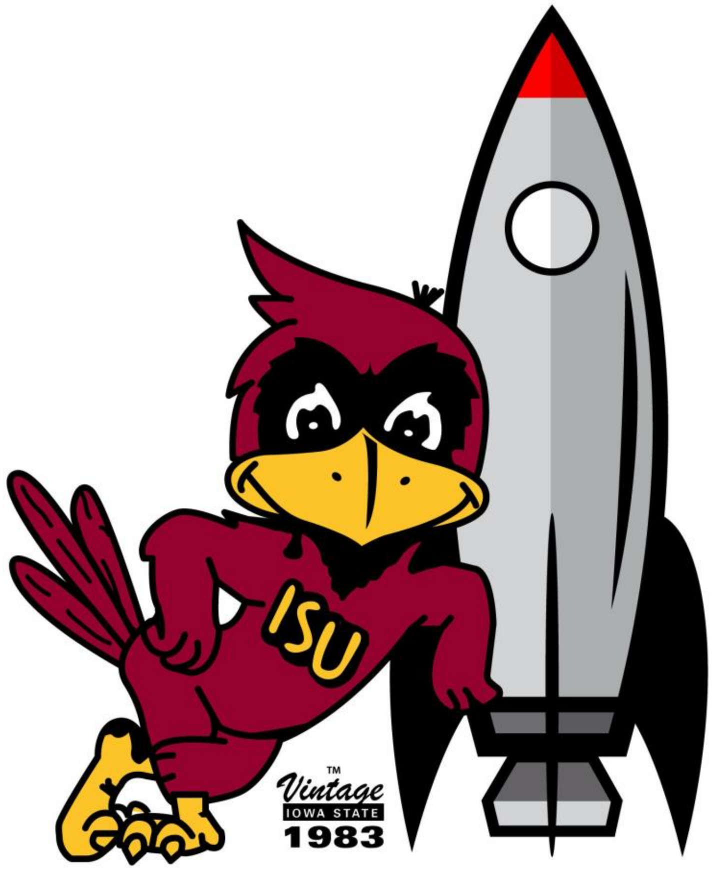

Team 20 Technical Project Report for the 2018 IREC

INVICTUS I

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1. Abstract

INVICTUS I is Cyclone Rocketry's launch vehicle; designed, manufactured, and constructed to be flown in the 2018 IREC Spaceport America Cup. This rocket will be powered by a Cesaroni N2850 Blue Streak rocket motor. Cyclone Rocketry will attempt to fly *INVICTUS I* to an apogee of 10,000 feet while carrying a payload of at least 8.8 pounds. A student designed, electrostatic measurement system housed in a 3U CubeSat will be carried onboard during flight. The airframe consists of off-the-shelf and student manufactured carbon fiber components. Built onto the motor tube, is an autonomous air brake system. Driven by a linear actuator, the system will attempt to decelerate the launch vehicle to our target altitude. The autonomy of this system is orchestrated by numerous onboard sensors and hardware secured on a student designed printed circuit board (PCB). At apogee, a COTS altimeter will trigger and ignite the aft internal black powder charge to separate the rocket and release a 24 inch elliptical drogue parachute. At 1,400 feet above ground level, the forward internal black powder charge will be ignited to separate the rocket again and release a 30 inch elliptical pilot parachute. This pilot parachute ultimately guides out the 144 inch toroidal main parachute, housed in a deployment bag for a "lines-first" deployment. This provides a proper and safe recovery to reduce shock loading as much as possible. For added safety, *INVICTUS I* will be equipped with a separate recovery electronic system containing an additional altimeter, an aft and forward black powder charge for both events, a switch, a battery, and wiring to deploy all parachutes if the first system fails. This dually redundant system ensures the safety of those in attendance.

2. Introduction

2.1 Team Overview

Cyclone Rocketry, a first-year student organization at Iowa State University, is a club affiliated with the Aerospace Engineering Department and College of Engineering. Iowa Space Grant Consortium, ISU Student Body Government, and generous donations from the public were the primary sources of funding and support for this project.

Five different sub-teams were involved in bringing this project to fruition:

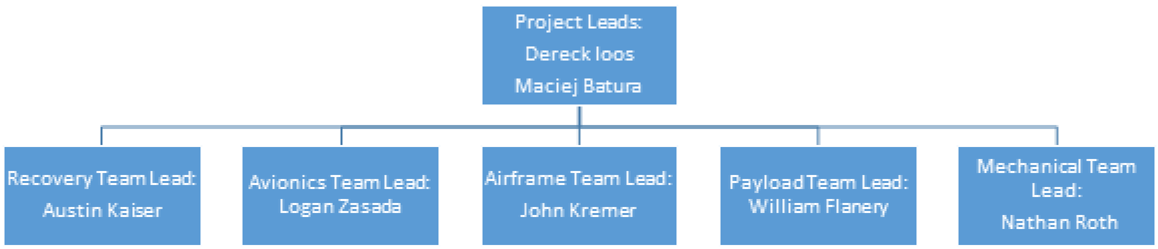

Figure 1: Cyclone Rocketry Team Structure

2.2 AIRFRAME STRATEGY

Cyclone Rocketry had initially planned to build a rocket capable of an apogee of 30,000 feet above ground level. A rocket of this magnitude required the use of high performance materials. Composite materials were explored to meet these requirements. Due to the Aero-Structure team lead's experience and familiarity with carbon fiber components, carbon fiber was heavily researched and ultimately selected for use. Weight is a premium on a rocket, and the main benefit of composite structures is a high strength to weight ratio. All types of composite materials were explored and researched in preparation for the rocket.

