff, decreasing to $53.8\ lbm$ by burnout and chute deployment. The system-level breakdown of masses is given in Table 1 based on real measurements of as-built systems.

Two tools were used to evaluate trajectories and flight characteristics: OpenRocket and RASAero II. Since the vehicle will travel into the transonic region by max-q, RASAero is used to ground results from OpenRocket which is less accurate in the supersonic regime.

All models run at local atmospheric pressures of $1.03\ bar$ and temperatures of $35°C$ according to historical weather data for Las Cruces, NM in June. Simulated launch elevation angles are $84 \pm 1°$ in accordance with IREC Requirement 10.1. At liftoff, the vehicle has a thrust to weight ratio (TWR) of 5.69 based on the M1939's initial thrust of $1,744.7\ N$ and a liftoff mass of $65.7\ lbm$. Assuming a $4.88\ m$ ($16.0\ ft$) launch rail is provided by ESRA at Spaceport America, the vehicle will have an off-the-rail velocity of $78.9\ ft/s$. Stability margin is computed in dimensionless calibers by the following equation

$$\text{Stability } = \frac{C_p - C_g}{D_{\text{airframe}}} \tag{1}$$

$$C_p = \frac{\int x p(x) dx}{\int p(x) dx} = \frac{\sum_i A_i x_i}{\sum_i A_i} \tag{2}$$

$$C_g = \frac{\int x W(x) dx}{\int W(x) dx} = \frac{\sum_i W_i x_i}{\sum_i W_i} \tag{3}$$

where C_p and C_g are the distances from the tip of the vehicle to its center of pressure and center of mass, respectively, while $D_{airframe}$ is the vehicle's body diameter. Based on this, the vehicle has a stability margin of 2.40 calibers when leaving the launch rail, rising to 4.86 as the center of mass shifts forward by $0.17\ m$ during flight. This stability range, in addition to the estimated off-the-rail velocity, satisfies the stability requirements (10.2, 10.3, and 10.4) outlined by IREC.

Based on the average of the three models' uncorrected (by ADS deployment) apogee predictions, the vehicle is expected to achieve an apogee of $11.078\ ft$ AGL in $0\ mph$ winds and $10,608\ ft$ AGL in the extreme case of $20\ mph$ winds. The tendency of the vehicle to overshoot the target apogee is intended to ensure the vehicle is capable of breaking $10,000\ ft$ with the remaining altitude to be scrubbed off by ADS deployment. All models estimate a maximum velocity of $912 ft/s$ or Mach 0.80. A Mach number and altitude plot for an ideal, zero wind flight profile are given in Figure 4. A summary of the vehicle's flight characteristics is given in Table 2.

Table 1 Mass Breakdown of the 2022-2023 Launch Vehicle

Subteam	System	Mass (lb)
Structures	Nosecone	7.5
Structures	Internal Structure	9.6
Structures	Aeroshell	8.1
Structures	Fins	0.9
Avionics	Active Drag System	1.8
Avionics	Electronics Bay	1.6
Avionics	Camera	0.1
Recovery	Chutes + Hardware	9.0
Payload	3U CubeSat	8.8
Prop.	Casing Hardware	6.4
Prop.	Propellant	11.9
	Liftoff	**65.7**
	Burnout	**53.8**

Table 2 Predicted flight data of the 2022-2023 launch vehicle.

Characteristic	Value	Unit
Liftoff TWR	5.69	N/A
Off-Rail Velocity	78.9	ft/s
Liftoff Stability	2.40	N/A
Burnout Stability	4.86	N/A
Burnout Mach	0.80	N/A
Maximum Velocity	912	ft/s
Maximum Acceleration	6.96	g
Uncorrected Apogee	$11,078$	ft
Corrected Apogee	$10,000$	ft

Table 3 Simulation atmospheric data for Las Cruces, New Mexico based on historical data in the month of June.

Characteristic	Value	Unit
Atmospheric Pressure	1.03	bar
Temperature	35	$°C$
Elevation Angles	84 ± 1	°

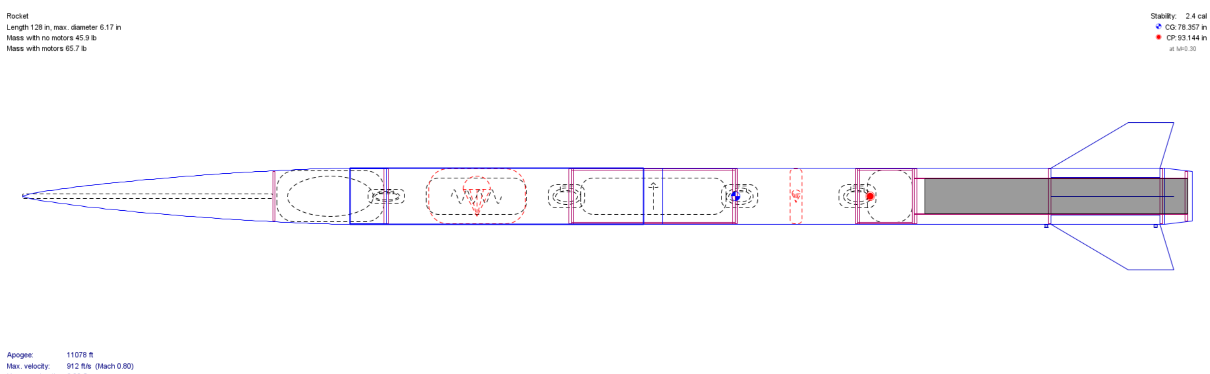


Fig. 4 Open Rocket model.

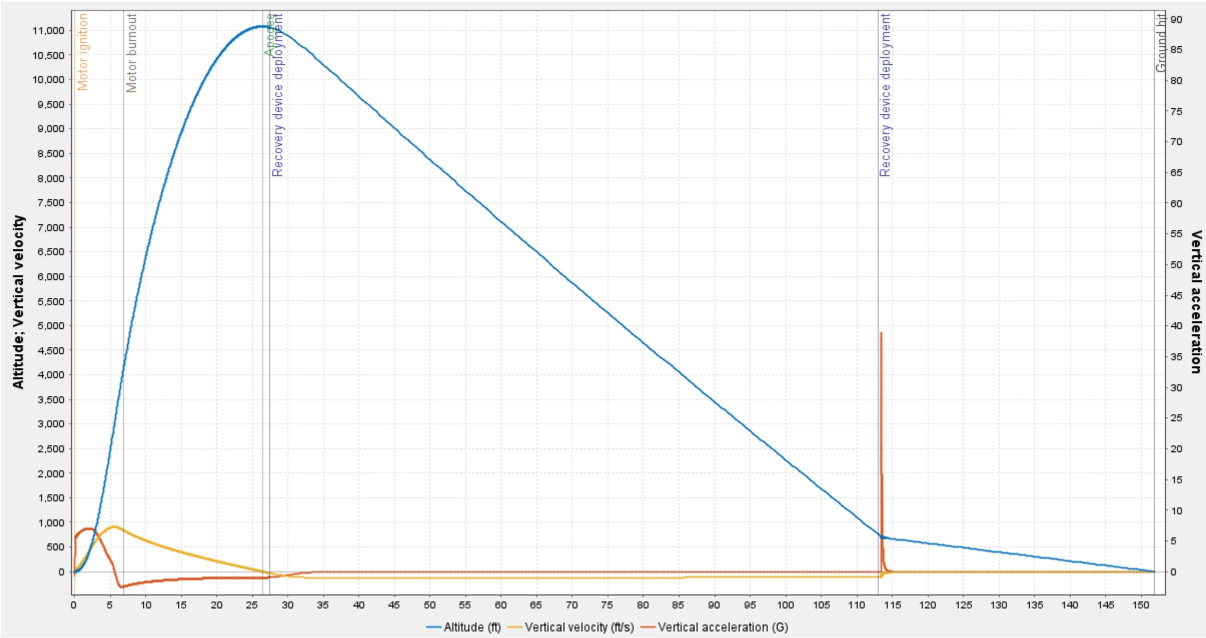


Fig. 5 Open Rocket simulation.

C. Propulsion Subsystems

Rocketry at Virginia Tech's 2023 launch vehicle is flying on an Aerotech M1939W, a 98 mm diameter COTS motor with a total impulse of 10,481.5 $N \cdot s$. The motor burns for 6.2 s and provides a maximum thrust of 2,429.7 N. The characteristics of the M1939W are summarized in Appendix B. The motor was chosen due to meeting SAC requirements of having a minimum off-the-rail velocity of between 50 ft/s and 100 ft/s as well keeping the launch vehicle's stability nominal during ascent, which is defined as being under 6 calibers of stability. The M1939 has a high initial thrust of 1,744.7 N compared to the rest of the burn's duration, which contributes to the higher off-the-rail velocity. [4] The motor's thrust curve can be seen below in Figure 6.

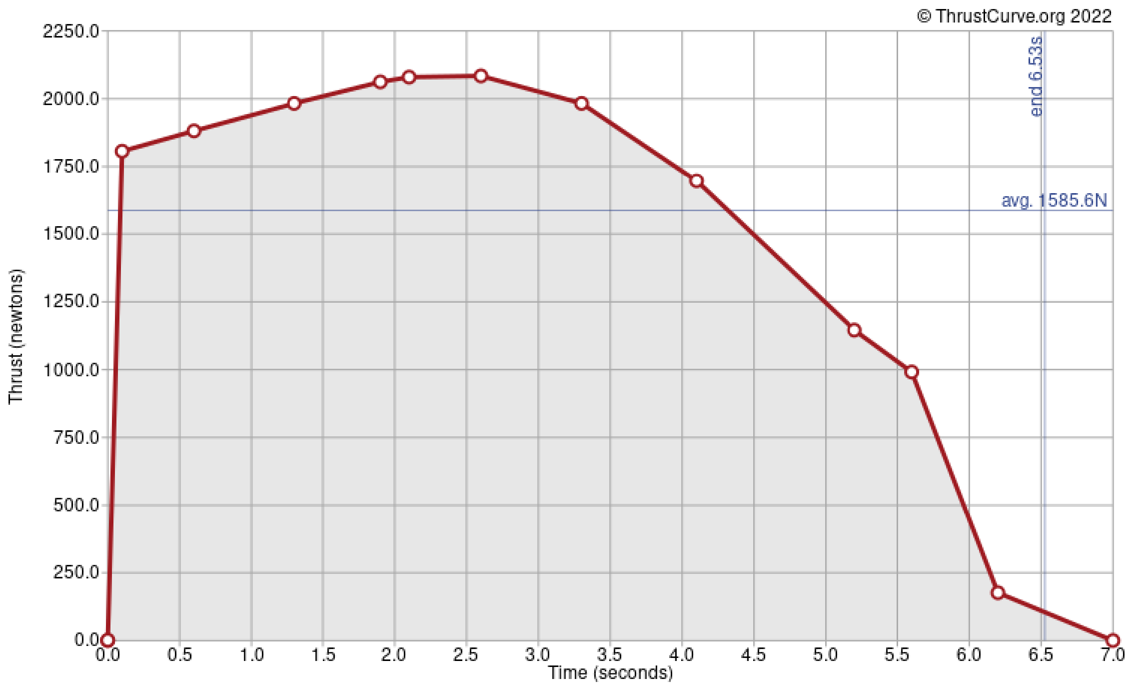


Fig. 6 Thrust curve of an Aerotech M1939W COTS motor for Rocketry at Virginia Tech's SAC launch. [4]

Rocketry at Virginia Tech completed a first test launch on 2/18/2023 in Dalzell, South Carolina on an Aerotech L1300R and completed a second test launch on 4/15/2023 in Dalzell, South Carolina on an Aerotech M1800FJ motor. Both motors were chosen due to high total thrust values in addition to complying with launch site FAA waivers. Thrust curves of both motors can be seen below in Figure 7.

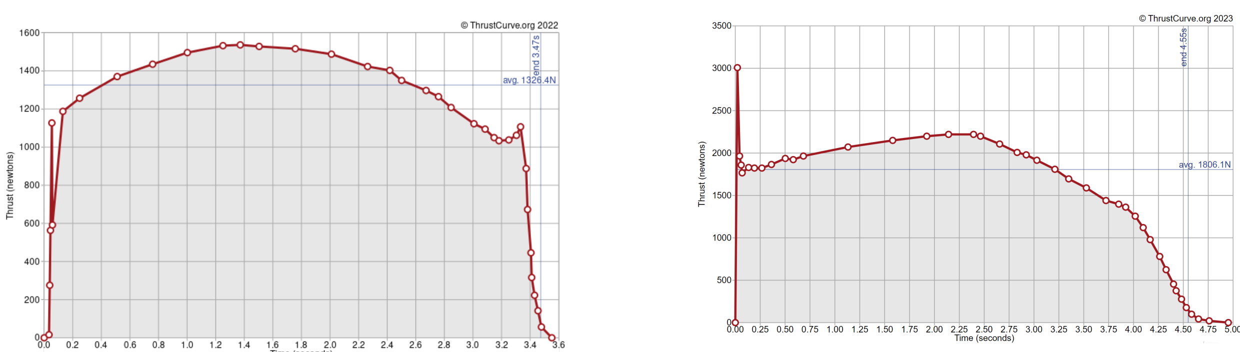


Fig. 7 Rocketry at Virginia Tech's test motors, an Aerotech L1300R (left) and an Aerotech M1800FJ (right). [2] [3]

While deciding on a COTS motor for the team's competition launch, the team conducted a trade study of available

COTS motors in order to select a motor that best meets the requirements set by the team and by SAC. Four motors were selected for examination that are compatible with motor hardware owned by the team due to financial constraints. The four criteria that were considered were the apogee that the motor produced and how close it came to the 10,000 ft goal, the launch vehicle's off-the-rail velocity, the minimum stability of the launch vehicle during ascent, and the cost required to purchase the motor. The apogee produced by the motor was weighted the heaviest due to altitude accuracy having the most significant impact on the team's score, with off-the-rail velocity and minimum stability the next heaviest weighted since both are important for a nominal and safe vehicle ascent.

Table 4 Structural Data Regarding the Launch Vehicle

Criteria	Mandatory (Y=1/N=0)?	Weight	Scale	M2500	M6000	M1939	N2220
Apogee	1	40%	1-10	7.9	9.6	10.0	6.2
Off-the-Rail Velocity	1	25%	1-100	9.7	10.0	9.8	8.1
Minimum Stability	1	20%	1-100	3.3	4.5	3.6	10.0
Cost	0	15%	1-10	10.0	9.5	10.0	9.2
Weighted Totals in %		10%		77.6%	86.6%	86.8%	78.6%

The results of the trade study can be seen in Table 4 above, with the Aerotech M1939 having a high score percentage of 86.8% and the Aerotech M6000 having a similar score of 86.6%. Due to both motors being readily available with vendors, the Aerotech M1939 was chosen as the team's competition motor for SAC 2023.

D. Aero-structure Subsystems

The Aerostructures subteam is responsible for the design, analysis, manufacturing, and testing of the launch vehicle.Additionally, the subteam works with other subteams to integrate avionics, payload, and recovery into a unified launch system. The subteam's goals included manufacturing precise components for increased ease of integration, to analyze and test all load bearing components, and that the launch vehicle should have the ability to be assembled using only basic hand tools.

1. Vehicle architecture

The launch vehicle serves the purpose of housing the many subsystems necessary for flight. These include avionics, payload, propulsion and recovery. The vehicle was designed to meet all of the integration requirements of these subsystems. The rocket has an overall length of 3.25 m (10.67 ft) and an outer diameter of 6.17 in. The rocket has the ability to use any 98mm Aerotech motor casing however it was designed to fit a Aerotech 98/10260. A general layout of the launch vehicle can be seen in Figure 8.

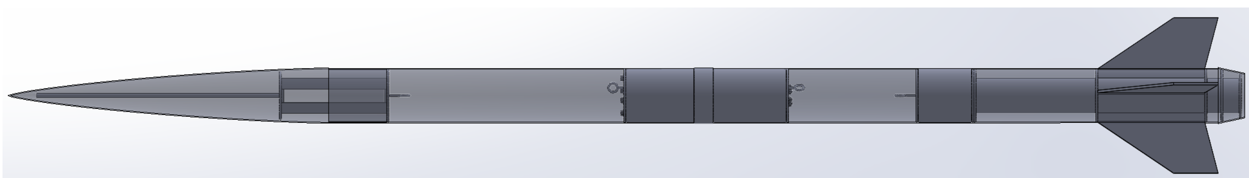


Fig. 8 Rocketry at Virginia Tech 2023 full rocket assembly.

The fin can or thrust structure is built to house the motor casing, Aerotech 98/10240, and mount the four composite fins which will be described in further detail in the Fins subsection. A fiberglass motor mount tube with a 98 mm diameter was used with four fiberglass centering rings that were cut out on a water jet. The motor mount was secured to the boat tail and motor casing with a centering ring and bulkhead epoxied at the base. Two more of the centering rings were epoxied on both the top and bottom of the fins, to aid in securing them in place. The last centering ring was epoxied to the top of the motor mount.

Forward of the motor casing is the Active Drag System bay. The bay is 0.15 m (6 in) in length. It houses the ADS. The ADS is located in the aft-most location possible. This was done to minimize the destabilizing effect of deploying control surfaces into the airstream forward of the vehicle's initial center of pressure.

Forward of the ADS bay is the drogue chute bay. This houses the drogue chute used for the recovery of the rocket. The drogue chute is deployed at apogee through a break in the body tube caused by ejection charges.

Immediately forward of the drogue chute bay is the electronics bay. Here, the recovery electronics, altimeters, and tracking electronics are located. More details about the exact components located inside of the electronics bay can be found in the Recovery section. The electronics bay also serves as a coupler between two body tubes, and is capped off on each end with fiberglass bulkheads. This prevents pressure from the ejection charges to escape and prevent the body tubes from separating. The coupler has a 2 inch switch band around it, and extends 8 inches into each body tube, for a grand total of 18 inches long.

Above the electronics bay is the main parachute bay. Here, the main parachute will be housed until the nosecone is ejected and the main parachute is deployed at 800 feet.

Enclosing the payload section and the body tubes is the nose cone. The nose cone is made of fiberglass and is Von Karman shaped. Extended out of the nose cone is a shoulder allowing it to couple with body tubes. This shoulder will extend 0.16 m (6.25 in) into the body tube, satisfying the requirement that all couplers extend at least one body tube diameter. Additionally, a third recovery bulkhead will be placed in the nose cone. The dry mass of the vehicle is 20.8 kg. A breakdown of the mass can be seen in Table 1.

The motor being used is an Aerotech M-1939 and has a maximum thrust of 2,429.7 N. To meet the requirements of designs having a safety factor of 2 or greater, the thrust structure will be designed to withstand 5,000 N. The design safety factors used for analyzing yield strength, ultimate strength and flutter stability failure are listed in Table 5.

The primary load considered when designing the thrust structure is peak thrust. Based on how the thrust structure was designed, the thrust load is transferred up the motor tube, through the epoxy fillets holding the centering rings and supported by the centering rings themselves. To verify that the load path and structural design considerations were

Table 5 Design Safety Factors

Driving Failure	Mode	Design Safety Factor
Strength	Yield	1.50
Strength	Ultimate	2.00
Stability	Flutter	1.50

accurately estimated, a Finite Element Method (FEM) of the structure was generated by the Design Validation subteam using Ansys.