2.3 MECHANICAL STRATEGY

The mechanical sub team was tasked with designing an air brake system capable of producing enough drag on the rocket to slow its ascent to apogee. The use of these brakes should decrease the probable apogee of *INVICTUS I* from above 10,000 feet, to our target altitude of 10,000 feet AGL. Research was done to determine what type of air brake would be the most efficient. Our team selected a design that converts the motion of a linear actuator into the angular displacement needed for air brake deployment. With the help of an on-board flight computer and the utilization of a predetermined flight profile, our brakes are set to deploy if the rocket is ever on track to fly above 10,000 feet. Once the flight computer determines that *INVICTUS I* will reach an apogee of 10,000 feet, the air brakes will be retracted.

2.4 AVIONICS STRATEGY

The main priority of the avionics sub-team was to take in sensor data during flight and communicate to our system's linear actuator whether or not it was to deploy the air brakes. If the on board flight computer intakes and analyzes data that determines *INVICTUS I* is on track to fly above 10,000 feet, the air brakes will be deployed until the flight computer has determined that an altitude of 10,000 feet will be the apogee of the rocket's flight. On descent, the rocket contains a GPS and radio transmitter that can locate the rocket in the event of a loss of sight.

2.5 RECOVERY STRATEGY

The recovery sub team's main objective was to safely recover the entire rocket and its components. This was accomplished using a typical dual deployment recovery method including: a drogue parachute deployed at apogee, a pilot parachute, and a main parachute deployed at a much lower altitude to reduce drift while still ensuring the rocket's safety. To keep costs down on a tight budget, the team chose to use black powder over other alternatives like carbon dioxide cartridges to deploy the parachutes. Additionally, this method was comparatively easier to implement over others due to the team members' past experience.

2.6 PAYLOAD STRATEGY

The payload sub team's primary responsibility was to design and develop an onboard payload experiment. The experiment measures electrostatic charge incurred on the airframe of the rocket throughout its flight. This is accomplished by using an Arduino Uno R3 board which has built-in functions that allow voltage measurements to be taken. These allow for multiple measurements on the surface of the nose cone, which our team believes to be the location of highest electrostatic charge build up. Along with the experiment itself, Cyclone Rocketry designed and manufactured a CubeSat housing to follow CubeSat standard guidelines. The team chose a 3U configuration to allow for versatility in the alignment of the experiment as well as the possibility of additional experiments.

3. System Architecture Overview

3.1 *INVICTUS I* System Overview

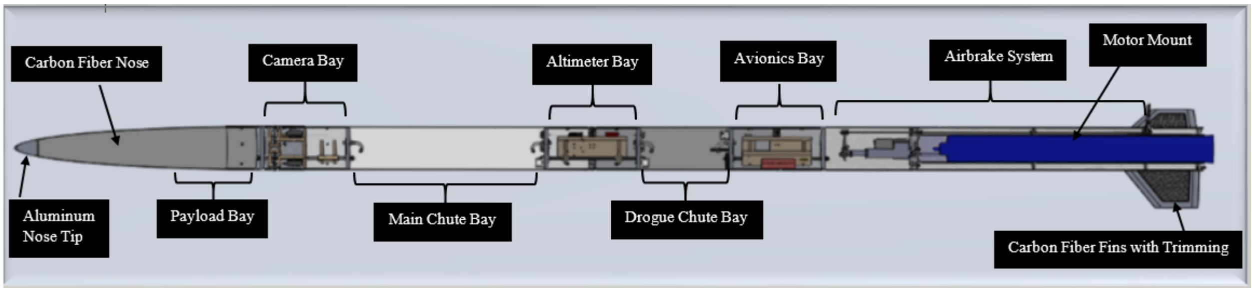

Figure 2: INVICTUS I

3.2 Aero-Structures

The following subsections outline the design, analysis, and manufacturing process of all Aero-Structures of *INVICTUS I*.

3.2.1 Main Body Tube

The first airframe section to be designed was the main body tube. The team started with this section as it was deemed to be the most important section of the whole rocket. The main tube dimensions drive the rest of the rocket dimensions and also drive the maximum performance of the rocket. The initial design phase was used to explore materials. The tube's mission requirements were driven initially by the air brake subsystem and by first order simulations. The initial design called for a minimum inner diameter of 6 inches and tube production options were explored. Blue tube and paper-based tubes were researched and removed from the potential material list fairly early due to lack of available material data. The two front running materials were fiberglass and carbon fiber. Fiberglass provides the benefit of being relatively cheap while having higher strength than any paper-based rocket tubing. Carbon fiber provides an even better strength to weight ratio than a fiberglass tube, but at the downside of cost. Different manufacturing options were explored such as: in-house production using a wet layup, in-house production using a pre-impregnated fabric, and buying a commercial off the shelf product. An in-house tube produced using a wet layup was evaluated and cost was projected. This method was deemed too inconsistent for the strength requirements of a high-powered rocket. A lot of additional testing would have been required to ensure tube strength. The next method of using a pre-impregnated fabric was also evaluated. While offering more consistent strength, this method required special facilities along with also requiring a large labor force to produce the tube. These resources were not available to the team when this project began. The option of using an off-the-shelf part was then selected, and carbon fiber tube options were explored. Fiberglass tubing was ruled out at this time because of the strength and weight requirements obtained from the first simulations. The actual tubing used on *INVICTUS I* provided a weight savings of 27.3 percent when compared to a fiberglass tube of the same dimensions.)