Since all of the components in the thrust structure are thin (or relatively thin) materials, the model was created using all Shell elements. Shell elements provide for a quick and accurate model which is ideal for design iteration and post processing. Since the elements in the model have only a defined thickness, transverse shear stress is not calculated through the thickness of the materials. This is a reasonable assumption for the structure as the primary load is expected to be axial tension and compression as well as hoop stress. Additionally, as mentioned previously the epoxy fillets are expected to carry a significant portion of the shear stress. In order to accurately model these, full seam welds with a conservative thickness of 3mm and no HAZ region were utilized. Figure 9 gives an example of one of the centering rings epoxied to the motor tube and body tube.

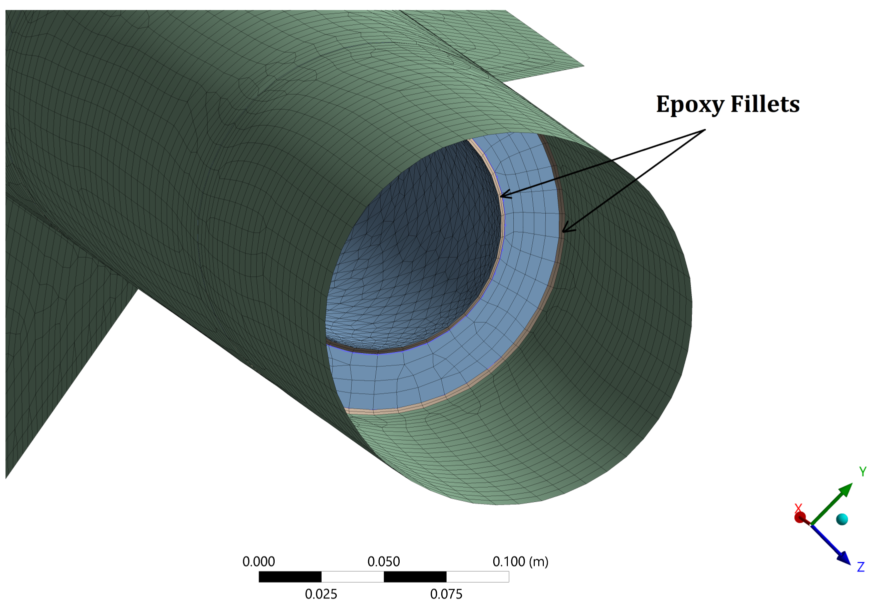


Fig. 9 Thrust Structure mesh with epoxy fillets.

The thrust load was applied to the aft end of the motor tube and the model was fixed at the forward end of the body tube. This is a conservative set of loads and boundary conditions but should provide accurate results. If necessary, a higher fidelity model would be generated if margins were lower than desired. The model was run using a liner elastic solver and produced the stress contour plots shown in Figure 10.

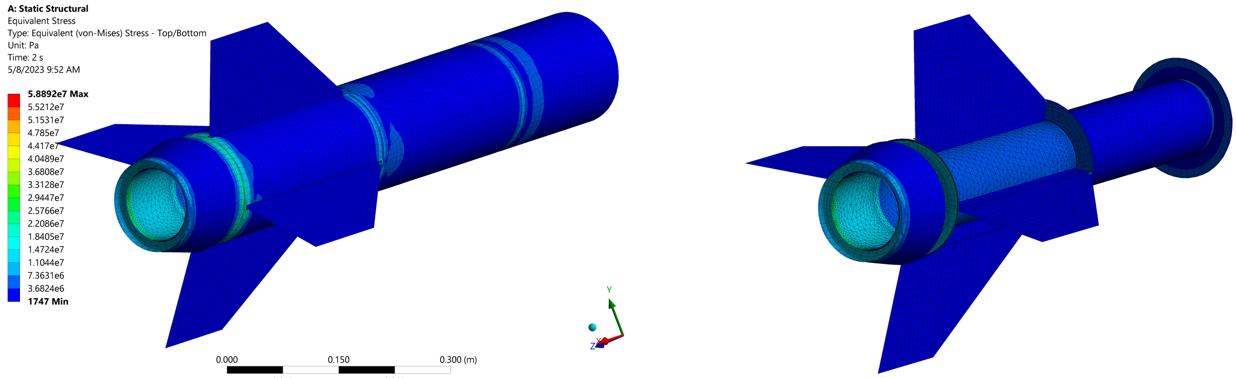


Fig. 10 Results of maximum thrust load case. Full thrust structure model (left). Internal Structure shown to display centering ring stress distribution (right).

As expected, the primary load was transferred through the motor tube which resulted in a forward deflection of the centering rings. Minimal thrust load was transferred through the body tube and the fins which leaves a large strength margin for aerodynamic loads experienced during MaxQ. Table X summarizes the margins of safety for the structural components during peak thrust. The design FS was applied to the load itself rather than the resulting stress to account for non-linearity in the model stiffness. It is important to mention that since the model utilized linear elastic materials, the MSu is a conservative estimate. If more accurate results were desired (i.e. the margins were low), then nonlinear elastic or nonlinear elastic-plastic materials could be implemented.

Table 6 Stress margins of thrust structure components under maximum thrust load.

Load Case	Component	Stress Output (Pa)		Factor of Safety		Allowables (Pa)		Margins	
		σ max Yield	σ max ult	FSy	FSu	Fty	Ftu	MSy	MSu
Max Thrust	Body Tube	20,424,000	27,232,000	1.5	2.0	311,000,000	400,000,000	14.23	14.69
	Boat Tail	9,010,000	12,014,000	1.5	2.0	311,000,000	400,000,000	33.52	33.29
	Motor Tube	25,337,000	33,782,000	1.5	2.0	200,000,000	250,000,000	6.89	7.40
	Fins	9,609,000	12,812,000	1.5	2.0	97,000,000	97,000,000	9.09	7.57
	Centering Rings	11,856,000	15,808,000	1.5	2.0	200,000,000	250,000,000	15.87	15.81
	Epoxy	6,454,000	8,605,300	1.5	2.0	22,100,000	34,000,000	2.42	3.95

2. Airframe

The launch vehicle's airframe is made of carbon fiber body tubes that encase the vehicle's internal structure and subsystems from the nose cone to the boat tail. Carbon fiber was selected because of its high strength to mass ratio. A large supply of carbon fiber was donated to our team, which makes it a cost effective material to consistently use based on its high quality. The body tubes slide over the vehicle's thrust structure and are secured in place along each aluminum square tube.

The carbon fiber composite's strength is critical in handling the compressive loads experienced during flight due to the inertia of the mass carried by the base of the aft-most body tube. Bending and shear loads from aerodynamic forces, which have not yet been analyzed, will further contribute to loading the airframe's body tubes.

The composite body tubes are made using a wet layup process on a 6-inch diameter blue tube. The tubes are wrapped in layers of 6K carbon fiber weave. The 0-90 weaves of the carbon fiber are oriented along the vehicle's primary axis to maximize tensile and compressive strength in these directions. The layup is held together and hardened by Fibreglast System 2000 Epoxy Resin. The blue tube is then removed at the end of the layup.

The carbon fiber composite's strength is critical in handling the compressive loads experienced during flight due to the inertia of the roughly 14.4 kg of mass carried by the base of the aft-most body tube. In 2019, the team compression tested one of these body tubes in excess of 111 kN before failure was achieved. Given the body tubes' diameter and wall thickness, this works out to a compressive strength of 44.9 MPa. For the body tubes, combined axial and bending stresses were estimated using Equation 4.

$$\sigma_{Combined} = \frac{F_{design}}{A} + \frac{M_{design}c}{I} \tag{4}$$

where F_{design} is the internal axial design load, M_{design} is the pitching moment, c is the distance between the body tube's center line and its extreme fiber, A is cross sectional area, and I is the area moment of inertia of the composite.

Three body tubes are used to encase all of the rocket's internal systems. The aft most body tube is 0.97 m (38 in) and covers from the aft end of the rocket to the aft end of the avionics bay. A second body tube extends 0.89 m (35 in) from the bottom of the avionics bay to the break in the recovery bay. The decision to start the second body tube at the aft end of the avionics bay was driven by the need for slots in the airframe for ADS flaps. Having these slots at the end

of a body tube will increase ease of manufacturing. The forward most body tube extends 1.14 m (45 in) from the split in the recovery bay to the nose cone. A carbon fiber coupler is used to connect the break in the recovery bay. This coupler will extend one body diameter into both body tubes, satisfying the SAC requirement.

3. Fins

The rocket's fins are constructed of a strong, lightweight Nomex honeycomb core sandwiched between two layers of carbon fiber hardened with epoxy resin. The layup method and materials endures strong, lightweight fins for the rocket that can withstand maximum forces upon flight and landing. When manufacturing the fins, first epoxy is spread over a layer of mylar, which wont stick to the epoxy. The carbon fiber is then laid on top of the epoxy coat, with more epoxy added to ensure there are no holes in the epoxy and fins. After, the Nomex is laid on the layup, and the composite is sandwiched between two flat surfaces, and weight is added to maintain a flat, and straight shape to the composite. After being left to dry the same method is used to produce another sheet of carbon fiber, and added to the layup. It is then sandwiched together again with weight added to create a flat sheet for the fins to be cut out of.

There are a total of 4 identical fins on the rocket, which are connected directly to the motor tube through fin slots cut out of the lower body tube. The inside of the fin can is made with carbon fiber reinforced fillets, connecting the fin to the motor tube, then to the next fin. The outside of the rocket connects to the fins with a layer of epoxy to form a clean connection between the body tube and the fins. The fins are manufactured in a 1 foot by 2 foot sheet, and cut with a water jet to be the shape and size needed for the rocket to be about 2 to 2.5 calipers in stability. To create an aerodynamic shape 3D printed edges are added to the end of the fins and connected with epoxy.

To test the consistency of our production along with the measured effective elastic modulus, we made coupons out of a randomly selected fin section. These coupons were made into the shape of dog bones; tapered in the middle with a wide base at both ends for the Instron grips. To minimize the error from cutting these coupons by hand, we used the water jet to make 6 identical coupons. To measure an accurate elastic modulus we then tested the tensile strength of these coupons in an Instron thanks to the Aerospace Structures and Materials Lab (ASML) at Virginia Tech.

Fig. 11   Setup of Instron tensile testing.

Fig. 12   Fin material sample post-test. Ultimate failure occurred within the expected region.

Samples 3, 5, and 6 were first tested with a less reliable clamp configuration which led to considerable slipping during testing. This led to the strain measurement reading inaccurate results which can be seen in the left plot in Figure 13. Samples 1, 2, and 4 were all tested after the Nomex interior had been crushed. This needed to be done in order for the coupon to fit into the more reliable instron clamps. The results from this round of testing can be seen in the right plot in Figure X. As the Nomex was designed to provide negligible tensile strength, it was determined that this procedure was acceptable. Overall, the results for each coupon in the second test yielded consistent strength and elastic modulus results.

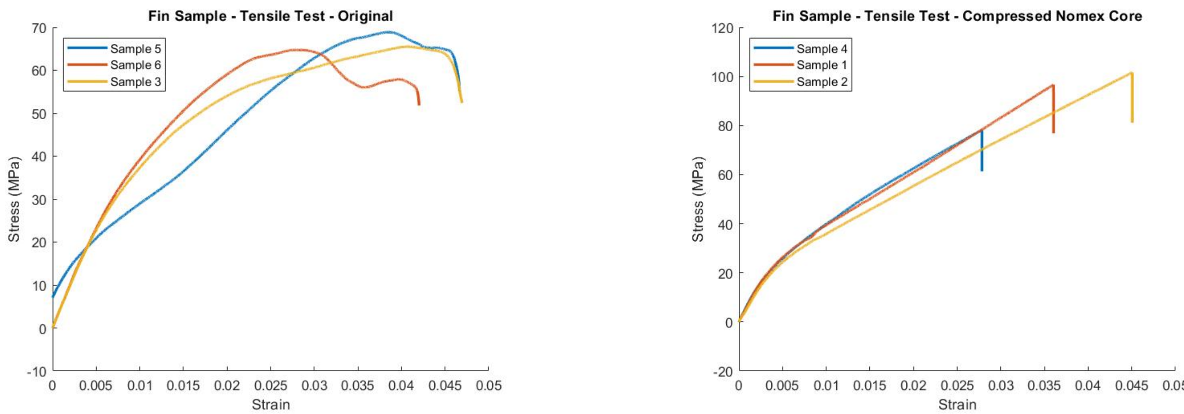


Fig. 13 Stress-strain curve results from Intron testing. Results from initial testing (left). Results after Nomex was pre-crushed (right).

Using the lowest slope result for the most conservative estimate, the E_{eff} of the fin material was determined to be 1.8 GPa. This does, however, assume the Nomex is included in the cross-sectional area. From there, the G_{eff} was calculated using equation 5 below and a conservative Poisson's ratio of 0.3.

$$G_{eff} = \frac{E_{eff}}{2(1+\nu)} \tag{5}$$

Equation 6 calculates the flutter velocity of the fins based on the known geometry and material properties of the fins as well as the estimated atmospheric properties during flight (Apogee Components).

$$V_f = a\sqrt{\frac{G_{eff}}{\frac{1.337AR^2P(\lambda+1)}{2(AR+2)(\frac{t}{c})^3}}} \tag{6}$$

With the known geometry and G_{eff} of the fins as well as the estimated flight conditions, the V_f was determined to be $1,571\ ^{ft}/_{s}$ or M1.37. With a maximum expected velocity of $901\ ^{ft}/_{s}$, this gives us a MS for flutter stability of +0.16.

E. Recovery subsystems

1. Electronics Bay

An iterative design process was used in order to design the electronics sled core. One of the primary reasons for printing the structure is that it improves the reliability of flight telemetry electronics as they are more secure. The recovery electronics are mounted on a fully 3D-printed core structure that is slid onto the four threaded rods that go down the middle of the rocket. This structure was fully CAD-designed and printed using PLA plastic. Initial mounts for the electronics were prototyped as individual pieces that could be epoxied onto a larger structure. This was later optimized to be more robust by having the entire structure printed at once. The electronics that are mounted are the EasyMini Altimeter, RRC3 Altimeter, Featherweight GPS, as well as avionics electronics supporting the SRAD telemetry which includes an Arduino Mega with an attached cape and an RFD 900x radio modem. As a redundancy measure to increase recovery reliability and comply with Spaceport requirements, two altimeter units (mentioned above) are integrated here.

An additional driving factor behind our design was space management. The electronics core has a hollow center with a magazine structure that holds the necessary batteries and can slide inside. The stack also has exit holes for the wires of the batteries in order to allow them to be recharged without disassembling the entire electronics bay. This increases the available surface area of the electronics sled, which enables future integration of more electronics. This design also improves the security of the batteries, as they are unable to move in any direction even if the internal structure were to fail under unexpected flight loads. The battery sled has a feature of cable tunnels that allow for battery recharging. Many of these design choices improve interoperability. One necessary addition for the desert environment at Spaceport America is the ease of charging the batteries to keep them at full charge before a launch. In addition, we have the GPS on a switch in order to prevent unwarranted battery drain. More details regarding wiring and electronics setup are included below.

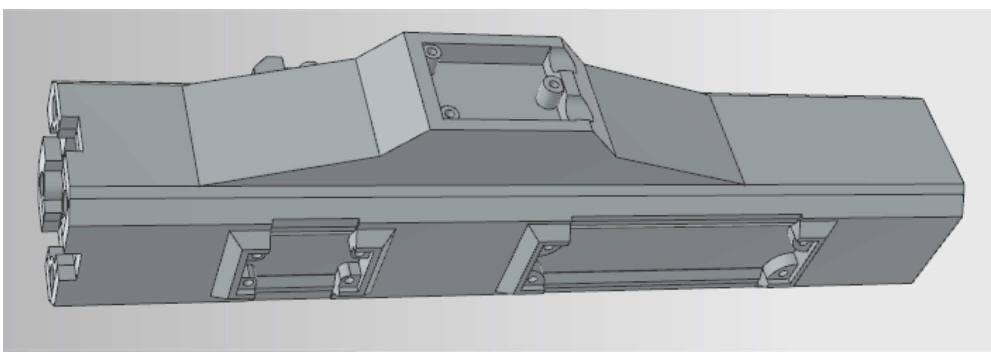


Fig. 14 Full 3D render of the sled design without electronics or battery "magazine." Visible from this angle are the two altimeter mounts (bottom), and the RFD modem with standoff ramp (top). See appendices for additional engineering drawings and dimensions.

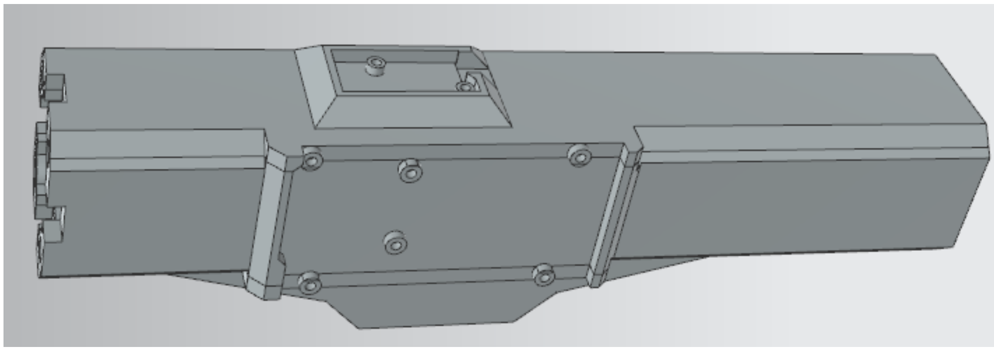


Fig. 15 Full 3D render of the sled design without electronics or battery "magazine." Visible from this angle is the Arduino Mega mount (bottom), and the COTS GPS mount (top). See appendices for additional engineering drawings and dimensions.

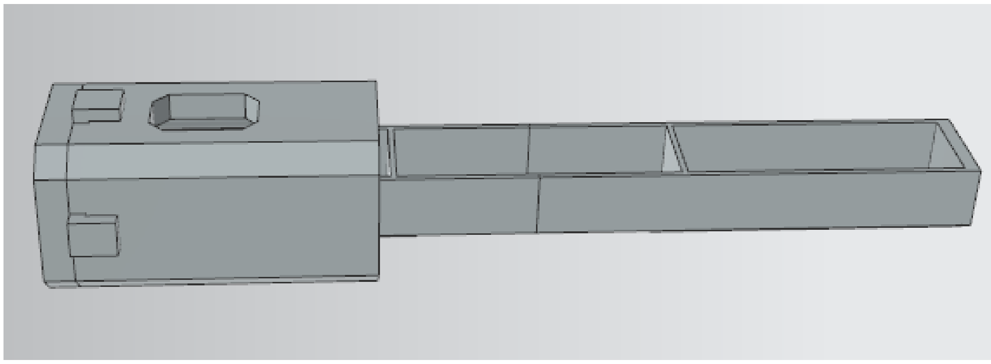


Fig. 16 Battery "magazine" mount with part of the outer sled structure for clarity. See appendices for additional engineering drawings and dimensions.

The recovery altimeters are powered by 2-cell 2000 mAh lithium polymer (LiPo) batteries. These have a higher capacity than common alkaline 9 volt batteries (9 volt alkalines are typically 500 mAh), which will drastically extend useful life in the field. The altimeter power systems are completely isolated from one another to ensure total independent redundancy. The GPS tracker is powered by a 3000 mAh 3.7 volt single cell LiPo battery, as GPS longevity is imperative for successful recovery operations. The altimeter power connections are soldered directly, which prevents the failure mode of connector separation and loss of that is possible with 9 volt batteries. The GPS battery is connected to the Featherweight GPS via a standard 3.7 volt LiPo connector, which includes clips to prevent unwanted separation. MissileWorks screw switches are installed as arming switches at the pad for both GPS and altimeter systems, and are mounted flush to the external switch band for easy access at the pad. These are connected to the altimeters with JST-type pigtail connectors, which also include a clip that prevents them from coming loose and cutting power. The electronic matches are connected to the pyro channels of the altimeters via screw terminals on the bulkheads, and all running wires are managed and relieved of strain by being glued to the electronics bay structure at appropriate intervals. This prevents wires from vibrating loose under flight loading and disconnecting a charge from an altimeter.

Redundant recovery altimeters installed in the electronics bay are a MissileWorks RRC3 (primary deployment) and an AltusMetrum EasyMini (backup deployment and scoring). These altimeters were validated via a vacuum chamber test prior to installation in the electronics bay. Powering, wiring, and switch layout are detailed above.

The COTS GPS system installed in the electronics bay is a Featherweight GPS Tracker. This operates in the unregistered 900-915 mHz frequency band. This system has been previously flight tested and is confirmed to work in our current design. The electronics bay coupler, switch band, and the surrounding airframe are fiberglass to allow for Radio Frequency (RF) transmission of GPS coordinates. Powering and switch layout are detailed above.

2. Parachutes and Recovery Hardware

The main parachute used for our design is a SkyAngle Cert-3 XL. The drogue used is a Skyangle Cert-s Drogue. This provides our rocket a descent rate of 115 ft/s under drogue and 18 ft/s under main. Apart from the ideal descent rates, these parachutes were selected based on the strong over-the-crest shroud line construction (see image), weight, and packing size, which was factored into the structural design of the rocket. The main parachute fits into its bay without excessive friction or bunching, which will ensure an ideal deployment and recovery of the rocket.

Fig. 17 Example image of SkyAngle main parachute inflation. Stole this from SkyAngle site, [1]

½" tubular kevlar is used throughout the rocket for shock cord. The drogue parachute/apogee shock cord is 50 feet in length, and the main parachute shock cord is 30 feet in length. All structural points of attachment use either forged eyebolts or U-bolts, which circumvents the issue of non-closed eyebolts opening under recovery loads and disconnecting from the recovery harness. All shock cord points of attachment utilize quick-links for easy integration of the recovery system and prevents the soft kevlar from being damaged on the rough surface of the forged eyebolts. All parachute points of attachment have barrel swivels to prevent tangling.

36" square kevlar blankets are installed to protect each parachute from the hot ejection gasses. Kevlar is heat resistant up to 800 degrees Fahrenheit and does not burn, which is ideal for use as a parachute protector. In addition to this, "dog barf" fire-resistant insulation is added to each parachute bay to further protect the recovery components and provide redundancy.

3. Ejection Testing

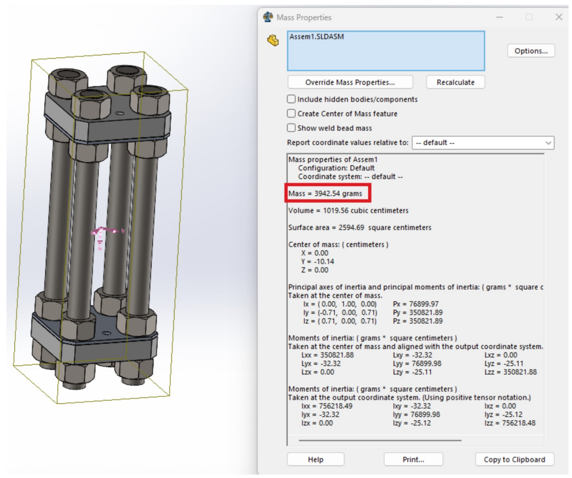
Ejection tests were repeatedly conducted to ensure ideal separation of the recovery bays. The backup charge will be oversized by 0.5 grams as a failsafe, in case flight loading renders the ground-tested amount ineffective and a stronger pressurization is needed. Electronic match connections to the pyro channels are completely isolated for each charge, and each backup event has a separate charge for complete independent redundancy. Backup events are programmed to occur after the primary event to avoid accidental overpressurization of the recovery bays (see table below for values).

Table 7

Final BP Charge Numbers	**Primary**	**Backup**
Drogue	3.5 grams (Apogee)	4 grams (Apogee + 2 seconds)
Main	1 gram (800 feet)	1.5 grams (700 feet)

F. Payload Subsystems

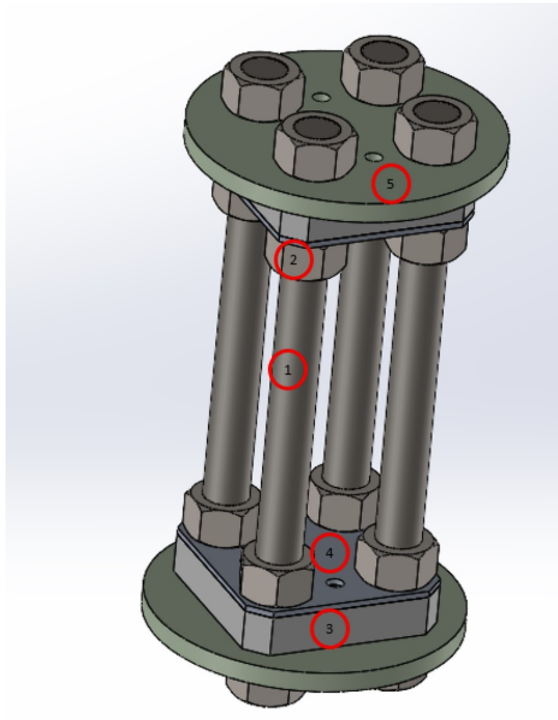
The payload for the rocket will be a standard boilerplate mass following the 3U cubesat form factor and weighing approximately 4kg. Figure 1 below shows the cubesat design as well as the simulated mass properties. The structure is made entirely from steel rods, aluminium plates, plastic (PLA:polylactic acid), and steel hex nuts.



The structure consists of four steel threaded rods which run the length of the cubesat and are supported on either end using hex nuts and plastic endcaps. These plastic endcaps are made from PLA as it allows for cheap and easy production while still being rigid enough to support the structure. Due to the potential forces the payload will experience along the threaded rods, we have opted to reinforce these endcaps with some eighth inch aluminium In order to better distribute the loads across the plastic. To secure the payload within the rocket we will be attaching fiberglass bulkheads to each endcap so that the structure fits snugly within the circular bodytubes. A total bill of materials has been included below as well as an additional figure that shows the additional bulkheads that will be secured to the endcaps.

Table 8 Payload parts list

Part number	Quantity	
7/8’ x 30cm Steel Rod		4
	1	
7/8’ Steel Hext Nut		16
	2	
Custom 3D Printed PLA Endcaps		2
	3	
Custom 1/8” aluminium endcap reinforcement		2
	4	
Custom fiberglass bulkhead		2
	5	



This structure uses a combination of purchased and custom parts. Namely, the steel rods and steel hex nuts were purchased from an online hardware store while the endcaps and fiberglass bulkheads were designed and manufactured by students. The relevant schematics for each of these has been included below. The plastic endcaps are made out of PLA using a 3d printer, the aluminium reinforcements are machined from aluminium, and the fiberglass bulkheads were made using a waterjet.

G. Avionics Subsystems

1. System Overview

The goal of the Avionics subteam is to improve upon the sophistication and capabilities of the rocket and to support team objectives. In order to accomplish this, the subteam designs, builds, tests, and integrates avionics systems into the launch vehicle to collect and transmit various flight data, support flight electronics, and assist with altitude control. Avionics' main projects this year are the Active Drag System and SRAD Telemetry.

2. Active Drag System

Due to multiple external factors affecting the rocket's flight that are outside the control of the engineers designing the rocket, including weather conditions and random differences in COTS solid motor manufacturing, Rocketry at Virginia Tech has developed a set of air brakes named the ADS. The ADS is a multi-year project designed to actuate four air brakes extruding from the side of the rocket which change the rocket's drag coefficient. The ADS becomes active after the detection of motor burnout and stays active until the rocket reaches apogee. A rendering of the ADS CAD can be seen in 18 below.

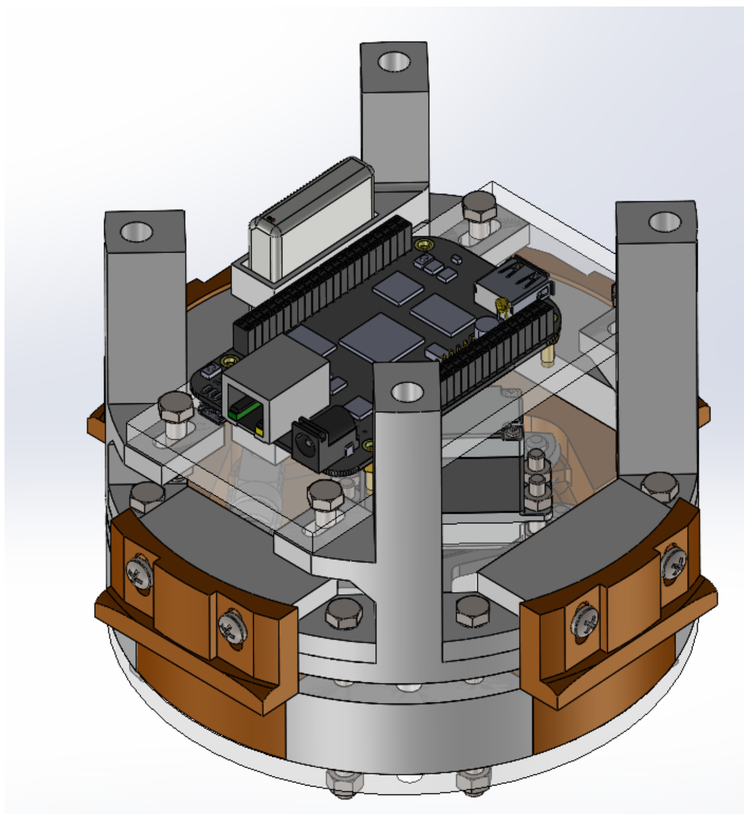


Fig. 18 CAD rendering of the ADS with fins fully actuated (left) and with fins fully closed (right)

The ADS structure consists of two sections, the fin deck, and the electronics deck. The fin deck houses the mechanism that actuates the fins, it consists of the fin spacers, fins, clevis pin, rod connector, and servo connector. Each fin is held in place by the fin spacers which have been designed with enough tolerance to allow for smooth actuation of the fins. The fins are attached to the servo motor via two clevis rod ends connected together by a stainless steel threaded rod and a 3D-printed arm that attaches to the servo motor. The mechanism is designed so that all of the fins can only actuate together and evenly out of the rocket. The fin deck is capped with two quarter inch acrylic bulkheads cut out using a water jet. These bulkheads provide a smooth flat surface for the fins to slide across when actuating.

The electronics deck houses all of the electronics and batteries that the ADS uses to operate. The main structure of the electronics deck consists of four 3D-printed support columns. These columns support an acrylic shelf that the

Beaglebone is attached to with standoffs. The columns are also designed with a battery holder and voltage converter holder. The servo motor is also housed in the electronics deck where it is connected to the acyclic bulkhead that separates the two decks by four bolts. Lastly, the electronics deck contains the 3D-printed parts that attach the fin guides to the structure of the ADS. The fin guides are fixed above the fins to help prevent the fins from bending or getting stuck when fully actuated. The fin guides are attached to the ADS structure by screws that screw into threaded inserts epoxied into the 3D-printed fin guide connectors.

The two decks are connected together with eight stainless steel bolts which keep the spacers and fin guide holders in place. An exploded view of the ADS assembly can be seen in appendix IV. The ADS is fixed inside the rocket by four threaded rods that run through the holes in the bulkheads, spacers, and columns. A capped bulkhead is bolted on top of the ADS holding it in place within the rocket.

The Avionics subteam worked alongside the Design Validation subteam to verify that the ADS can withstand the expected flight loads as well as to estimated the CD during flight at various ADS deployments.

An Ansys FEM of the ADS was generated with the relevant structural components as well as only one ADS fin to reduce computation time. With the center servo actuation arm fixed in all degrees of freedom at the center, the model accurately models the system's deflection and stress resulting from drag forces. A drag force of 25N/fin per the Computational Fluid Dynamics (CFD) results was used in the FEM as well as linear elastic materials properties. The mesh was also refined at locations that required a higher level of accuracy such as the clevis and the lug that connects the fin to the clevis. These are the two locations that were expected to have the lowest MS and therefore we decided to refine the mesh at these locations. Bonded connection types were used at threaded locations with all other connections being of the frictionless type to yield the most conservative model stiffness. Figure 19 below shows the meshed ADS with the top bulkhead removed for better visualization of the internal mesh structure.

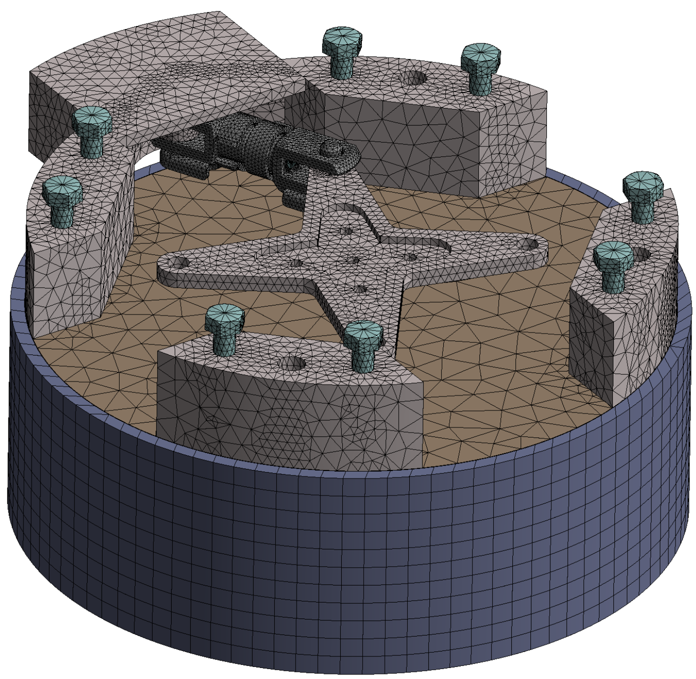


Fig. 19 Mesh of ADS with single fin and a short section of the body tube to accurately model the deflection of the fin.

Table 9 summarizes the margins of safety for the structural components during maximum drag (i.e. maximum velocity). The design FS was applied to the load itself rather than the resulting stress to account for any nonlinearities in the model stiffness. Since the system is expected to operate repeatedly during flight, it is important that MSy » 0 so the system does not permanently deform (yield) mid-flight. This occurrence could result in the mechanism locking up or result in the inability to deploy the desired amount.

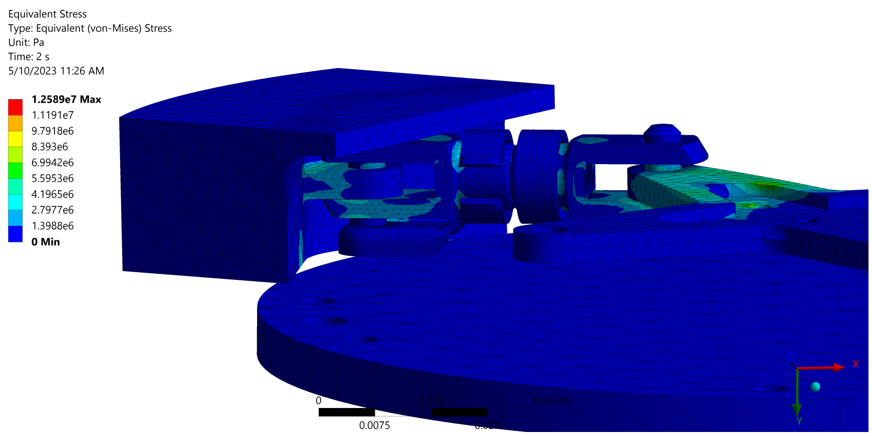


Fig. 20 Resulting von-Mises stress on clevis, fin and servo arm.

Table 9 Stress margins of ADS under maximum expected drag force.

Load Case	Component	Stress Output (Pa)		Factor of Safety		Allowables (Pa)		Margins	
		σ max Yield	σ max ult	FSy	FSu	Fty	Ftu	MSy	MSu
Max Drag Force	ADS Fin	3,968,300	5,026,500	1.5	2.0	28,000,000	40,000,000	6.06	7.96
	Clevis	11,731,000	12,589,000	1.5	2.0	248,210,000	482,630,000	20.16	38.34
	Servo Arm	9,699,400	9,285,000	1.5	2.0	28,000,000	40,000,000	1.89	4.31

3. Electronics

A combination of sensors and electronics collaborate to actively control the drag of a model rocket by deploying fins, ultimately controlling the rocket's apogee. Sensors and the actuating servo connect to the microcontroller that serves as the flight computer for the ADS.

The team selected the Beaglebone Black as the microcontroller for the ADS. The BeagleBone Black is a compact, low-cost, and powerful Linux-based single-board computer designed for use in a wide range of embedded systems and DIY projects. It is built around a Texas Instruments Sitara AM335x processor, which has a 1 GHz ARM Cortex-A8 core and supports up to 512 MB of DDR3 RAM. The BeagleBone Black has a number of onboard peripherals and interfaces, including: a 10/100 Ethernet port for network connectivity, a microSD card slot for storage and booting the operating system, 65 GPIO pins with 7 analog input pins and 4 PWM pins, and a sets of I2C interface. The Beaglebone Black also features a 4 GB eMMC onboard flash storage. The housed 1 GHz ARM Cortex-A8 processor provides ample computing power for a wide range of applications, including multimedia processing, data acquisition, and real-time control. The onboard DDR3 RAM provides fast and reliable memory access for running applications and multitasking. The Beaglebone Black accepts various powering methods. The team decided to utilize the 5V DC power barrel jack connector on board to power the Beaglebone Black.

The team selected the SunFounder High Torque 25kg Digital Servo as the actuation mechanism for the ADS fin deployment. The servo features a 25 kg/cm torque and a 180-degree rotation angle, which makes it ideal for use in applications that require high torque and precise motion control. The servo has a pulse width modulation (PWM) input signal, which can be used to control the position of the servo motor. It also includes an adjustable potentiometer for fine-tuning the motor's position and a 3-pin connector for easy wiring to a microcontroller or other control system. The servo motor is powered by a 5-7.2 V DC power supply and draws a maximum current of 1.5 A during operation. It also includes a built-in protection circuit to prevent damage from overloading, overvoltage, and overheating.