Material	Young's Modulus (Fiber Direction) MSI	Flexural Strength (Fiber Direction) MSI
G10/FR4 Fiberglass	3.5	2.7
Grafil 34-700 CFRP (Filament Wound Tubing)	19.9	19.1
Grafil TR50s CFRP (Fabric Wound Tubing)	20.6	19

Table 1: Mechanical Properties of Tube Materials

The two major manufacturing methods of commercial tubing are filament wound tubing and fabric wound tubing. The team had trouble finding tubing manufactured at the diameter required and selection was limited. The two final tube options were both manufactured by Rockwest Composites. Rockwest offered a fabric wound and filament wound tube of an inner diameter of 6 inches. The filament wound tube offered a slightly larger wall thickness while having a lower density than the fabric tube. The fabric tube was projected to weigh 1.84 pounds per foot while the filament wound tube was 1.14 pounds per foot. Both were competitively priced, so the final tube selection was in favor of the filament wound tube due to its weight. The tube is manufactured with Grafil 34-700 24k Fibers using a pre-impregnated resin system. While a filament wound tube cannot achieve 0-degree fibers, something that a fabric wound tube can, it was deemed that the tube would provide more benefit than this inherent weakness. The actual tube layup is proprietary of Rockwest Composites and could not be obtained, however, certain assumptions were made about the tube in order to proceed with analysis. The tube was assumed to have the theoretical strength listed on the Grafil 34-700 TDS as shown in *Table 1*.

Fiber Direction (Deg)	Tensile Strength (ksi)
0	373
90	11.17

Table 2: Tensile Strength with Fiber Direction

Upon parachute ejection, each shear pin hole experiences bearing stresses in excess of 7,300 pounds per square inch**.** With a “worst case scenario” of a full tube of 90-degree fibers, the tube theoretically would not fail. With this loading there is a factor of safety of 1.53. This was found to be acceptable considering the true strength of the tubing is significantly higher. The tube was ejection tested at a later date and there was no observable failure after testing. Non-Destructive Evaluation testing was performed on the shear pin holes to determine if there was any interlaminar failure: these results came back negative. The main tube holes experience a bearing stress of 4,032 pounds per square inch upon a

12G acceleration main parachute deployment. This value is less than the stress experienced by the shear pin holes so there was no concern of failure here. Aluminum tube fasteners were inserted and bonded into each hole experiencing a recovery load. These help keep the tube from fracturing and delaminating when a load is suddenly applied, further reducing the chance of failure. The tube was fully flight tested in May when *INVICTUS I* was launched. The rocket was launched and recovered successfully with no tube delamination or failure, further validating the design.

3.2.2 Nose Cone

The nose cone is a parabolic shape of 32 inches in length. The parabolic shape was selected for multiple reasons, the most important being manufacturability. Since the team planned on manufacturing the nose cone in-house due to cost, a design that was easier to manufacture was important. Carbon fiber was selected as the material of choice due to the weight savings over a fiberglass nose cone. These potential savings in weight allowed the team to use a lower impulse motor. The manufacturing process used was a wet layup. The reasoning for the manufacturing process chosen was mostly driven by cost and in-house ability. Pre-impregnated carbon fiber, while more consistent in strength and weight, has very high initial costs. An autoclave large enough to fit the part created is needed, and molds have to be incredibly strong to survive the curing process. Tooling foam capable of withstanding this process is prohibitively expensive. The cost and tools needed for a pre-impregnated manufacturing process were the reason why this method was not selected. Resin infusion was another option, but due to the lack of prior team experience, this process was also ruled out. To create molds for wet layups, high density tooling foam or some other form of tooling material would be needed. A 10 pound per cubic foot density foam was selected and machined in house using a CNC router. The mold was a two-part-mold, allowing the nose cone to be made in two halves and bonded together. Since the team did not have access to a bladder, a standard vacuum bagging approach was selected. Laying up the nose cone in one section would have proven very difficult to get right towards the tip of the nose, further backing the rationale to manufacture the nose in two sections. The material used was a 3K filament fabric of Toray T300 fiber. This was selected to keep costs down while still having large amounts of strength. T300 based fabrics are readily available to order and less expensive than fabrics with larger filament counts. The nose was initially designed to have a layup of [0, 45, 0]. A program to solve for the maximum dynamic pressure was written using data generated by simulation programs. The nose was analyzed with ANSYS ACP for a given maximum dynamic pressure loading and was shown to be more than adequate. Doubt was expressed whether this nose would survive an impact with the ground while carrying the required payload. The nose cone was then redesigned to incorporate a new stack-up of six layers oriented in the same direction. A simulation using the final rocket parameters was run and an analysis was performed in ANSYS ACP. With the given loading at maximum dynamic pressure of 930 pounds per square foot, the nose cone was found to have a minimum Margin of Safety of 96.32 (*Figure 4*). A graph depicting this simulation is displayed in *Figure 3*.

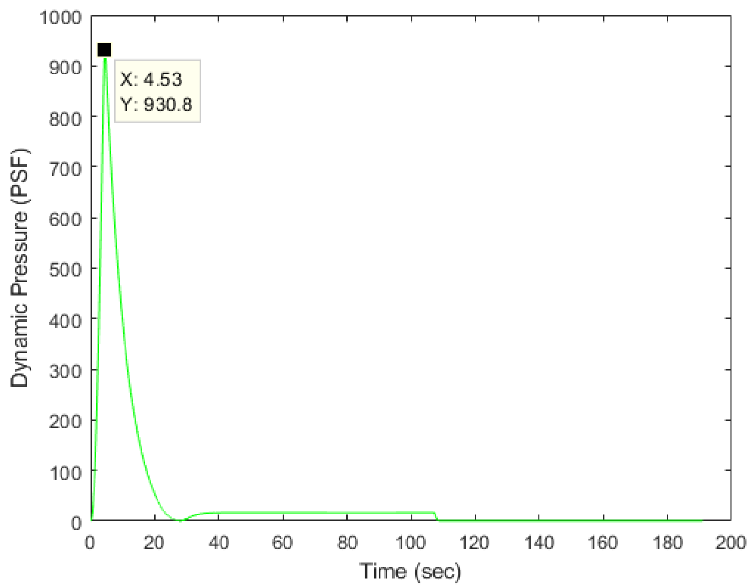

Figure 3: Dynamic Pressure Simulation

This was deemed a satisfactory Margin of safety, even with the inherent weaknesses being added by using a wet layup process and by creating the nose in two halves. The Nose halves were bonded with 3M DP420 and JB Weld epoxy with the proper surface preparation required to achieve a strong bond. The final nose cone was tested during a test launch and was returned safely.