The sensor suite consists of an Internal Measurement Unit (IMU) and a barometer. The team selected BNO055 as the IMU for the ADS. The BNO055 sensor is a 9-axis sensor that measures acceleration, rotation, and magnetic fields. It provides data on the orientation and movement of the rocket. This data is used to determine the launch vehicle's zenith acceleration and attitude primarily during the flight, which is then used to determine the current coefficient of drag and other dynamical parameters for the launch vehicle. The BNO055 combines a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer, along with a built-in 32-bit ARM Cortex M0+ microcontroller. The BNO055 sensor operates under a 3.3 V DC power supply, and it consumes a maximum of 40 mA of current during operation. It also includes a power management system that allows for low-power operation modes to reduce power consumption. The BNO055 sensor provides a variety of operating modes including fusion mode, accelerometer-only mode, gyroscope-only mode, and magnetometer-only mode. The accelerometer features four different measurement ranges by user's selection. The BNO055 has the following specifications on noise levels: accelerometer noise level at 0.1 $m/s^2/Hz$, gyroscope noise level at 0.01 dps/Hz; magnetometer noise level at 0.5 T/Hz. The BNO055 sensor also includes an internal low-pass filter that can be used to reduce the noise and vibration in the accelerometer readings. The BNO055 communicates with Beaglebone Black microcontroller through I2C protocol acting as a slave device on the I2C bus on default address 0x28. The Beaglebone Black microcontroller also provides power to the BNO055 sensor via a 3.3 V DC power output port on board. For the barometer, the team selected MPL3115A2 digital barometric pressure and temperature sensor. The MPL3115A2 sensor features a microelectromechanical systems (MEMS) pressure sensor and a temperature sensor. The MPL3115A2 sensor can operate in two different modes: altimeter mode and barometer mode. In altimeter mode, the sensor measures the relative altitude of the sensor based on changes in air pressure. In barometer mode, the sensor measures the pressure of the surrounding air. The MPL3115A2 sensor measures pressure ranging from 20 to 110 kPa with an accuracy of 0.4 kPa and measures temperature ranging from -40 °C to +85 °C with an accuracy of 1 °C. The MPL3115A2 sensor operates under a voltage range from 1.95 V to 3.6 V with a low power consumption at 1.5 A in standby mode. The sensor also includes a FIFO (first-in, first-out) buffer to store up to eight pressure and temperature samples for later retrieval. The MPL3115A2 sensor has the ability of outputting 20-bit pressure and temperature data through I2C protocol to the Beaglebone Black microcontroller along with the NBO055 sensor on the default address 0x61. The Beaglebone Black microcontroller also provides power to the BNO055 sensor via a 3.3 V DC power output port on board.

In order to power the ADS, the team selected the MakerFocus 3.7 V 3000 mAh Lithium Rechargeable Battery. This battery was selected because of its high charge capacity and power. The battery is used to power all of the electronics on the ADS as well as the servo motor. The battery is first connected to a voltage booster which boosts the 3.7 V provided by the lithium battery up to 5 V. Both the Beaglebone and the servo motor are powered by 5 V so the output of the voltage booster is wired to both components. Both components share a ground so that the servo can be controlled by the Beaglebone via the PWM control signal.

4. Algorithm

The ADS algorithm is divided into two parts based on their functionality during the algorithm timeline as initialization and operation. The initialization establishes the sensor objects for both the IMU and the barometer, sends the initial PWM signal to the command servo to a preset servo position, applies a time averaged filter to the live barometer data to obtain the launch pad altitude, and sets up an unbuffered log file object.

The operation is structured around a state machine, which allows the ADS to define different stages of flight and switch between these stages based on real-time measurement. The state machine consists of each stage of a launch event: on pad idle, boost stage, coasting stage, apogee, and complete. The algorithm logs real time measurements made by the sensors and actively determines the launch vehicle's current status using this data. State changing logic uses multiple conditions and redundancies where possible to most accurately determine the current state. State change conditions are as follows: the state will change from on pad idle to boost stage if and only if the IMU senses a zenith acceleration greater than 3 g and the barometer reads an altitude at least 20 m higher than the on pad averaged altitude; from boost stage to coasting stage if the IMU senses a zenith acceleration less than 0.9 g – signaling free fall – or the time passed after boost stage first triggered is longer than 120% of the simulated time; from coasting stage to apogee if the barometer reads an altitude that is 3 m below the apogee altitude; finally, from apogee to complete if the barometer reads an altitude that is 200 m above the on pad altitude. The state changes from on pad to boost to coasting has been verified by the team from test flights.

The algorithm features several failsafe features to mitigate risk, such as fully retracting the fins to remove the ADS's aerodynamic effects on the rocket in the event of losing connection to a sensor or detecting an attitude of more than 30 degrees. In the event error produced in operation, the algorithm reports the error to the log file. The algorithm actively searches for a re-connection in the event of a sensor connection loss. Flow chart for the algorithm is shown in Figure 21.

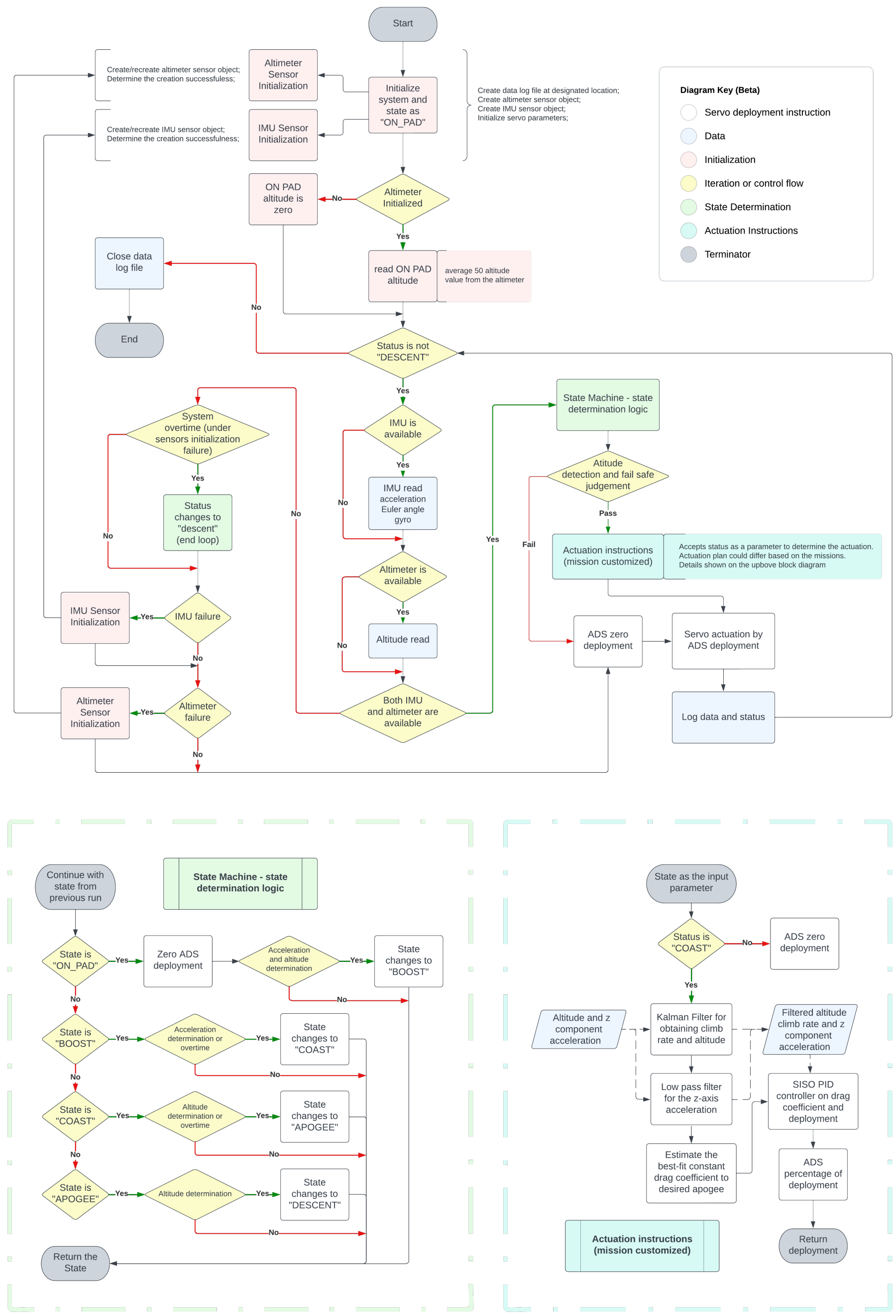


Fig. 21 ADS Algorithm Flowchart

Along with the state machine framework, the team designed the actuation instructions only available during the coasting stage for guiding the launch vehicle to a desired apogee. The team designed a two state Kalman filter based on kinematics incorporating altitude data from the barometer sensor as the measurement and the component of the acceleration in the sensor z-axis direction as the control for the climb rate. Climb rate and filtered altitude is stored by the algorithm. The team also designed a second order low pass filter on the accelerometer readings to obtain a smoothed out component of the acceleration in the sensor z-axis direction. The team developed an one dimensional dynamic model that considers the standard atmosphere environment, as defined by the U.S. Standard Atmosphere. The algorithm carries out this model for apogee determination and iterative estimates best fit drag coefficient for targeted apogee of

10000 ft. The team computes current step drag coefficient from filtered altitude and component of acceleration in the sensor z-axis direction along with fused climb rate. The difference of the estimated best fit drag coefficient and the current computed drag coefficient is given as the input for a Single Input Single Output (SISO) PID controller. The team designed the PID controller to adapt an interpolated curve correlating the simulated drag coefficient and percentage deployment of the ADS.

Design Validation worked with Avionics to set up a CFD model in order to determine the aerodynamic characteristics of the launch vehicle under the influence of ADS deployment. Since the algorithm utilizes CD to determine the necessary ADS deployment, five models were run at 0%, 25%, 50%, 75% and 100% deployment. The cylindrical domain used for the analysis is shown in Figure 22 below. Mesh refinement was used in locations that were expected to generate the most stagnation and turbulence. Areas such as the body tubes used a larger mesh size to limit the number of elements and reduce computation time. It was also important to ensure a large enough domain was utilized to fully calculate the aerodynamic effects.

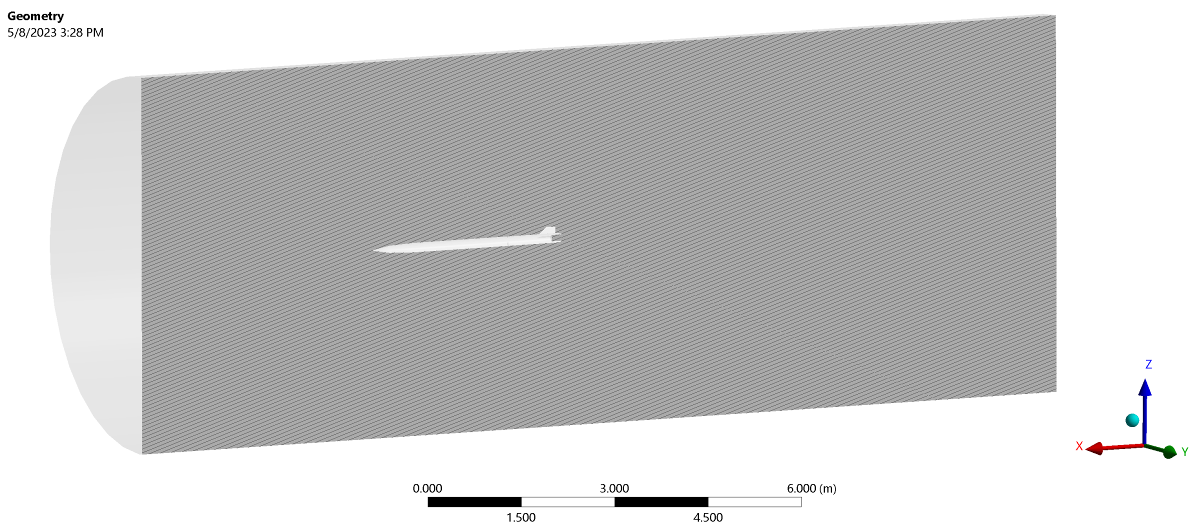


Fig. 22 Cross section of domain used in the CFD analysis.

To visualize the airflow around the ADS fins and to see the effects of the ADS on the aft rocket fins, several streamlines were plotted as shown in Figure 23. It can be seen that the air accelerates over the top of the ADS fins and then reduces as it approaches the aft fins. This is the expected result and shows little to no influence on the aft fin airflow other than velocity.

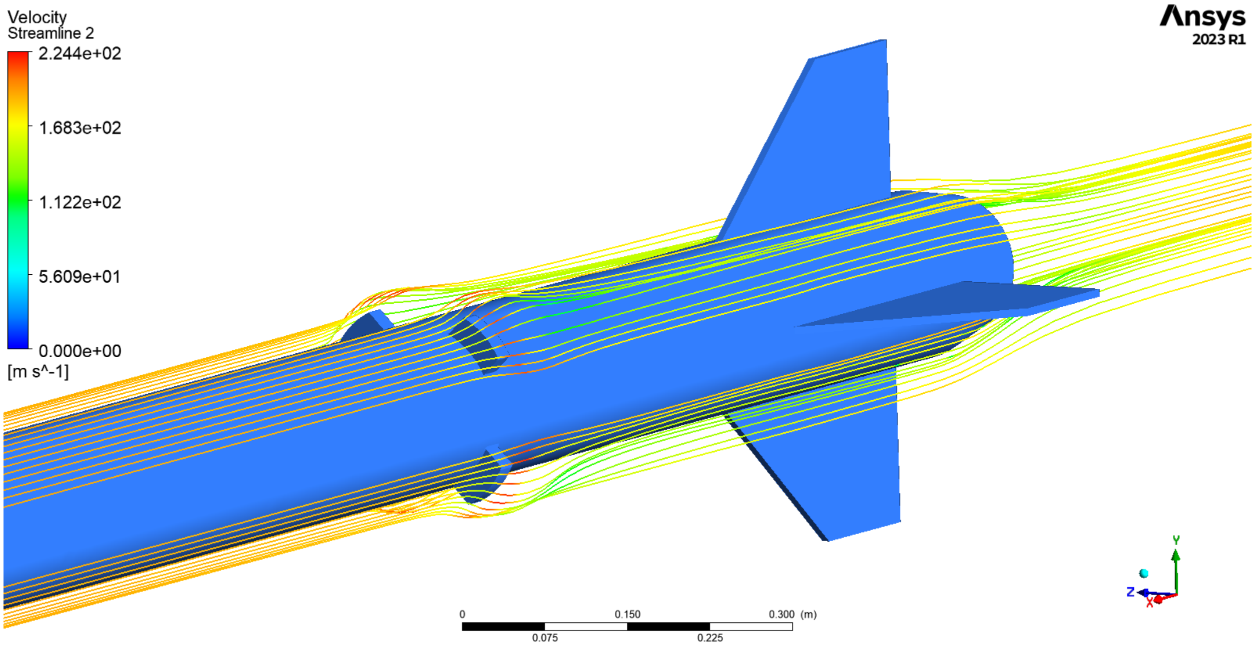


Fig. 23 200 m/s flight velocity streamlines passing over the fully deployed ADS fins.

To ensure the ADS does not negatively impact the stability of the launch vehicle, Design Validation also performed a stability study using the CFD results. The data used for this calculation was the pressure distribution over the surface of the rocket at each element. As to not skew the data with the high element density regions (refined mesh), the pressure values were segmented and averaged over 0.5 inch increments. Figure 1 depicts the pressure distribution at full ADS deployment in units of psi.

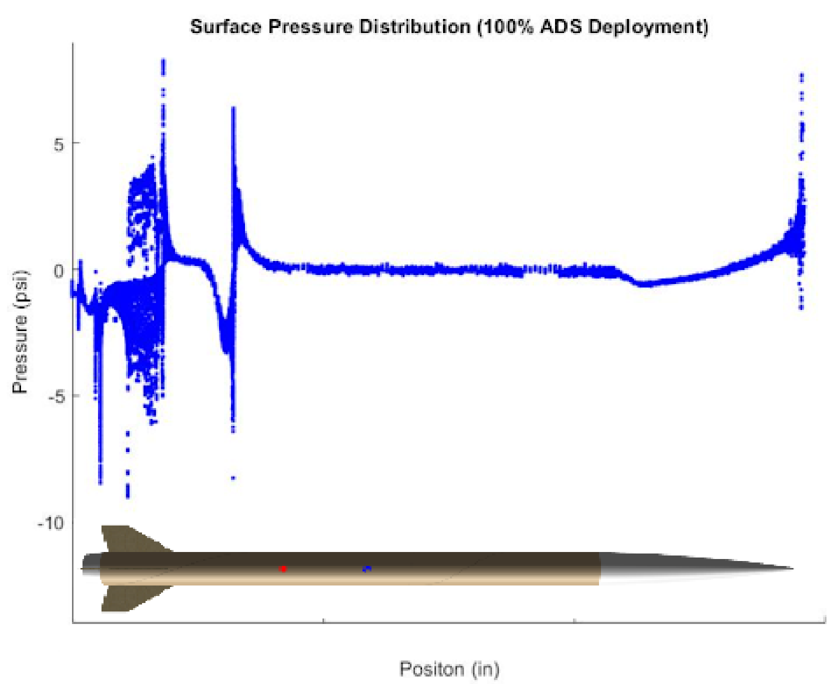


Fig. 24 Pressure distribution along the surface of the launch vehicle.

Equation 7 was used to determine the location of the C_p based on these average pressure values, p_n, and the position of the respective pressure, x_1.

$$C_p = \frac{p_1 x_1 + p_2 x_2 + \ldots + p_n x_n}{\sum_i p_i} \tag{7}$$

Table 10 includes the stability caliber at each stage of ascent based on the Center of Pressure (Cp) and Center of Gravity (Cg) locations. Since the ADS is not deployed until after burnout, the stability during burn can be interpolated between the ignition and 0% ADS deployment conditions (i.e. between 2.44 and 3.98).

Table 10 Stability of the Launch Vehicle at All Stages of Flight

Condition	Stability Caliber
Ignition	2.44
Burnout / 0% ADS deployment	3.98
25% ADS deployment	4.07
50% ADS deployment	4.17
75% ADS deployment	4.25
100% ADS deployment	4.31

After burnout, the rocket naturally increases its' stability since the reduction in motor mass results in a forward shift of the C_g. Additionally, deployment of the ADS does not result in a decrease in stability which concludes that the rocket is stable at all stages of ascent, both with and without the use of active flight control systems.

5. Telemetry

For the telemetry portion of the rocket, it is crucial that the rocket can send and receive a constant flow of data to and from the ground team. Within the telemetry/electronics bay of the rocket, there are two main systems that will be implemented into the design to complete all of our objectives.

The first system is the data obtaining system that involves both an IMU module and a GPS module hooked up to an Arduino Uno. This Arduino will be powered with a 5V lithium battery to power itself and all of the modules connected to it. Starting with the IMU, the specific part being used is the HiLetGo GY-521 MPU-6050 that is able to obtain the rocket's pitch, yaw, and roll data in real time and send it to the ground team. The module is also fitted with an accelerometer within it so we can also calculate the rocket's acceleration and current velocity. The IMU will be hooked up to the Arduino Uno via I2C communications. Looking at the GPS module, the specific part used is the Adafruit Ultimate GPS Breakout 66. This GPS's main task is to send the coordinates and location of the rocket during and after the launch of the rocket, allowing for the tracking of location during flight and to help with the recovery of the Avionics Bay. The GPS will let the ground team understand whether or not the rocket is performing nominally and will give a general estimate to the rocket's current altitude with the altimeter. The GPS will also be connected to the Arduino Uno, however it is connected through UART communication, utilizing the RX and TX pins. It should be noted that the GPS will send the coordinate and location data using NMEA sentences, allowing for as accurate data as possible.

The second system onboard the telemetry system is the communication system that does the actual data transfer between the onboard systems and the ground team. The electronic being used is the RFD900+ Telemetry Modem. By utilizing the 905MHz-928MHz range, we can perform long range serial communication to send the data being received from the IMU and GPS modems in real time The RFD900+ is located within an RF transparent section of the rocket, allowing for clean and clear transfers of data. The modem is also connected to the Arduino by another set of RX and TX pins, using UART communication.

In total, everything is connected tightly packed on a custom created, 3D printed electronics bay that resides within the body tube of the rocket. The GPS and IMU are connected by a protoboard shield that will reside on top of the Arduino UNO with pins being connected to multiple ports of the Arduino making it multi-functional and very compact. Overall, the telemetry system of the rocket allows the rocket to send and receive crucial data needed to operate and to test, helping the health and future of the rocket and this team.

IV. Conclusion

For the 2023 Spaceport America Cup in the 10k COTS category, Rocketry at Virginia Tech has designed and manufactured a launch vehicle that features a precision altitude control active drag system and a fully SRAD carbon fiber composite airframe. In the process of designing one of the team's most complex projects to date, Rocketry at Virginia Tech aimed to improve on past iterations of subsystems as well as lay the groundwork for future team members to expand on these same subsystems.

The team was able to learn from many failures this year within several different sub-teams. The aerostructures team obtained practice manufacturing SRAD body tubes in a variety of different ways in order to learn which technique would be most suitable for future rockets. The avionics team was able successfully complete the Active Drag System, which will most likely be utilized and perfected by the team in the coming years. The recovery team was able to experiment and learn how to deploy both the main and drogue parachutes from one separation point, and the propulsion team continued their research into a hybrid rocket motor for future competitions.

Rocketry at Virginia Tech's 2022-2023 leadership team is the youngest it has ever been since the team's initial formation in 2015, and with that came a diligent effort not only to thoroughly understand previous design decisions, but also to continue developing these projects for future generations on the team. With the help of the team's university mentors and generous alumni network, the team was able to construct one of its most ambitious project to date and looks forward to pushing the envelope in the future.

Going forward, the team seeks to continue improving our manufacturing, design, and analysis to do more than just build a high-powered rocket, but also to expose our members to industry standard engineering practices by giving them the opportunity to apply what they've learned in the classroom to one of Virginia Tech's most complex student researched and designed engineering projects.

Appendix A: System Requirements

S.5. PROPULSION SYSTEMS

- S.5.1. Commercial of The Shelf Motors (COTS) is defined as a motor that has been certified by both the Tripoli and NAR associations.

S.8. JOINTS IMPLEMENTING COUPLING TUBES

- S.8.5. Airframe joints which implement "coupling tubes" should be designed such that the coupling tube extends no less than one body tube caliber on either side of the joint – measured from the separation plane.
  - S.8.5.1. Regardless of implementation (e.g., RADAX or other join types) airframe joints shall be "stiff" (i.e., prevent bending).
  - S.8.5.2. It is up to the team to demonstrate that joints are sufficiently stiff.
  - S.8.5.3. Note: this applies specifically to airframe joints using a piece of coupling tube to join airframe sections. Nose cone and boat tail "shoulders" shall be no less than 0.5 body tube caliber in length.

S.10. LAUNCH AND ASCENT TRAJECTORY REQUIREMENTS

- S.10.1. Launch vehicles shall nominally launch at an elevation angle of 84°±1° and a launch azimuth defined by competition officials at the IREC.
  - S.10.1.1. Range Safety Officers reserve the right to require certain vehicles' launch elevation be lower if possible flight safety issues are identified during pre-launch activities.
  - S.10.1.2. Competition officials may allow staged flights to launch at 87°+1° if the rocket is using "tilt" to inhibit air-start motor ignition.
- S.10.2. Launch vehicles shall have sufficient velocity upon departing the launch rail to assure they will follow predictable flight paths.
  - S.10.2.1. A rail departure velocity of at least 100 ft/s (30.5 m/s) is generally acceptable.
  - S.10.2.2. Teams unable to meet this velocity requirement may use detailed analysis to prove stability is achieved at a lower rail departure velocity (greater than 50 ft/s [15.24 m/s]), preferably via flight testing. Alternatively, computer simulation can be used, but must evaluate stability under a variety of launch conditions — a single simulation run is not sufficient.
  - S.10.2.3. Teams shall comply with all rules, regulations and best practices imposed by the authorities at their chosen test location(s).
  - S.10.2.4. Departing the launch rail is defined as the first instant in which the launch vehicle becomes free to move about the pitch, yaw, or roll axis.
  - S.10.2.5. This generally occurs at the instant the last rail guide forward of the vehicle's center of gravity (CG) separates from the launch rail. Accordingly, teams should adjust the rail length in their simulation to account for the location of this rail guide (e.g., if the last rail guide forward of the center of gravity is 3 ft from the bottom of the 17 ft rail, then effective rail length is 14 feet)
  - S.10.2.6. Note that ESRA will provide teams with launch rails measuring 17 ft (5.2 m) in length.
  - S.10.2.7. Teams whose designs anticipate requiring a longer launch rail to achieve stability during launch must provide their own.
- S.10.3. Launch vehicles shall remain "stable" for the entire ascent.
  - S.10.3.1. Stable is defined as maintaining a static margin of at least 1.5 to 2 body calibers, regardless of CG movement due to depleting consumables and shifting center of pressure (CP) location due to wave drag effects (which may become significant as low as 0.5 M).
  - S.10.3.2. Stability shall not fall below 1.5 body calibers to be considered nominal, while falling below 1.5 body calibers will be considered a loss of stability.
- S.10.4. Launch vehicles shall not be "over-stable" during their ascent.
  - S.10.4.1. A launch vehicle may be considered over-stable when it has a static marginsignificantly greater than 2 body calibers (e.g., greater than 6 body calibers at liftoff
  - S.10.4.2. Over-stable rockets are particularly vulnerable to crosswind or wind shear effects, which often occur in New Mexico.

Appendix B: System Weights, Measures, and Performance Data

Table 11 Basic Rocket Information

Stages	1
Length	10 ft 8 in
Airframe Diameter	6.17 in
number of fins	4
fin Semi-span	5in
Fin Tip	5in
Root Cord	12 in
Fin Thickness	.275
Vehicle Weight	1051 oz
Propellant Weight	5,719 g
Motor Case Empty Weight	72oz
Structure Weight	734oz
Payload Weight	141oz
liftoff weight	1051oz
Center of Pressure	93.144in
Center of Gravity	78.357in

Table 12 COTS Aerotech M1939W Characteristics

Characteristic	Quantity
Manufacturer	Aerotech
Designation	M1939W
Diameter	98mm
Length	732 mm
Total Weight	8988g
Prop Weight	5,719 g
Avg Thrust	1939.0 N
Initial Thrust	1,744.7 N
Max. Thrust	2,429.7 N
Total Impulse	10,481.5 Ns
Burn Time	6.2s
Isp	187s
Motor Case	RMS-98/10240
Propellant	White Lightening

Table 13 COTS altimeters and specifications

Alimeter	Manufacturer	Model	Charges Controlled (See Parachute Table for sizing)	Used for scoring?
Primary	MissileWorks	RRC3	Primary Drogue, Primary Main	No
Backup	Altus Metrum	EasyMini	Backup Drogue, Backup Main	Yes

Table 14 COTS parachutes and specifications

Parachute Data	Type	Black Powder Charges (primary, Backup)	Deployment Altitude (primary, backup)	Descent Rate
Drogue	Skyangle C-3 Drogue	3.5, 4 grams	apogee (10,000 ft), Apogee +2 seconds	115 ft/s
Main	Skyangle C-3 XL	1, 1.5 grams	800 ft, 700 ft	18 ft/second

Table 15 Shock Cord and Linkages

Shock Cord + POA Data	Type	Test Strength	Length	Supplier	Knots Used	POA Hardware
Drogue	½” Tubular Kevlar	7800 lb	50 ft	Chris Rocket Supply	2x Bowline (attachment ends)	2x ½” Quick Link
Main	½” Tubular Kevlar	7800 lb	30 ft	Chris Rocket Supply	2x Bowline (attachment ends)	2x ½” Quick Link

Appendix C: Project Test Reports

PAGE INTENTIONALLY LEFT BLANK

2022 - 2023 Rocketry at Virginia Tech Testing Form

Before submitting for approval, please fill out all of the text boxes below in the test information section. Upon the completion, submit by emailing the form to hannak@vt.edu. Feel free to attach any additional documentation that is critical to testing procedure. After submission, the test plan will be reviewed by the Rocketry at Virginia Tech Captain for approval. Upon approval, the test supervisor will be notified and the testing can commence. Conducting testing without captain approval may result in dismissal from the team. Please note that depending on the test further cooperation may be required with Rocketry at Virginia Tech leads and college of engineering faculty. Upon completion of the test, fill out the data and results documentation text box, attach any additional test results, and upload a finalized copy to the testing form folder in the team shared Google Drive.

What testing requires submission of this form and what testing requires further action after submission?

Testing of critical flight systems (i.e. flight systems such that if they fail the launch vehicle will also fail) requires submission of this form. Examples of this include airframe stress testing, propulsion system testing, active drag flap stress testing, fin flutter or stress testing, recovery systems testing, ect. In addition, any testing that requires university equipment, or has significant safety concerns require submission of this form. Examples include any tests that require a shaker table, compression testing machine, or use of hazardous chemicals (such as nitrous oxide or black powder). Any testing that requires private contractors (such as hydro-testing with an independent firm) also requires submission of this form. Testing that does NOT require submission of this form includes testing of non-critical flight systems that have no safety concerns associated with testing, compilation tests of software, or tests of prototypes that will be significantly altered before final integration into the launch vehicle do not require submission of this form. Examples include testing a rough prototype of active drag flap deployment that will be rebuilt, prototype software tests, prototype actuator tests, ect. If unsure whether or not the test you want to conduct requires submission of this form, please contact the Rocketry at Virginia Tech captain at hannak@vt.edu or on Microsoft Teams.

Test Information

Test Supervisor: Gabe Mills

Test Name: Test Flight 2

Test Date: 4/15/2023

Test Location: Dalzell, South Carolina

Test Objective: Flight testing Active Drag System (ADS) to confirm deployment after burnout stage.

Test Description:

This test occurred during the team's final test launch before the Spaceport America Cup competition. As per the guidelines provided by the competition, it was necessary to ensure that the ADS did not deploy before the burnout of the motor. In order to determine this, a camera was placed on board the rocket.

Data and Results Documentation

Successfully confirmed ADS deployment occurred after motor burnout. Collected video of ADS deployment during flight. Were unable to obtain on-board data from ADS.

2022 - 2023 Rocketry at Virginia Tech Testing Form

Before submitting for approval, please fill out all of the text boxes below in the test information section. Upon the completion, submit by emailing the form to hannak@vt.edu. Feel free to attach any additional documentation that is critical to testing procedure. After submission, the test plan will be reviewed by the Rocketry at Virginia Tech Captain for approval. Upon approval, the test supervisor will be notified and the testing can commence. Conducting testing without captain approval may result in dismissal from the team. Please note that depending on the test further cooperation may be required with Rocketry at Virginia Tech leads and college of engineering faculty. Upon completion of the test, fill out the data and results documentation text box, attach any additional test results, and upload a finalized copy to the testing form folder in the team shared Google Drive.

What testing requires submission of this form and what testing requires further action after submission?

Testing of critical flight systems (i.e. flight systems such that if they fail the launch vehicle will also fail) requires submission of this form. Examples of this include airframe stress testing, propulsion system testing, active drag flap stress testing, fin flutter or stress testing, recovery systems testing, ect. In addition, any testing that requires university equipment, or has significant safety concerns require submission of this form. Examples include any tests that require a shaker table, compression testing machine, or use of hazardous chemicals (such as nitrous oxide or black powder). Any testing that requires private contractors (such as hydro-testing with an independent firm) also requires submission of this form. Testing that does NOT require submission of this form includes testing of non-critical flight systems that have no safety concerns associated with testing, compilation tests of software, or tests of prototypes that will be significantly altered before final integration into the launch vehicle do not require submission of this form. Examples include testing a rough prototype of active drag flap deployment that will be rebuilt, prototype software tests, prototype actuator tests, ect. If unsure whether or not the test you want to conduct requires submission of this form, please contact the Rocketry at Virginia Tech captain at hannak@vt.edu or on Microsoft Teams.

Test Information

Test Supervisor: Gabe Mills

Test Name: Recovery Ejection test

Test Date: 5/4/2023

Test Location: Blacksburg, Virginia

Test Objective:

Demonstrate separation of rocket sections for recovery deployment.

Test Description:

The purpose of this test was to ground test the separation of rocket section in order for the recovery system to be deployed during flight. This was tested at points where both the main parachute and the drogue chute would be deployed from.

Data and Results Documentation

Both separation points detached from the rest of the rocket successfully. For the main parachute's separation point, 1 gram of black powder charge was used as the primary fuse, and 1.5 grams were used as the backup. For the drogue chute's separation point, 3.5 grams of black powder charge were used as the primary fuse, and 4 grams were used as the backup.

Appendix D: Hazard Analysis

Hazard	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
Black powder	Mishandling of rocket before flight/poor arming procedures	Medium Risk Black powder charges pose a significant risk to personnel if mishandled. Poorly planned ejection tests also have the potential to damage flight vehicle.	Proper distancing from BP tests	Low Risk
	Poor ground test procedures		Arm deployment electronics for flight on pad, not before	
			Utilize proper switches for electronics (screw switches or similar device)	
LiPo battery burn/fire	Shorting battery terminals	Medium Risk Lithium-Polymer batteries are used frequently, so they pose a significant risk to team personnel if mishandled	Instruct team members of correct handling of LiPo batteries	Low Risk
	Dropping/Cutting/Crushing batteries		Use different types of batteries where it is advantageous to do so	
Falling rockets	Recovery system failure	High Risk Ballistic descent could have a catastrophic effect on the flight vehicle and poses an extreme risk to personnel and property.	Follow SRR guidelines to make recovery system as robust as possible	Low Risk
	Public rocket launches		Instruct team members on proper launch day etiquette (point to descending rockets, give verbal warnings, etc.)	
Unstable flight; could cause unpredictable trajectory, endangering personnel	Improperly sized fins	Medium; Occurs if improper analysis and testing are done beforehand or if improperly integrated	Test fin assembly to point of yielding and/or failure	Low
	Loss of fins		Simulate fin flutter and size fins to avoid resonance	
	Rail button failure		Calculate maximum loading on rail buttons to ensure safety factor	
Motor failing to be restrained inside the vehicle; could cause unrestrained motor to fly towards	Thrust plate failing/ yielding	High; loading from thrust is hard to determine analytically in each component of the	FEA simulation to verify safety factor >2	Medium
	Bolts responsible for restraining thrust		Compression testing the internal structure/	

<table>
<tr><td rowspan="2">people</td><td>plate fail in shear</td><td rowspan="2">rocket, leading to some uncertainty in the factor of safety</td><td rowspan="2">airframe assembly to yield/failure</td><td rowspan="2"></td></tr>
<tr><td>Bearing stress on aluminum channels deforms holes</td></tr>
<tr><td rowspan="2">Recovery system fails</td><td>Parachute/foil get damaged during ejection, Payload descends at terminal velocity</td><td rowspan="2">Low; CO2 is unlikely to damage parachute
Medium; Depending on placement could get caught between payload and wall</td><td>The payload alignment bulkheads shield the parachute</td><td rowspan="2">Low</td></tr>
<tr><td>Parachute/foil gets caught on hardware during ejection
Payload descends at terminal velocity</td><td>Insulating the parachute with dog barf</td></tr>
<tr><td>Ejection system goes off at the wrong time</td><td>Circuit breaks during handling
Payload misfires and harms personnel</td><td>Medium; Could happen while loading the top section of the rocket</td><td>Arming switch so that the system isn’t armed until rocket is ready for launch</td><td>Low</td></tr>
</table>

Appendix E: Risk Assessment

Risk	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
GPS/Health Monitor system malfunction	Loss of satellite connection	Medium Risk Consequences could include failure to locate rocket after landing which would mean a total loss of flight vehicle	Integrated and non-integrated test of GPS hardware to find and document limitations in range	Low Risk
	Loss of power		Use shake table and pressure testing to ensure batteries and wiring are secure	
	Interrupted RF signal to ground station			
Altimeter malfunction	Loss of power	Medium Risk Consequences could include failure to deploy parachute which could cause ballistic descent, which can be catastrophic to the flight vehicle as well as dangerous to personnel	Follow all manufacturer guidelines on powering and static port sizing/placement	Low Risk
	Poor static port hole placement/sizing		Use shake table and pressure testing to ensure batteries and wiring are secure	
Parachute/recovery harness tangling	Poor folding	Medium Risk Parachute tangling could be dangerous to flight vehicle as higher descent rates mean higher probability of damage to rocket upon landing. Higher descent rates also pose a risk to personnel.	Instruct all members on proper parachute folding	Low Risk
	Ejection charge malfunction		Use ejection charge tests to ensure parachute is completely deployed from airframe	
Unstable flight; could cause unpredictable trajectory, endangering the launch vehicle	Improperly sized fins	Medium; Occurs if improper analysis and testing are done beforehand or if improperly integrated.	Test fin assembly to point of yielding and/or failure	Low
	Loss of fin(s)		Simulate fin flutter and size fins to avoid resonance	
	Rail button failure		Calculate maximum loading on rail buttons to ensure safety factor	
Motor failing to be	Thrust plate	High; Loading from	FEA Simulation to verify	Medium

restrained inside airframe	failure/yielding under normal load	thrust is hard to determine analytically in each component of the rocket, leading to some uncertainty in the factor of safety.	safety factor >2	
	Bolts responsible for restraining thrust plate fail in shear		Compression testing the internal structure/airframe assembly to yield/failure	
Yielding of internal structure	Actual max stress > expected max stress	Medium; Occurs if improper analysis and testing are done beforehand or if improperly integrated.	Bulkheads prevent aluminum from buckling to the point of structural failure	Low
Premature drag separation	Pressure differential between chute bay and free stream	Low	Calculating the max pressure differential and required shear pins to prevent separation	Low
Errors in Active Drag System structural analysis	Imperfect drag force load conditions used in simulations	Medium - Unsymmetric failure of ADS may result in instability during flight.	Determine there is a safety factor of at least 2 (TBR)	Low
	Internal Forces (i.e. friction, etc.) are ignored		Physical testing performed by Avionics subteam	
	Material properties do not align with the actual materials used in the system (especially non-isotropic materials)		Design ADS such that unsymmetric failure is unlikely	
Incorrect Stability Calculations	Component layout experiences significant changes	Medium - Pressure distributions on a rocket vary depending on angle of attack and trajectory. Simulations may not be able to account for these flight activities. Also, CG is likely to move as development progresses. This may result in unstable flight.	Results compared with Open Rocket and other softwares	Low
Active Drag System structural failure	Inaccurate results determined from	Low - ADS will not deploy until after	Avionics will perform testing on the system	Low