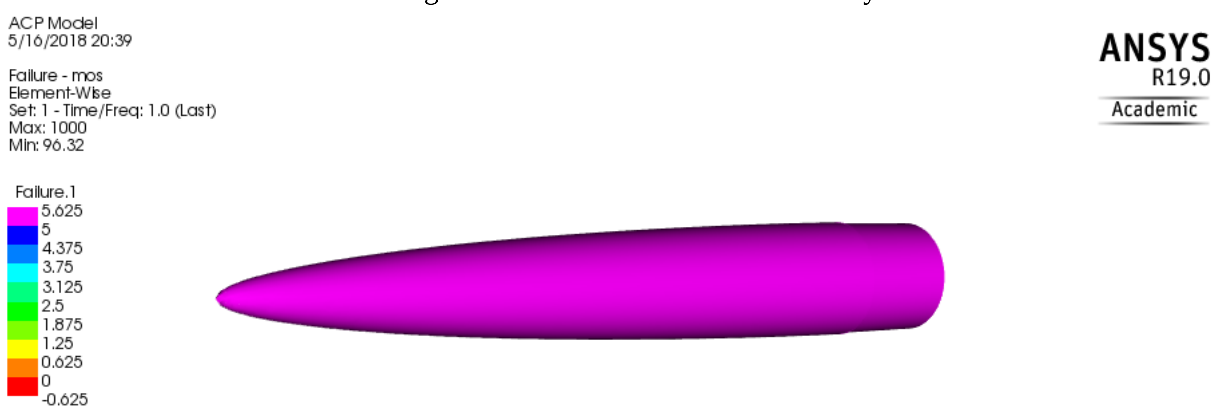

Figure 4: Nose cone Margin of Safety

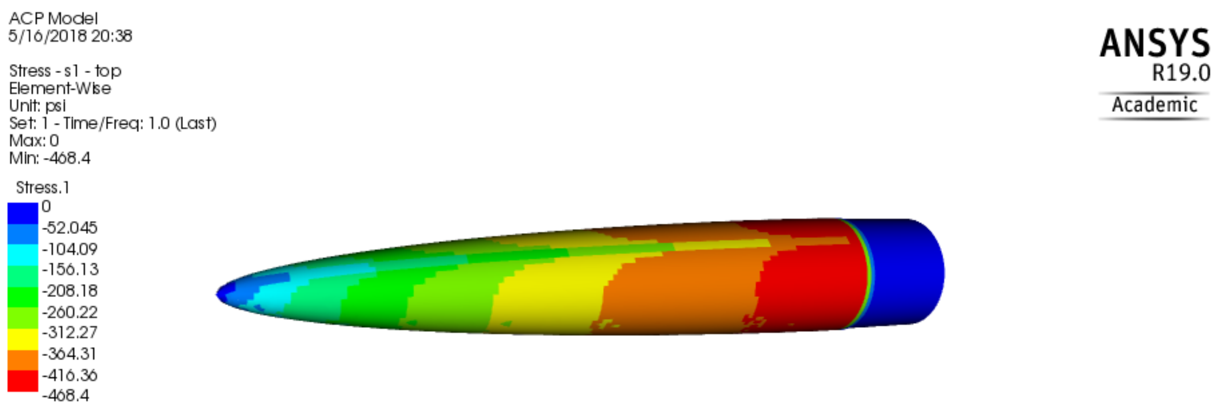

Figure 5: Principal Stress on Nose Cone (S1)

3.2.3 Couplers

The rocket was initially designed to have couplers made of carbon fiber with ½ inch aluminum bulkheads. By being incredibly stiff and strong for their weight, the couplers were able to be optimized for the projected loading during flight. The couplers were to be manufactured using a two-part mold and then bonded using DP420. The high shear strength of the DP420 adhesive would keep the couplers for separating into halves when the rocket was experiencing a bending load. Initially the couplers were to be of 4 plies, with a stack up of [0, 45]. There was doubt expressed to whether the coupler had a large enough bonding surface for the adhesive to attach, so the number of plies was doubled. The new laminates were $[0_8]$ since producing 45-degree plies is very wasteful of material and there would not have been enough material to finish three couplers with our monetary constraints. Two couplers were produced and bonded using the method above. The molds manufactured for the couplers were not made with the tolerances required and the resulting couplers were not circular. The team attempted to machine the couplers to fit the tube, but too much material would have to be removed to make them fit. The decision was made to take a weight penalty and purchase thin walled 6061-T6 aluminum cylinders. These cylinders were more round than the carbon couplers produced. With the same ejection loading as aforementioned, the eighth inch thick couplers experience a bearing stress of 4.497 thousand pounds per square inch. The yielding stress for 6061-T6 aluminum is 35 thousand pounds per square inch, providing a 7.78 factor of safety. These couplers used the same aluminum bulkheads as before. Threaded metal rods connected to each bulkhead were used to transport tensile loading during recovery.