	FEA simulations Flight Loads not properly implemented into simulations	burnout (high altitude), so launch vehicle should be at a safe distance from personnel. Also, launch vehicle should be stable without ADS. A failure could result in unstable flight and difficulties with recovery.	 Safety factor determined to be greater than 2	
Instability of the LV during ascent	ADS deployment failure Inaccurate stability caliper calculations Damage to fins or other external components	Medium - Personnel will be at a safe distance from the launch pad. Also, the likelihood of the LV heading towards people is relatively low	Personnel will be far from launch pad CFD will be performed to verify stability at all stages of ascent Stability caliper will be verified using multiple methods	Low
Lithium batteries are damaged or shorted	Batteries are not properly handled Batteries are not properly mounted Batteries are not properly stored	Medium: Damaged or shorted lithium batteries could combust and harm directly harm personnel or destroy other parts of the vehicle structure which could become harmful debris, posing a danger to personnel.	Training all team members in battery handling Ensuring mounted power supplies and connections are secure	Low
RF telemetry link is broken	Power failure with electronics RF equipment gets damaged The rocket structure blocks RF signals	Medium: A failure to establish and hold an RF link would result in failure of the SRAD telemetry and GPS system and would result in losing all data is is not logged onboard the electronics and recovered. A GPS failure would also force complete reliance on the COTS GPS's for recovery.	Perform telemetry range tests Test the efficacy of RF transparent sections of the rocket after the launch vehicle is fully assembled	Low
ADS structure or	ADS is not properly	High: A collapsing	Iteratively running	Low

deployment fails during flight	integrated	ADS structure could produce damaging debris during flight. Additionally, uneven deploy of fins would produce uneven drag and could rapidly change the trajectory of the rocket.	integrated, simulated, and flight tests	
	ADS structure is weak		Ensuring proper algorithm safe guards	
	ADS is poorly manufactured		Ensure quality manufacturing standards are met	

Appendix F: Assembly, Preflight, Launch, and Recovery Checklists

PAGE INTENTIONALLY LEFT BLANK

Launch Location: Spaceport America, New Mexico **Launch Date:** 6/21 - 6/24

Flyer of Record: Bob Schoner

Pre-Flight Field Assembly

Avionics Checks

Action	Executor Initials	Witness Initials
☐ Check ADS algorithm settings to see if they align with launch site conditions.		
☐ Tug test all wires, if fail, see item 1		
☐ Check ADS structure		
☐ Confirm DC Voltage to be 3.7 V. if fail see item 2		
☐ Place Battery in vertical pocket		
☐ Connect Battery to boost converter		
☐ Check converter remains off		
☐ Tug test all connection points if fail see item 1		
☐ Align ADS with arming access hole		
☐ Insert ADS into the booster section of the rocket		
☐ Confirm ADS fin slots are unobstructed if fail see item 3		
☐ Attatch ADS guides		
☐ Check ADS and guides secured it fail see item 3		
☐ Secure 4 lock nuts on ADS alignment rods		
☐ Insert Aft drogue Parachute bulkhead		
☐ Secure 4 washers and 4 lock nuts on ADS alignment rods, on top of bulkhead		
☐ Apply locktite to the ADS mounts.		

Payload Checks

Action	Executor Initials	Witness Initials
☐ Weigh payload, must be greater then 8.8lbs		
☐ Thread a Nut onto the nose cone tip and threaded rod		
☐ Insert threaded rod onto forward bulkhead		
☐ Secure bulkhead in place with second nut		
☐ Tighten both nuts into place, test for bulkhead security on threaded rods		
☐ Insert threaded rod into the nose cone, secure nose con tip on the threaded rod		

Electronics Bay Checks

Action	Executor Initials	Witness Initials
☐ Check Battery voltages, must be 8.2 V if fail see item 2		
☐ Tug test all wires if fail see item 1		
☐ Attach switch pigtails		
☐ Check wire holes are properly sealed		
☐ Attach bulkheads to either side of the assembly		
☐ Secure bulkheads in place with nuts		
☐ Secure Purple wire to apogee charge		
☐ Secure Blue wire to main charge		
☐ Check wire holes are secured if fail see item 3		
☐ Attach ematches to screw terminals		
☐ Measure out main black powder charges,Primary charge 1g, backup 1.5g		
☐ Place charges into main wells, upper bulkhead		
☐ Cover charge wells in blue tape		
☐ Measure out Drogue black powder charges, Primary 4g, back up 4.5g		
☐ Place drogue black powder charges in drogue wells, lower bulkhead		
☐ Cover charge wells in blue tape		

Lower Section Assembly

Action	Executor Initials	Witness Initials
☐ Attach recovery quick links to shock cord, chute, and protector		
☐ Attach long end of shock cord to ADS upper bulkhead		
☐ Attach middle quick link to drogue		
☐ Attach final quick link to lower electronics bay bulkhead		
☐ Fold drogue		
☐ Cover drogue in chute protector		
☐ Add dog barf to booster section		
☐Insert Drogue, chute protector, and shock cord into booster section		
☐ Secure Electronics bay on top of booster section if fail see item 3		
☐ Secure 4 shear pins in place		
☐ Connect quick links to main shock cord and chute, and protector		
☐ Connect quick links to Electronics bay, and nose cone		
☐ Fold Main chute		
☐ Cover Main with chute Protector		
☐ Insert chute into upper body tube, Chute protector facing towards body of the tube, funneling shock cord with it		
☐ Add dog barf below chutes in the tube		
☐ Slide upper body tube ontop of the electronics bay		
☐ Attach 6 rivets to secure body tube in place		
☐ Slide nose cone onto top of upper body tube, secure with 8 shear pins if fail see item 3		

Launch Pad Preparations

Action	Executor Initials	Witness Initials
☐ Weigh the dry mass of the launch vehicle and record dry mass CG.		
☐ Remove motor retainer cap.		
☐ Insert motor into the rocket.		
☐ Screw motor retainer cap back on.		
☐ Weigh the fully integrated launch vehicle.		
☐ Update OpenRocket numbers. if fail see item 4		
☐ Mark vehicle CG and CP.		
☐ Record final off the rail velocities.		
☐ Notify RSO of preparation for inspection.		
☐ Tape motor ignitor to the outside of the rocket.		
☐ Engage walkie talkies between launch crew and bystander crew.		
☐ Alert RSO's of impending move to launch rail.		

CG$_{dry}$ __________ **CG**$_{wet}$ __________ **CP** __________

Leadership Approval Signatures

By signing this document, you verify that to the extent of your knowledge this launch vehicle has been assembled and prepared following the exact steps of this checklist. Any deviation from the procedure in this document or any belief that this launch vehicle is unsafe or unprepared for flight should result in a refusal to sign. A missing signature from any of the following individuals will halt operations and the test flight will not proceed.

Approved: ______________________________

Hanna Kruse
Captain

Approved: ______________________________

Ben Piper
Aerostructures Lead

Approved: ______________________________

Ben Anderson
Avionics Lead

Approved: ______________________________

Gabe Mills
Recovery Lead

Approved: ______________________________

Demetra Kohart
Safety Officer

Approved: ______________________________

Bob Schoner
Flyer of Record

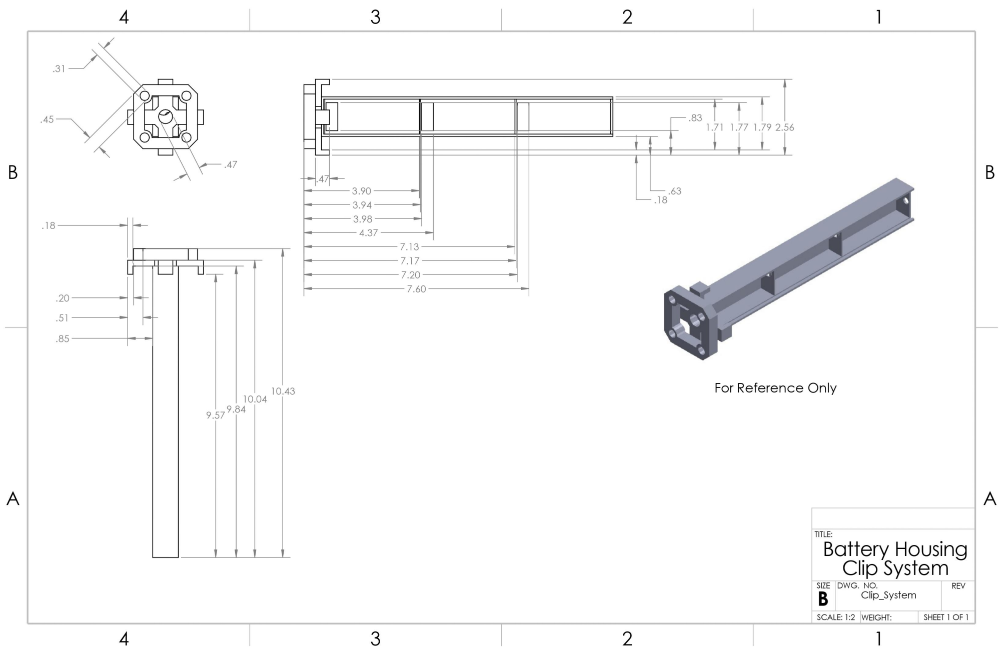
On Launch Pad

Action	Executor Initials	Witness Initials
☐ Ensure pad is disarmed. **		
☐ Clear movement to rail with RSOs.		
☐ 3x people carry the vehicle to the launch rail, 1x additional for support and communications.		
☐ Discontinuity check of igniter leads (DO AWAY FROM VEHICLE).if fail see item 5		
☐ Lay launch rail horizontal, align rail buttons.		
☐ Insert rail buttons on launch rail and move vehicle to base of rail.		
☐ Press camera button.		
☐ Arm the ADS **		
☐ Move rocket into the vertical launch position.		
☐ Arm primary screw switch (RRC3).		
☐ Arm secondary screw switch (easy mini).		
☐ Insert motor igniter.		
☐ Clear launch pad and return to launch control.		
☐ Ensure pad is clear, skies are blue, wind is low.		

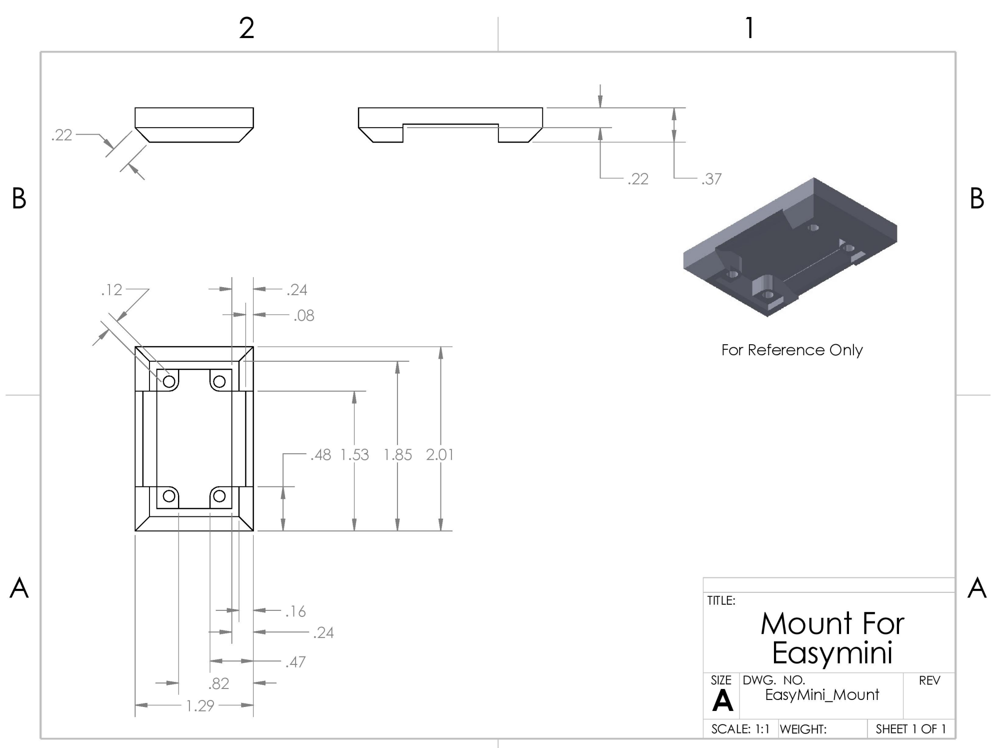
Emergency Procedures

1. Failed tug test
   (a) Identify loose wires and connections
   (b) Locate where they are supposed to be attached
   (c) Solder wires where needed
   (d) Secure wires in place
   (e) Tug test again
   (f) If continued failure in tug test
   (g) Scrub launch
2. Failed voltage checks
   (a) Identify failed batter
   (b) Charge the battery for 15 minutes
   (c) Check charge again
   (d) If charge increased continue charging until at required voltage
   (e) If charge has not changed then repeat 2x
   (f) Continued failure to charge, scrub launch
3. Failed securing system
   (a) Identify a possible fix
   (b) Attempt general fix
   (c) If fix fails repeat with new fix
   (d) Repeated failure to secure a system, scrub launch
4. Update open rocket
   (a) If numbers on open rocket are unacceptably different
   (b) Identify if flight essential systems meet ESRA requirements
   (c) If not no launch
   (d) If they do continue checklist
5. Pad not disarmed
   (a) Disarm pad
   (b) continue checklist

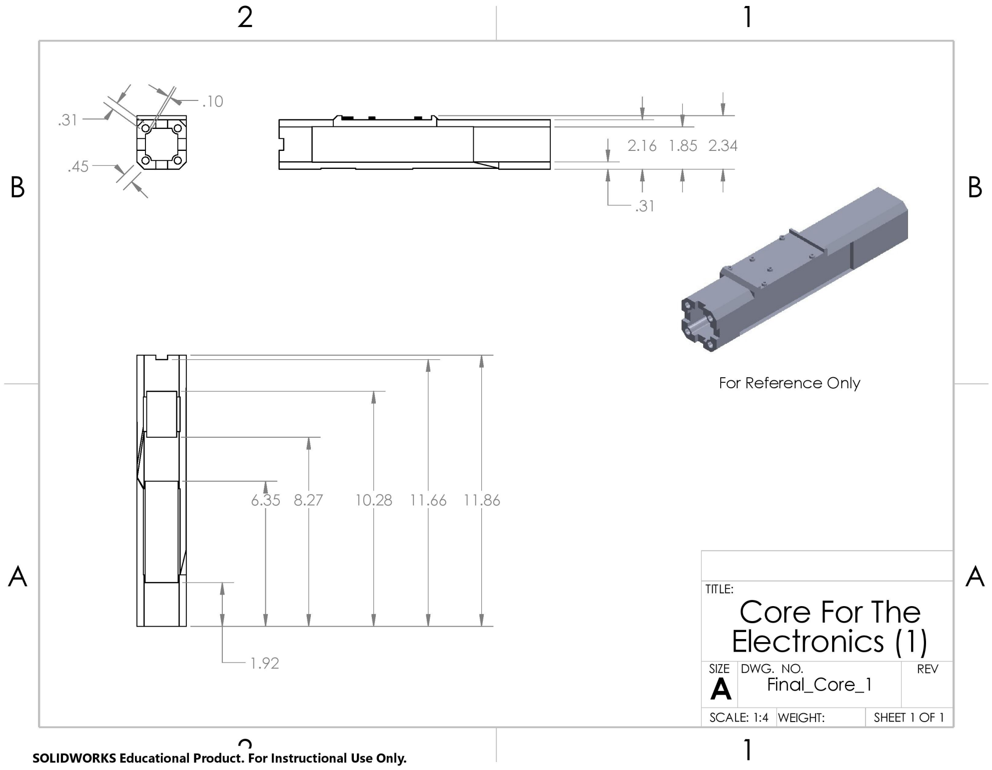
Appendix G: Engineering Drawings



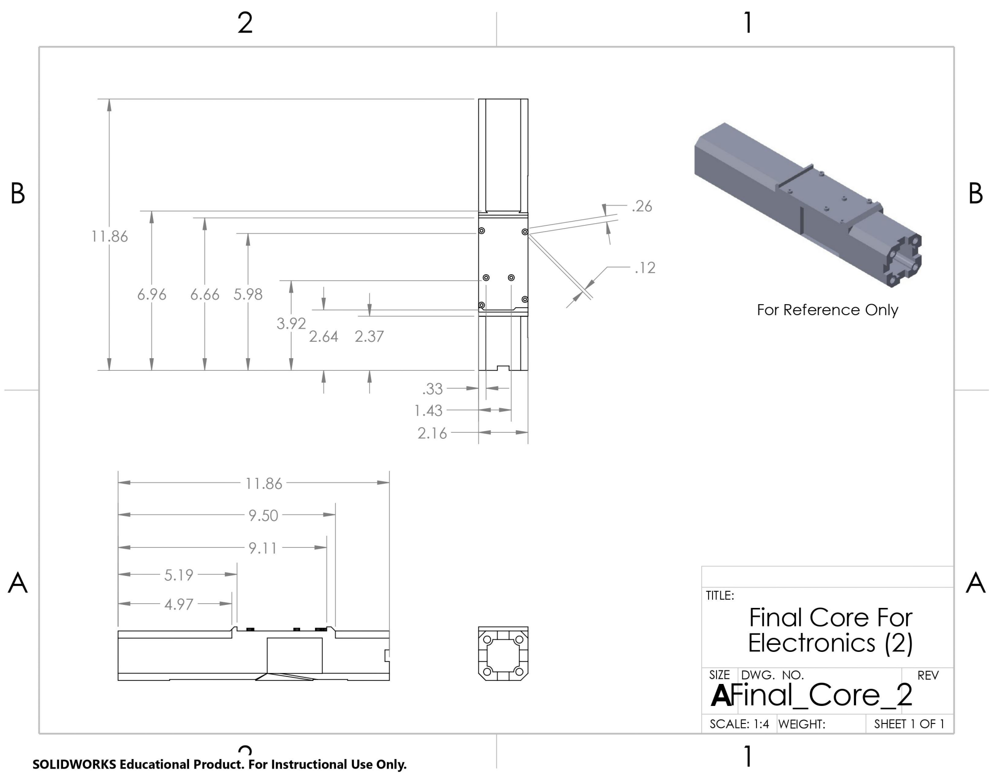
SOLIDWORKS Educational Product. For Instructional Use Only.