3.2.4 Fins

At the speeds projected to be achieved by the rocket during flight, fin flutter is a very real concern. An extremely stiff fin is needed to prevent fin flutter and potentially catastrophic failure. Fin material was explored using CES Edupack. Edupack allows the user to create laminates and sandwich panel materials. The program then outputs theoretical specifications for each material. The initial fin options researched were those made using a G10 fiberglass laminate, a Toray T300 Carbon Fiber laminate and a Sandwich panel laminate. Due to the need carbon fiber to produce our nose cone, the fiberglass laminate was not researched past the initial stage. A multiple ply carbon fin is extremely stiff but is fairly costly to make and not the lightest weight option. Producing a fin out of a sandwich panel laminate was selected as the direction for further fin development. Edupack was used to create multiple sandwich panels using different core and face sheet thicknesses. This was then processed and analyzed through a MatLab code developed using NASA TN D-3171. The code allowed the user to quickly test a fin design using different material properties and certain fin parameters. These fins were then compared to the simulated runs to determine if they failed. Each fin design generates 4 solutions and the user to determines what is a realistic result and what is not. The core materials explored were Divinycell three pound per cubic foot density foam, 1.8 pound per cubic foot Nomex honeycomb, and finally a three pound per cubic foot Nomex honeycomb core. The final fin design was one using a two-ply face sheet (four plies overall) and a 0.21 inch 1.8 pound per cubic foot Nomex honeycomb core. While the code was designed for isotropic core sandwich panels, something a honeycomb core panel is not, the program will simulate the open cell direction of the core and output results. *Figure 6* displays four solutions for the fin design used on *INVICTUS*. In flight, our rocket is projected to never exceed the expected fin flutter speed as referenced in *Figure 7*.

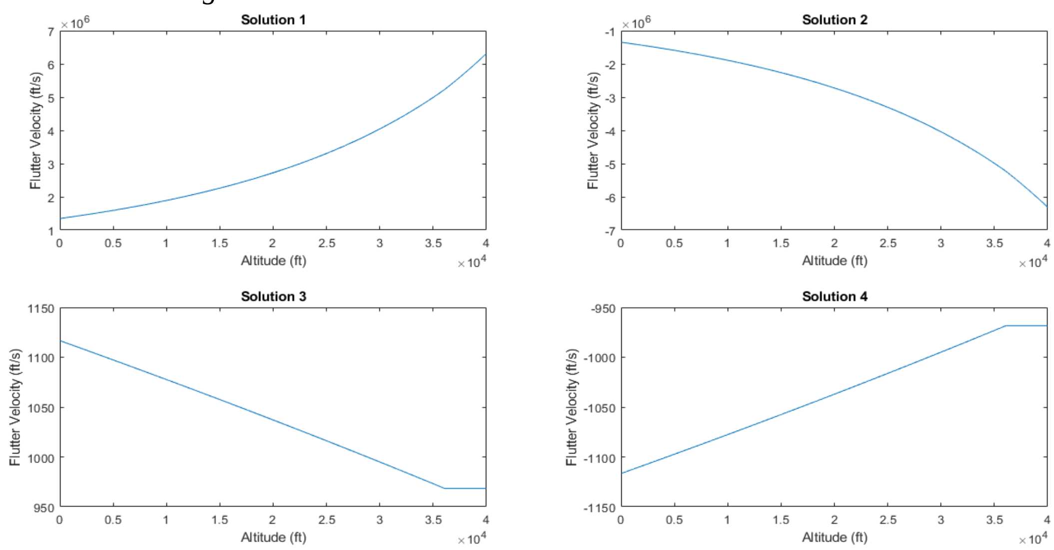

Figure 6: Four Solutions to Fin Flutter Speed

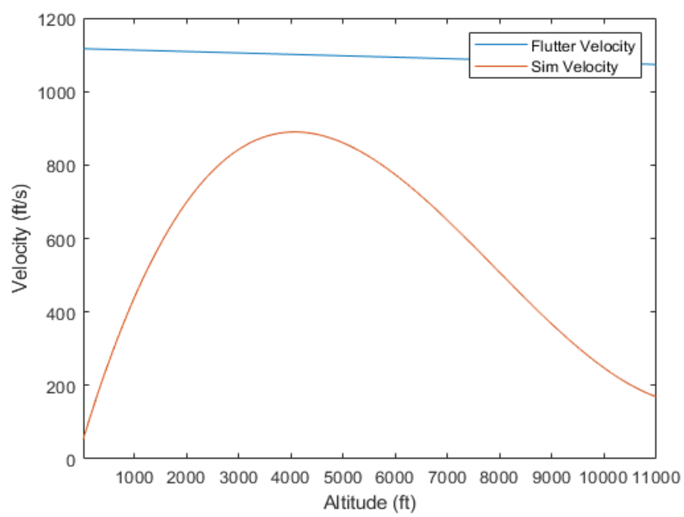

Figure 7: Flutter Velocity Vs Simulated Flight Velocity

The material was produced using a wet layup technique with the same resin and carbon fiber fabric as the nose. A large panel with excess material for backup fin sets was produced. The panel was then taken to a water jet and the fin profile was cut out of the panel. Water jetting the material allowed the fins to be produced rapidly while also minimizing the chance of panel delamination. The initial fin set produced does not have an aerodynamically efficient shape; having blunt faces. Producing symmetrical and sharp faces out of sandwich panel would have added large amounts of complexity so other options of trimming the fins were explored. The final fin design included aluminum trimming greatly reduced drag. The fin tips were then bonded using epoxy after the bonding surface was etched. The fins were attached to the main body tube using DP420 fillets along the side of the fin. After the epoxy cured, an additional 2 layers of carbon fiber were applied to the fins using a “tip to body” method. This method involved applying carbon fabric from the body tube to the tips of the fin, bonding both together and giving additional points of contact and reducing likelihood of failure upon touchdown impact.

3.3 Air Brakes

When designing the air brakes for *INVICTUS*, we researched a few different methods, ultimately deciding to use a design involving a linear actuator above the motor that extends three brake pads near the aft end of the rocket. One of the most important reasons that we selected this design, was because many of the parts were relatively easy to manufacture. The design is relatively simple; we have a linear actuator mounted just above the motor that actuates vertically, pulling three equally spaced rods with it. These rods are attached to a set of mechanical levers that pivot the air brake bracket about a hinge. The air brakes are attached to brackets in a fashion that when the linear actuator is activated it pulls the pads up and outwards at a constant rate. Since the linear actuator deploys at a predictable and controllable rate, we knew that we could design a system that measures the velocity of the rocket and air density and use it to inversely calculate the drag required by the air brakes to slow the rocket down enough to reach 10,000 feet above ground level. We also used SolidWorks Flow Simulation to get another estimate of aerodynamic performance. In this analysis, we had nearly 1000 design points which were set to a unique combination of angle of actuation, air density, and air velocity. We then used this data to get a better understanding of the performance of our air brake system. The avionics team used this idea to create a code that would allow the air brakes to independently extend and retract depending on the real-time flight profile. This robust design allows for the rocket to be flown in a variety of conditions.

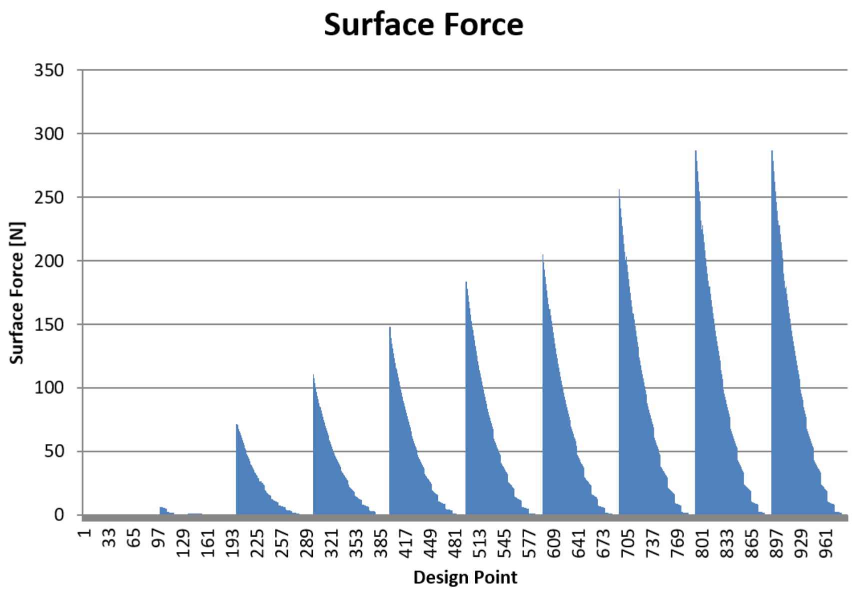

Figure 8: Simulated Airbrake Surface Force at Various Design Points

The challenge to the linear actuator design came when the mechanical had to integrate its design with the avionics. The avionics sub-team performed most of the technical work with the electronics, however the mechanical team was tasked to find an equation relating the linear displacement of the linear actuator to the angular displacement of the air brakes. This was done using a SolidWorks motion study on the air brake assembly. This in turn was implemented into the code that the avionics team created to actuate the air brakes at the correct rate. With all the variables that need to be accounted for, a test flight would allow us to refine the code for a more precise actuation. After performing our first test flight on May 13th, 2018, we were not able to learn more about the mechanical or aerodynamic aspects of our air brake system because the air brakes did not deploy, even though we exceeded our target altitude. We found software issues to be the culprit and hope to learn more from the competition launch.

3.4 Flight Avionics System

3.4.1 Altitude Sensing and Air Brake Actuation

To determine our current and future altitude during flight, we used multiple onboard sensors. A pressure sensor was helpful in achieving current altitude, but it would not be precise enough to calculate whether the air brakes should be actuated. Because velocity isn't easy to calculate, and pressure isn't precisely equal inside and outside of the rocket, we also receive data from two accelerometers. One of our accelerometers is used as our high accuracy, low force accelerometer. Our other accelerometer, however, will function at forces above 4.5 G's, so we switch to taking data from this accelerometer when the rocket is in the thrusting phase. Between the pressure sensor and two accelerometers, we can calculate altitude, velocity, and acceleration.

The values we calculate using these sensors would be useless, however, if we didn't have some way of calculating when the system should deploy the air brakes. Since aerodynamic equations are rather computationally heavy when running code onboard, we came up with a system where a graph is made, and for any given altitude and velocity, we calculate the altitude we'd reach if brakes were deployed at that moment. The main point of this code is to give us a graph for every likely pair of altitude and velocity. The graph below in *Figure 9* demonstrates the output of this program. The x-axis contains the "current" altitude, and the y-axis contains the "current" velocity. The blue curve on the graph represents every pair that will get us to 10,000 feet. This method allows us to do the heavy computation ahead of time and light computation during flight for increased speed and accuracy. If we are above the blue line, we're projected to fly above 10,000 feet. This triggers the brakes to deploy. If we're below the blue line, we will either undershoot the target, or maybe we will experience less drag than anticipated and will move closer towards the blue line that represents a flight path to 10,000 feet above ground level.