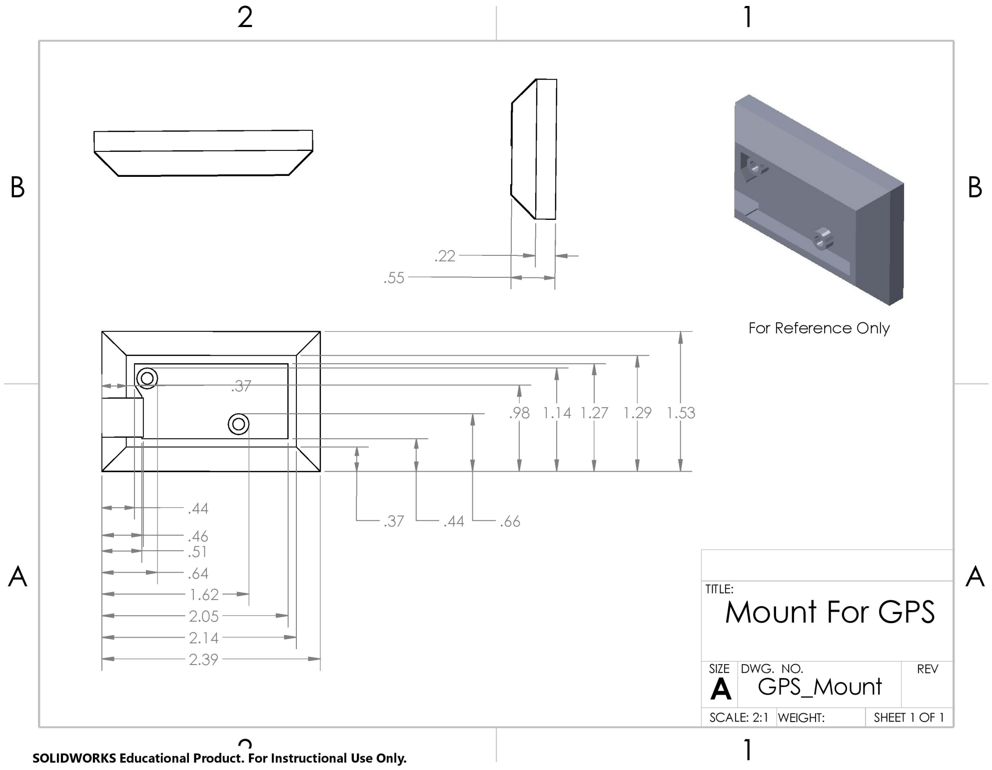
SOLIDWORKS Educational Product. For Instructional Use Only.



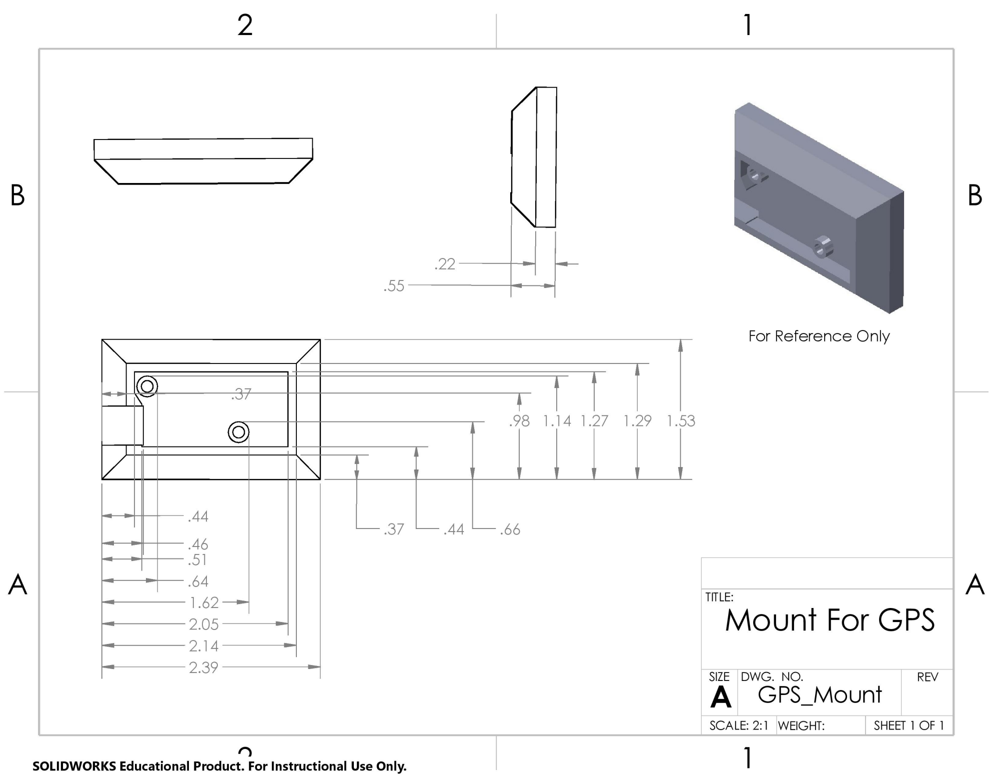
.10
.31
.45
2.16 1.85 2.34
.31
6.35 8.27 10.28 11.66 11.86
1.92
For Reference Only
TITLE:
Core For The Electronics (1)
SIZE A
DWG. NO. Final_Core_1
REV
SCALE: 1:4 WEIGHT: SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



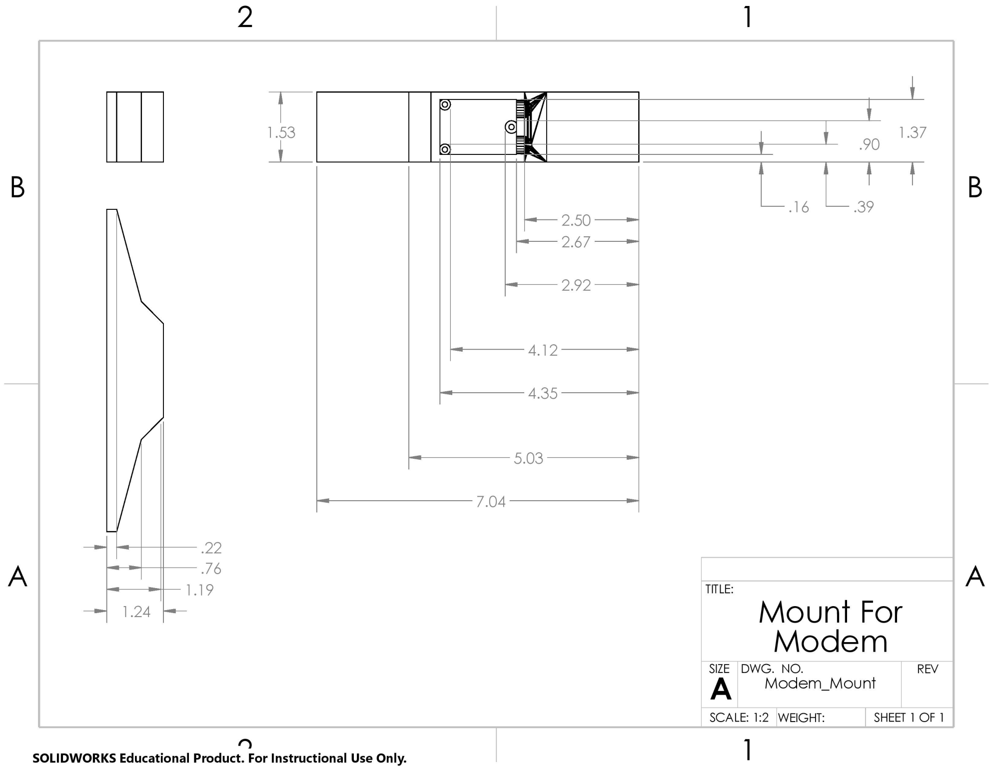
11.86
6.96 6.66 5.98
3.92 2.64 2.37
.26
.12
.33
1.43
2.16
11.86
9.50
9.11
5.19
4.97
For Reference Only
TITLE:
Final Core For Electronics (2)
SIZE A
DWG. NO. Final_Core_2
REV
SCALE: 1:4 WEIGHT: SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



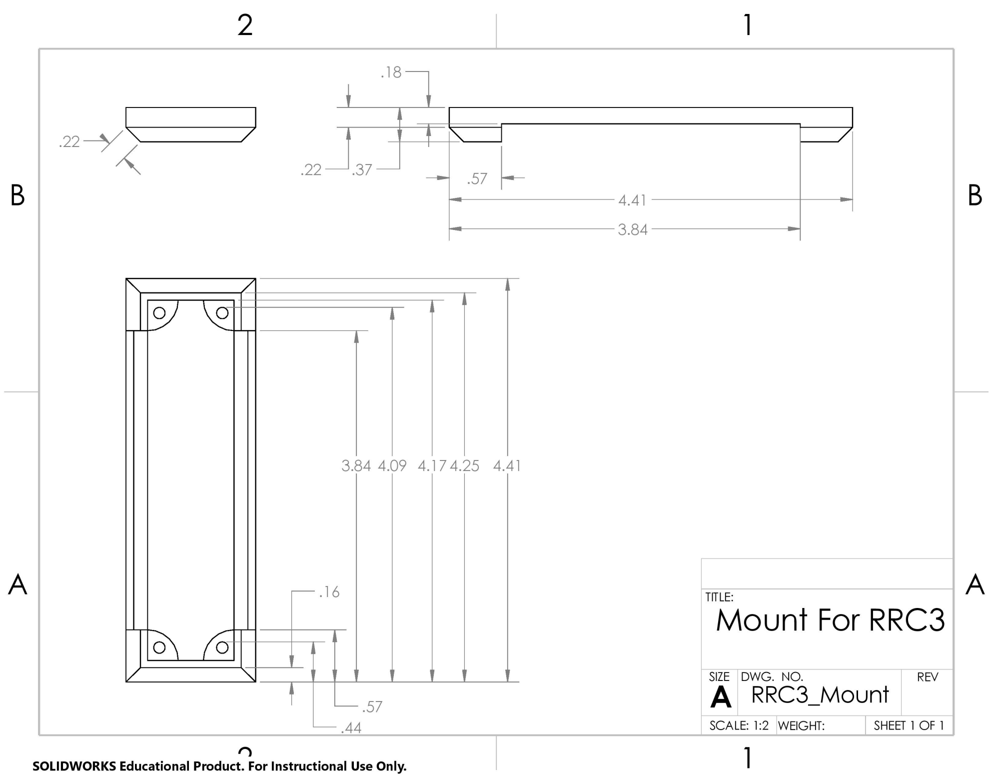
2
1
B
A
.22
.55
.37
.98
1.14
1.27
1.29
1.53
.37
.44
.66
.44
.46
.51
.64
1.62
2.05
2.14
2.39
For Reference Only
TITLE:
Mount For GPS
SIZE
A
DWG. NO.
GPS_Mount
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.



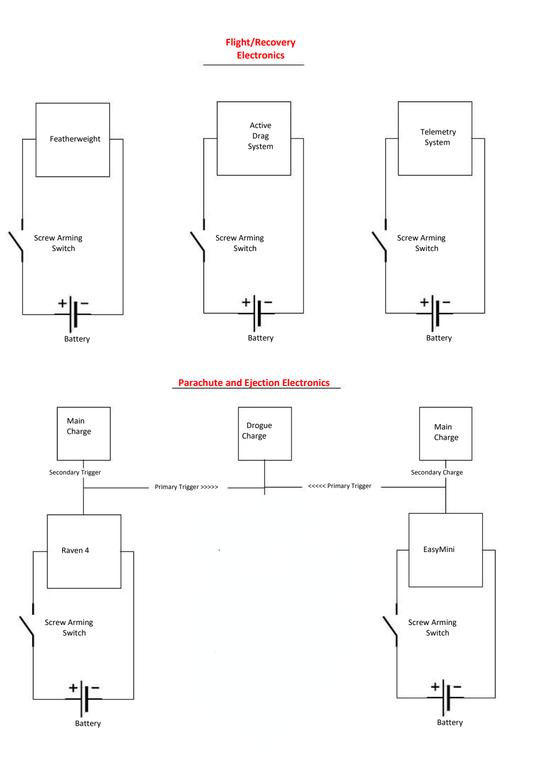
2
1
B
A
.22
.55
.37
.98
1.14
1.27
1.29
1.53
.37
.44
.66
.44
.46
.51
.64
1.62
2.05
2.14
2.39
For Reference Only
TITLE:
Mount For GPS
SIZE
A
DWG. NO.
GPS_Mount
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.

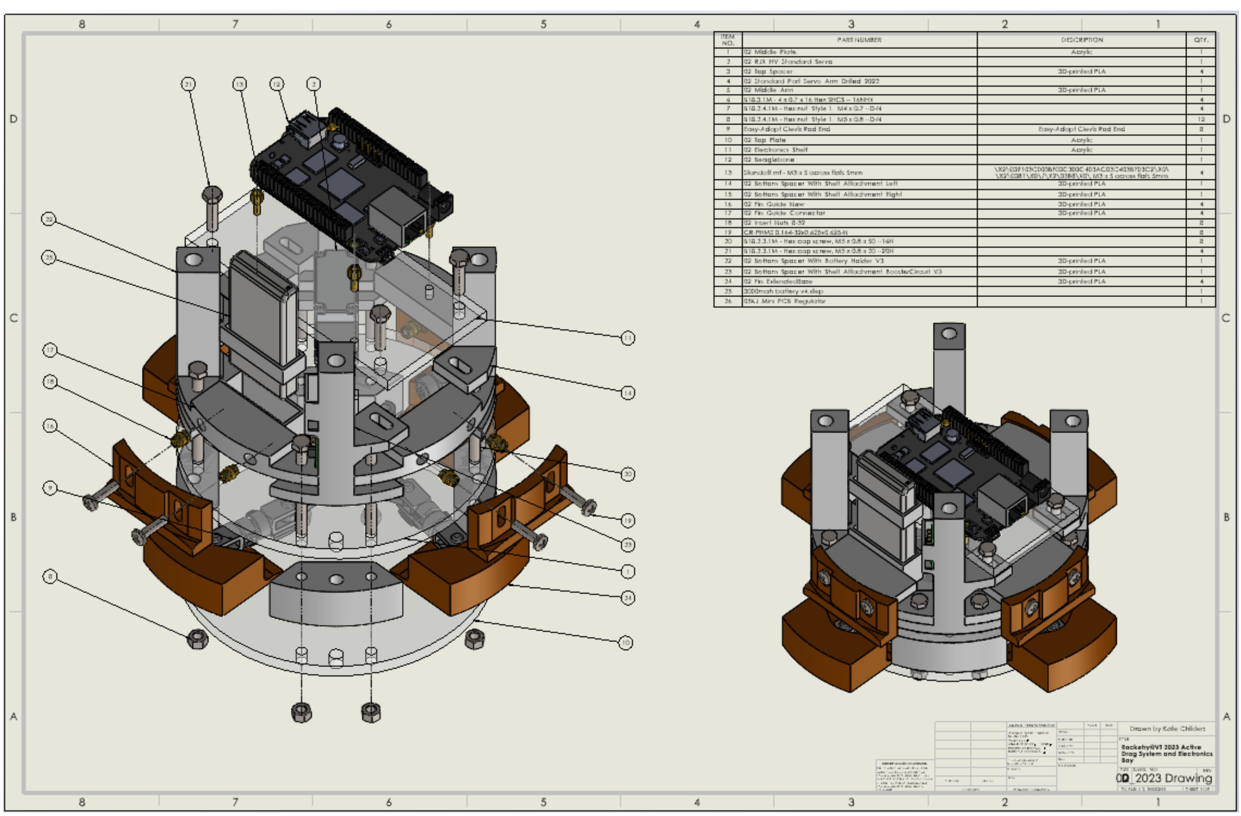


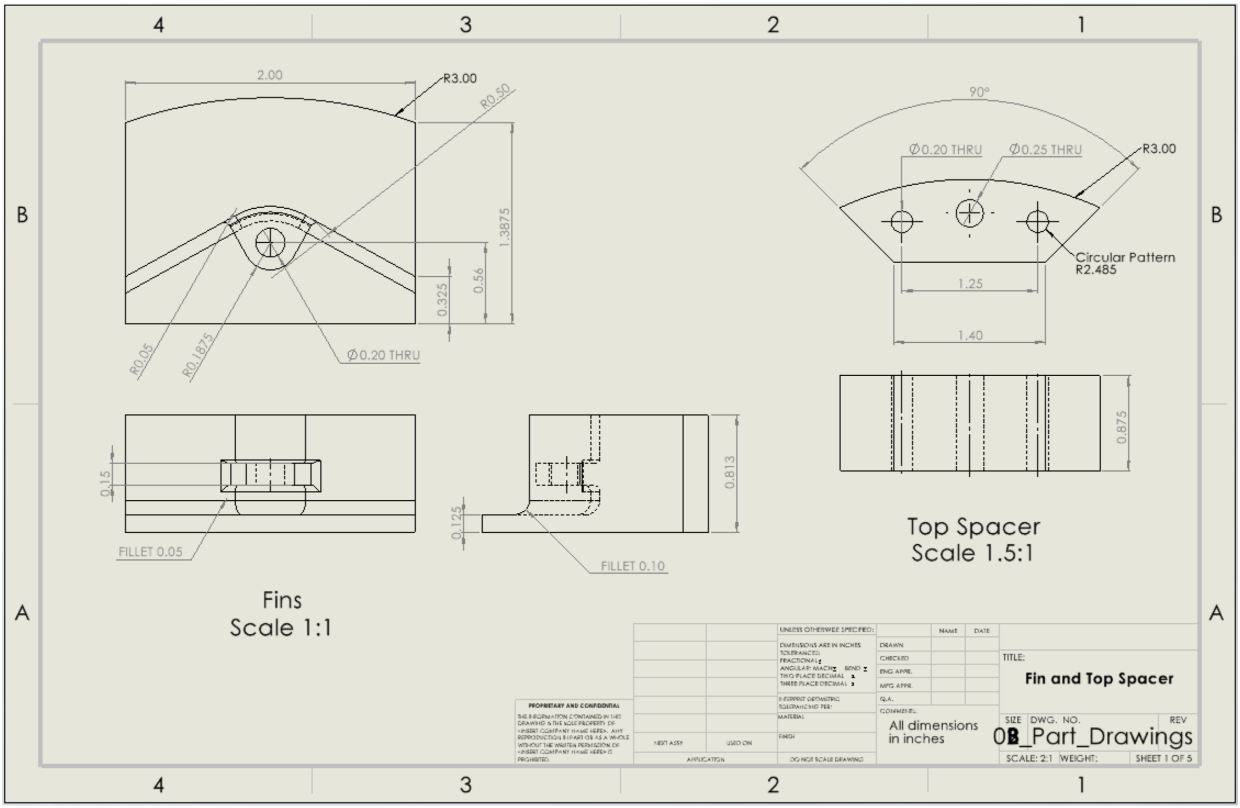
2
1
B
A
1.53
1.37
.90
.16
.39
2.50
2.67
2.92
4.12
4.35
5.03
7.04
.22
.76
1.19
1.24
TITLE:
Mount For Modem
SIZE
A
DWG. NO.
Modem_Mount
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.