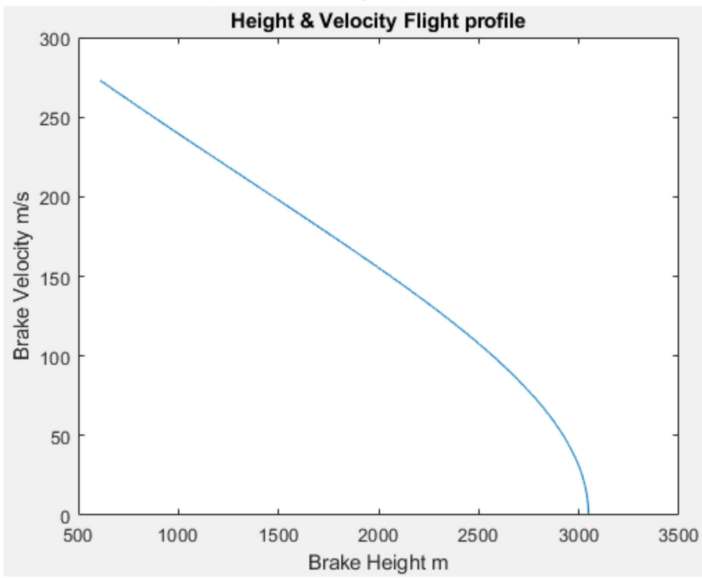

Figure 9: Pre-Calculated Flight Profile

3.4.2 Post-Flight Rocket Location System

The final task of the avionics team is to locate the rocket after it lands on the ground. With the rocket flying to 10,000 feet, we're almost certain to lose sight of it. Our team needed a surefire way to be able to find the rocket when it lands. To do this, we pipe data from a COTS GPS into a microcontroller, and the microcontroller then sends the data to a radio transmitter. Team members on the ground will have a receiver and an antenna hooked up to PUTTY on a computer to read the GPS data being sent to the ground. The first two pieces of data that get sent to the ground station in a string from the microcontroller are latitude and longitude of the rocket. We are then enabled to input these coordinates into Google Maps and find the exact location of the rocket regardless of mobile service availability.

3.5 Recovery Overview

Due to the weight of the launch vehicle, the recovery team found that deploying the main parachute by itself would break the shock cord from the snatch loading that would ensue from the rocket falling under an already inflated main parachute. After this discovery, a commonly used “lines-first” deployment method was chosen to reduce these shock loads significantly. This was achieved by including a small pilot parachute, which is attached to the main parachute, to be deployed and inflated first to ensure all shock cord lines become taut before the main parachute inflates. In addition to the pilot parachute, a deployment bag housing the main parachute was chosen to provide a neat and orderly deployment to make certain that the main parachute inflates. These considerations were chosen over a reefed parachute system due to complexity, experience, and budget issues while still maintaining a much lower shock to opening load ratio than a recovery system with no pilot parachute/deployment bag. Additionally, in choosing to use COTS recovery components, a high loading factor of safety for all recovery components was established early on to improve the safety of the rocket and the spectators below.

While implementing a pilot parachute “lines-first” deployment method, recovery of the rocket *INVICTUS* will still follow a typical dual deployment recovery profile using black powder charges to deploy the parachutes. At 10,000 feet above ground level, the rocket will deploy the drogue parachute and then at 1,400 feet, the rocket will deploy the pilot parachute to aid in pulling out the connected main parachute housed in a deployment bag. Under the drogue parachute, there will be two separate sections tethered together and under the main/pilot/drogue configuration, there will be three separate sections all tethered together. With this dual deployment configuration, the rocket will not drift considerably far. Under maximum winds of 25 miles per hour, *INVICTUS* will drift 5,870 feet under worst-case conditions, well within the launch area drift radius. It will land safely on New Mexico’s hard desert terrain and be recovered successfully to be re-flown if desired.

3.5.1 Drogue Parachute Deployment

At apogee, the rocket will separate just aft of the drogue parachute bay into two sections. This will result in the top nose cone/payload bay/main parachute bay/altimeter bay/drogue parachute bay combined section separating from the bottom flight computer bay/motor mount bay combined section. This will be done by igniting a six gram FFFF black powder charge from a COTS barometric dual-deploy AIM USB altimeter as shown below in *Figure 10.* We will use an e-match to pressurize the drogue parachute bay and shear off six 6-32 nylon shear pins. Another completely separate seven-gram redundant charge will also be ignited shortly thereafter from a COTS barometric dual-deploy StratologgerCF altimeter in the event that the first charge fails. These altimeters are stored in a dedicated and shielded altimeter bay with four ¼ inch static port holes to equalize the pressure adequately and read the correct altitude. In this altimeter bay, each of the drogue parachute charges have their own respective battery, switch, e-match, altimeter, and wiring for dual redundancy to ensure the sections separate. Once the sections separate, the 24-inch elliptical drogue parachute will deploy and slow the 82 pound rocket to 123 feet per second. Under this drogue parachute during descent, the flight computer bay and motor mount bay combined section will be well below the other combined section of *INVICTUS* to prevent them from colliding with each other. Having the motor mount combined section below the other combined section instead of the inverse is also specifically designed this way to deploy the main parachute correctly and prevent it from getting tangled on the motor mount and fins.