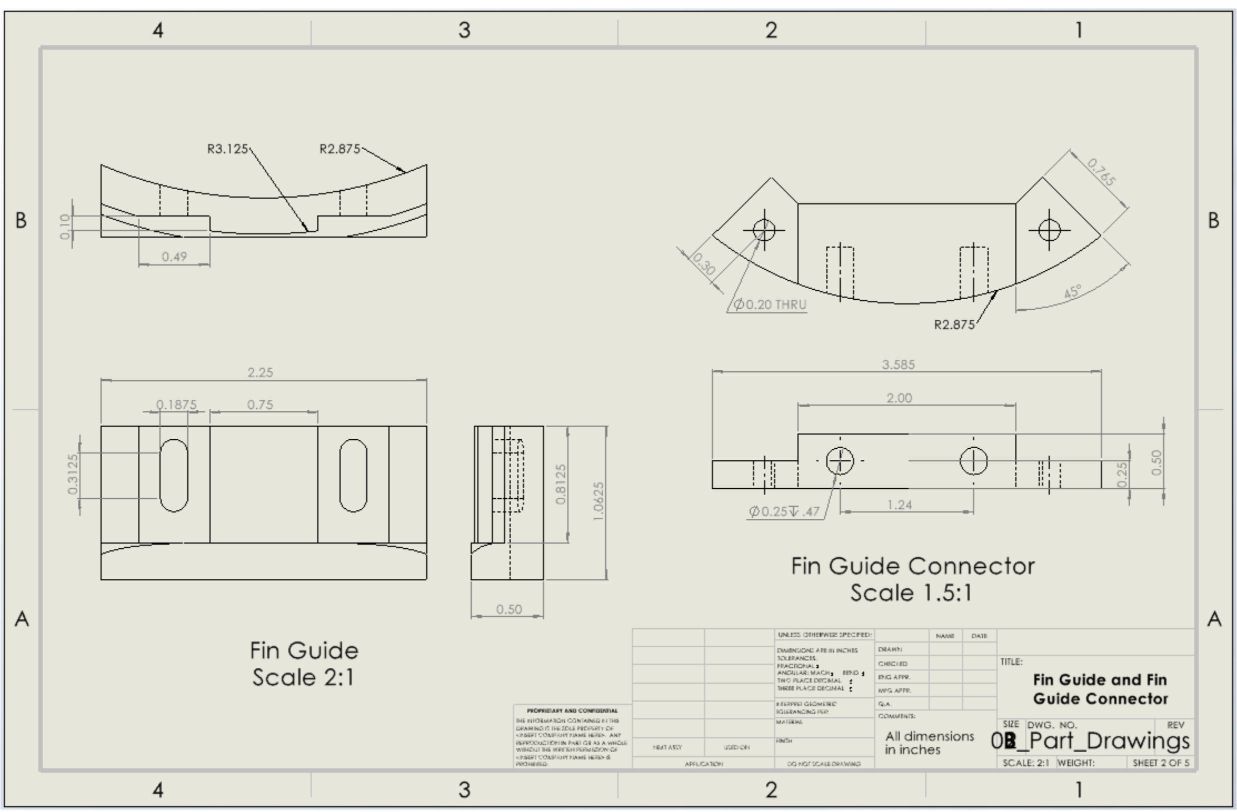


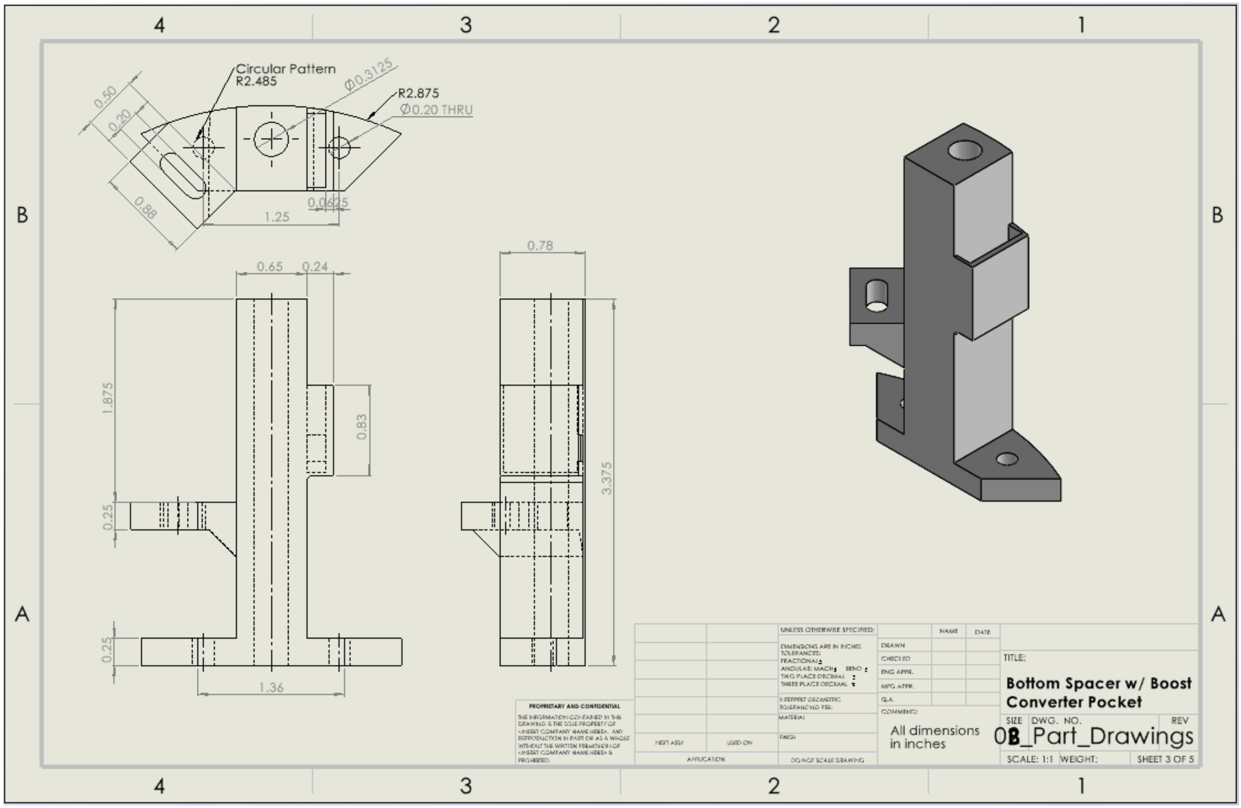
2
1
B
A
.18
.22
.22
.37
.57
4.41
3.84
3.84
4.09
4.17
4.25
4.41
.16
.57
.44
TITLE:
Mount For RRC3
SIZE
A
DWG. NO.
RRC3_Mount
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
SOLIDWORKS Educational Product. For Instructional Use Only.

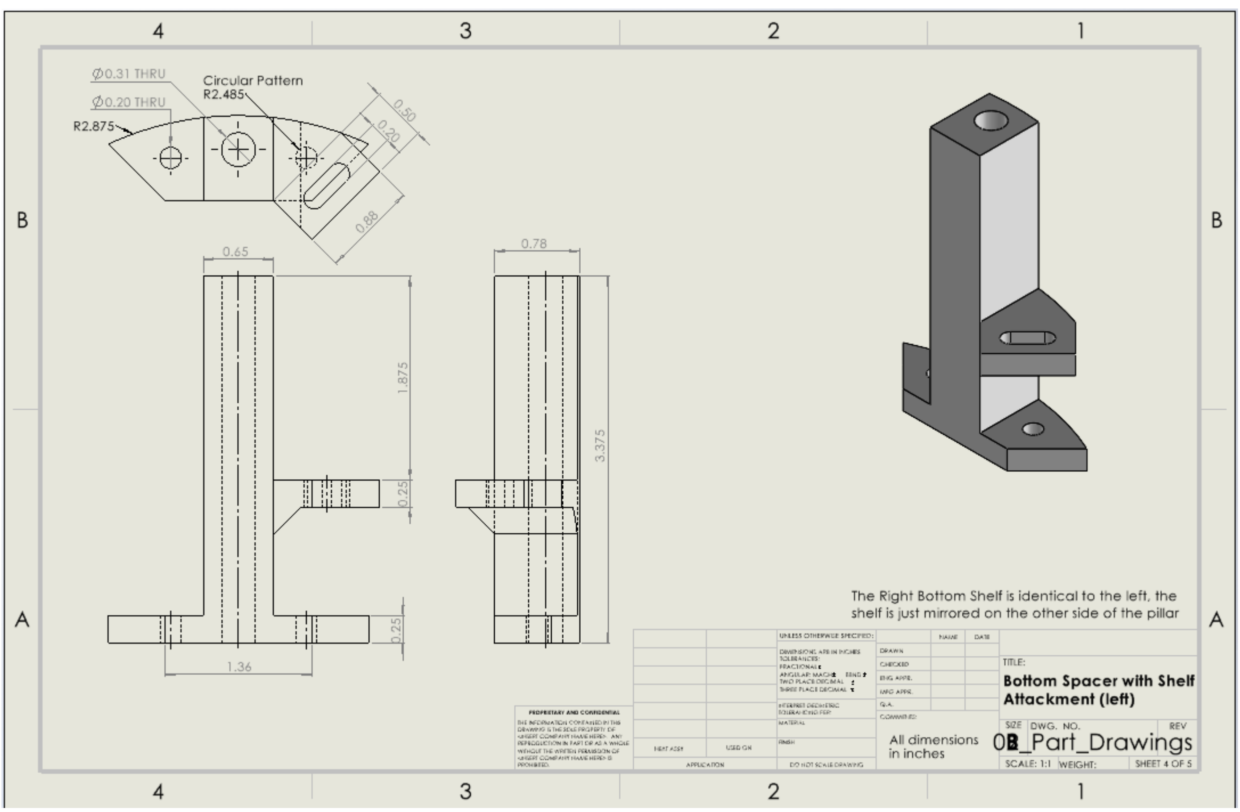

Flight/Recovery Electronics
Featherweight
Active Drag System
Telemetry System
Screw Arming Switch
Screw Arming Switch
Screw Arming Switch
Battery
Battery
Battery
Parachute and Ejection Electronics
Main Charge
Drogue Charge
Main Charge
Secondary Trigger
Primary Trigger >>>>>
<<<<< Primary Trigger
Secondary Charge
Raven 4
EasyMini
Screw Arming Switch
Screw Arming Switch
Battery
Battery

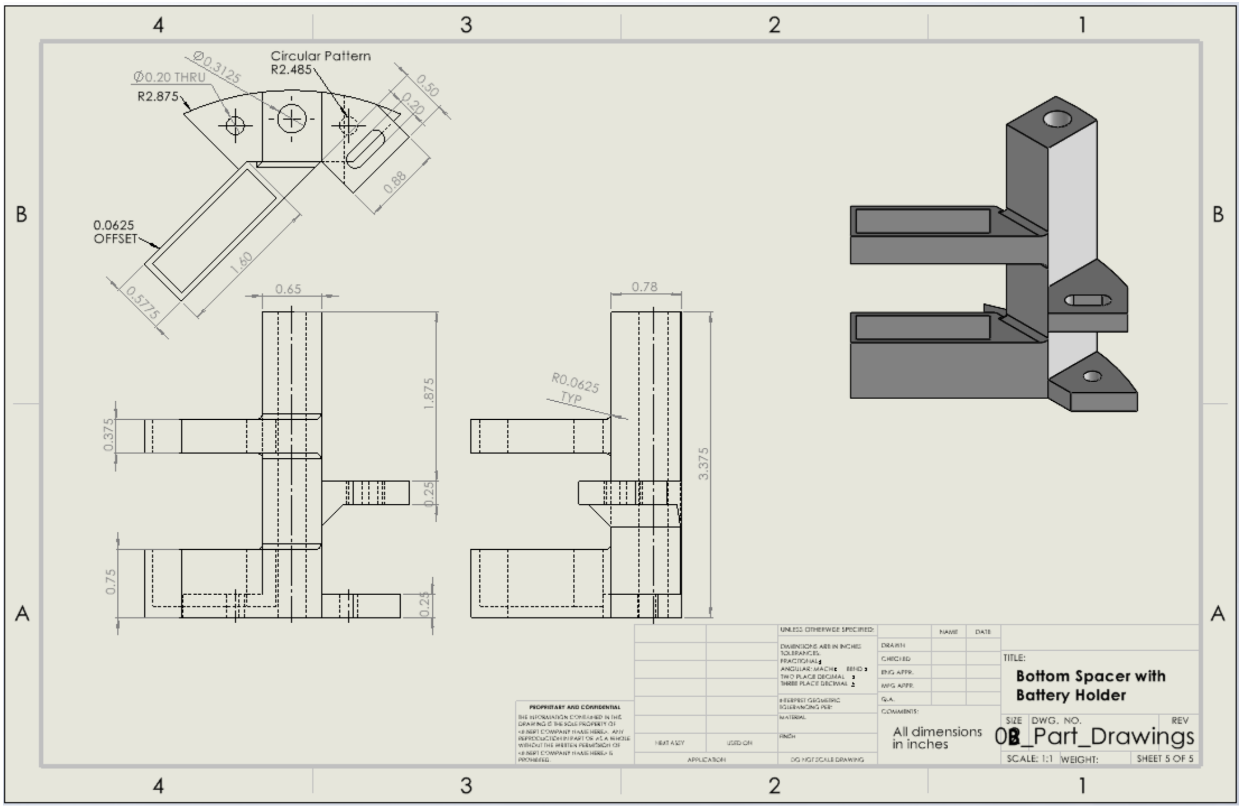

ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | 02 Middle Plate | Acrylic | 1
2 | 02 RJX HV Standard Servo | | 1
3 | 02 Top Spacer | 3D-printed PLA | 4
4 | 02 Standard Part Servo Arm Drilled 2022 | | 1
5 | 02 Middle Arm | 3D-printed PLA | 1
6 | B18.3.1M - 4 x 0.7 x 16 Hex SHCS -- 16NHX | | 4
7 | B18.2.4.1M - Hex nut Style 1, M4 x 0.7 --D-N | | 4
8 | B18.2.4.1M - Hex nut Style 1, M5 x 0.8 --D-N | | 12
9 | Easy-Adapt Clevis Rod End | Easy-Adapt Clevis Rod End | 8
10 | 02 Top Plate | Acrylic | 1
11 | 02 Electronics Shelf | Acrylic | 1
12 | 02 Beaglebone | | 1
13 | Standoff mf - M3 x 5 across flats 5mm | M3 x 5 across flats 5mm | 4
14 | 02 Bottom Spacer With Shelf Attachment Left | 3D-printed PLA | 1
15 | 02 Bottom Spacer With Shelf Attachment Right | 3D-printed PLA | 1
16 | 02 Fin Guide New | 3D-printed PLA | 4
17 | 02 Fin Guide Connector | 3D-printed PLA | 4
18 | 02 Insert Nuts 8-32 | | 8
19 | CR-PHMS 0.164-32x0.625x0.625-N | | 8
20 | B18.2.3.1M - Hex cap screw, M5 x 0.8 x 50 --16N | | 8
21 | B18.2.3.1M - Hex cap screw, M5 x 0.8 x 30 --30N | | 4
22 | 02 Bottom Spacer With Battery Holder V3 | 3D-printed PLA | 1
23 | 02 Bottom Spacer With Shelf Attachment BoosterCircuit V3 | 3D-printed PLA | 1
24 | 02 Fin ExtendedBase | 3D-printed PLA | 4
25 | 3000mah battery v4.step | | 1
26 | 05KJ Mini PCB Regulator | | 1
Drawn by Kale Childers
2023 Drawing

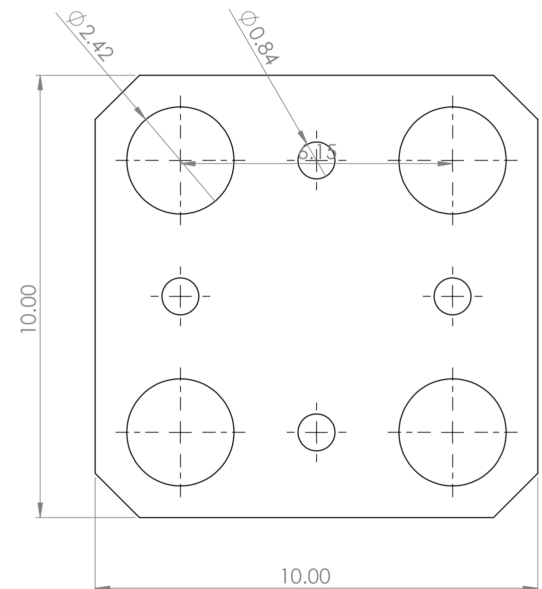

Fins
Scale 1:1
Top Spacer
Scale 1.5:1
TITLE:
Fin and Top Spacer
All dimensions in inches
0B_Part_Drawings
SCALE: 2:1 WEIGHT: SHEET 1 OF 5


Fin Guide
Scale 2:1
Fin Guide Connector
Scale 1.5:1
TITLE:
Fin Guide and Fin Guide Connector
All dimensions in inches
0B_Part_Drawings
SCALE: 2:1 WEIGHT: SHEET 2 OF 5


Circular Pattern
R2.485
Ø0.3125
R2.875
Ø0.20 THRU
0.50
0.20
0.88
1.25
0.0625
0.78
0.65
0.24
1.875
0.83
3.375
0.25
0.25
1.36
All dimensions in inches
TITLE:
Bottom Spacer w/ Boost Converter Pocket
0B_Part_Drawings
SCALE: 1:1
SHEET 3 OF 5


Ø0.31 THRU
Ø0.20 THRU
Circular Pattern
R2.485
R2.875
0.50
0.20
0.88
0.65
0.78
1.875
3.375
0.25
0.25
1.36
The Right Bottom Shelf is identical to the left, the shelf is just mirrored on the other side of the pillar
All dimensions in inches
TITLE:
Bottom Spacer with Shelf Attackment (left)
0B_Part_Drawings
SCALE: 1:1
SHEET 4 OF 5


Circular Pattern
R2.485
Ø0.3125
Ø0.20 THRU
R2.875
0.50
0.20
0.88
0.0625
OFFSET
1.60
0.5775
0.65
0.78
1.875
R0.0625
TYP
3.375
0.375
0.25
0.75
0.25
TITLE:
Bottom Spacer with Battery Holder
All dimensions in inches
DWG. NO.
0B_Part_Drawings
SCALE: 1:1
WEIGHT:
SHEET 5 OF 5



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN CENTIMETERS	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL : PLA	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

SIZE	DWG. NO.	REV
A	ENDCAP	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

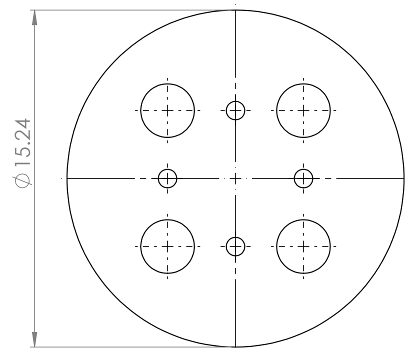
PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

SOLIDWORKS Educational Product. For Instructional Use Only.

2 1

B B



A A

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN CENTIMETERS	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

SIZE	DWG. NO.	REV
A	BULKHEAD	

SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

2 1

SOLIDWORKS Educational Product. For Instructional Use Only.

References

[1] "N.A.". *"SkyAngle CERT-3 Series"*. URL: `http://www.b2rocketry.com/`.

[2] N/A. *AeroTech L1300R*. May 7, 2023. URL: `https://www.thrustcurve.org/motors/AeroTech/L1300R/` (visited on 05/10/2021).

[3] N/A. *AeroTech M1800FJ*. May 7, 2023. URL: `https://www.thrustcurve.org/motors/AeroTech/M1800FJ/` (visited on 05/10/2021).

[4] N/A. *AeroTech M1939W*. May 7, 2023. URL: `https://www.thrustcurve.org/motors/AeroTech/M1939W/` (visited on 05/10/2021).