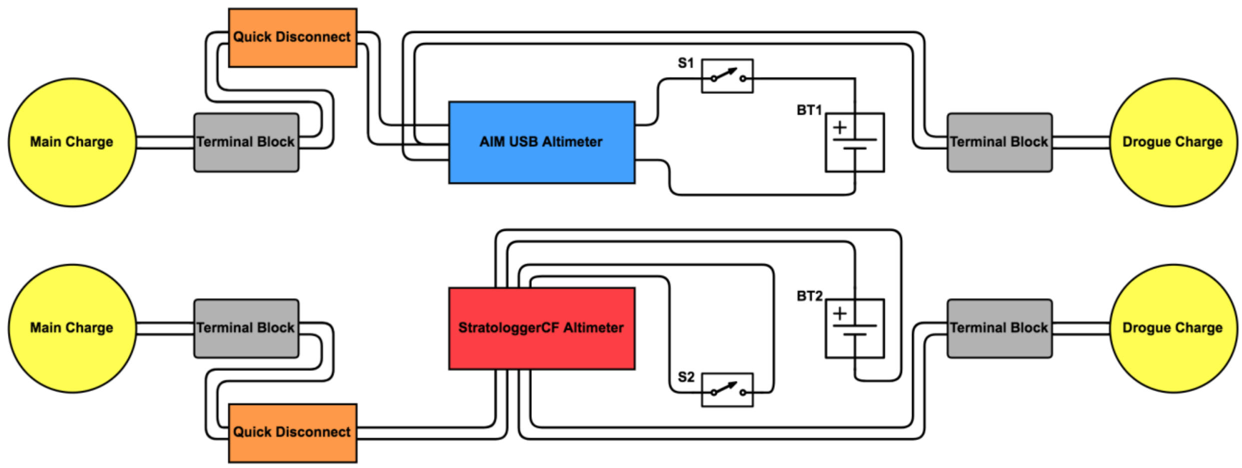

Figure 10: Altimeter Bay Electronics Diagram

3.5.2 Main Parachute Deployment

At 1,400 feet above ground level, the rocket will separate again just aft of the payload bay. This will result in the nose cone/payload bay combined section separating from the main parachute bay, altimeter bay, and drogue parachute bay combined section; thus creating a total of three combined sections to descend to the ground after the main deployment event. This event will occur by igniting a 10 gram FFFF black powder charge from the AIM USB altimeter as shown above again in *Figure 10* using an e-match to pressurize the main parachute bay and shear off six 6-32 nylon shear pins. Another completely separate 10.5 gram redundant charge will also go off at 1,300 feet from the StratologgerCF altimeter in case the first fails. Each of the main parachute charges has their own respective battery, switch, e-match, altimeter, and wiring for redundancy to ensure the sections separate. To clarify, since there are only two altimeters, each altimeter controls both one drogue and one main charge. This setup ensures redundancy because each altimeter system is independent of each other where one cannot directly fail the other. Once the sections separate, the 30-inch elliptical pilot parachute will deploy and inflate to pull out the 144 inch Iris Ultra main parachute from the deployment bag to slow the rocket down to 16 feet per second. Since the deployment bag is in-between the pilot parachute and the weight of the rocket, the main parachute will deploy from the bottom of the bag due to the natural tension the pilot parachute produces. Under descent in this configuration, the nose cone and payload bay combined section will be the upper section, followed by the main parachute bay, altimeter bay, and drogue parachute bay combined section the middle section, and lastly the flight computer bay and motor mount bay combined section the lower section. As mentioned, these sections will all be tethered together to descend to the ground.

3.5.3 Materials and Hardware

For recovery hardware, the rocket has a ⅜ inch steel U-bolt on each ½ inch thick 6061-T6 aluminum bulkhead where a 5/16-inch steel quick link connects to for the recovery harness. The rocket's recovery harness has a six-foot length of ½ inch diameter 5,500 pound rated tubular Kevlar leader shock cord on each side of the altimeter bay. The remaining lengths of shock cord on the rocket are 1 inch in diameter 4,040 pound rated tubular nylon (MIL-W-5625). The Kevlar leader better prevents the shock cord from burning/melting over nylon near the black powder charges while the nylon shock cord reduces shock loads due to its greater elongation over Kevlar. For all connections to hardware, the shock cord is sewed into a plain lap seam using a type 301 split three-point cross-stitch with size 138 Kevlar thread at eight threads per inch on the Kevlar leader and size 207 nylon thread at 11 threads per inch on the nylon harness. Nylon seams use six inches of sewing length while Kevlar seams use nine inches due to Kevlar thread's natural tendency to pull out, resulting in lower seam efficiencies when compared to nylon of equal length. This was all done instead of knotting the shock cord in order to retain a high tensile load rating with a high seam efficiency and form a permanent loop that can't be undone. This rationale is based off of tests conducted by Pioneer Parachute Company as shown in the Project Test Reports Appendix.

For ejection blast protection, the rocket uses biodegradable "dog barf" cellulose fiber that is fire retardant along with two Nomex parachute protectors that cover the parachutes. To allow the rocket to freely rotate under the main parachute, there is a 5/16-inch steel swivel connected to the shock cord. This will help in preventing the shock cord and parachute shroud lines getting tangled and twisted. Also, the rocket has an anti-zipper Kevlar foam ball to distribute any side loads and prevent the shock cord from ripping into the side of the airframe. Lastly, the pilot parachute assembly utilizes a 3/16-inch steel swivel with 3/16 inch steel quick links connected to ¼ inch diameter 3,000 pound rated tubular Kevlar shock cord. Attached to this shock cord is a 16-inch-long Nomex deployment bag that houses the 144 inch nylon main parachute and its nylon shroud lines in the sewn elastic loops.

3.6 Payload System

Our payload system will actively measure electrostatic charge accumulated on various sections of *INVICTUS*'s airframe during flight. Research was conducted about the topic and showed there was not much knowledge regarding rockets and the accumulation of static electricity during flight. It was found that in planes however, the presence of a charge build up is so significant it begins to affect navigation and radio communication systems; hence, the use of static wicks on the trailing edge of the wings. While airplanes have much longer flights to endure and more movement through cloud cover (a large source of the static electricity in the air), rockets move at much higher rates of speed. This build up is known to occur when rockets are launched in thick cloud cover, which is ultimately cause for flight delays in industry. The experiment was decided to run as a baseline collector to see if the build-up is as dramatic at such a small scale. The experiment will also shed some light on how carbon fiber, the main and relatively non-conductive material of our rocket's body, behaves in these conditions and if it can present itself as a reliable alternative despite its higher cost to aluminum. The ability to manage static charge could be vital to launch in overcast conditions and cause costly delays. Cyclone Rocketry expects this experiment to be a gateway into charge management for future launches.

The experiment relies on an Arduino to run a code (*Figure 56*) to read pins A0 and A1 on the Arduino. These reading present values from 0-1023 which can be converted into a voltage reading using the following formula:

$$V = \frac{Value * 5.0}{1024.0}$$

The formula converts the reading to an array ranging from zero to five volts; where, zero volts corresponds to a value of zero and five volts corresponds to a value of 1023. This range was chosen because it is the default for Arduino, without a protector circuit, and is safe due to the low conductivity of carbon fiber. These measurements will be taken from sensor wires that lay flat on the surface of the airframe. The data will be recorded to an SD card with a timestamp relative to flight time. The experiment will be powered by a 9-volt battery and will record for the duration of the flight.

4. Mission Concepts of Operation Overview

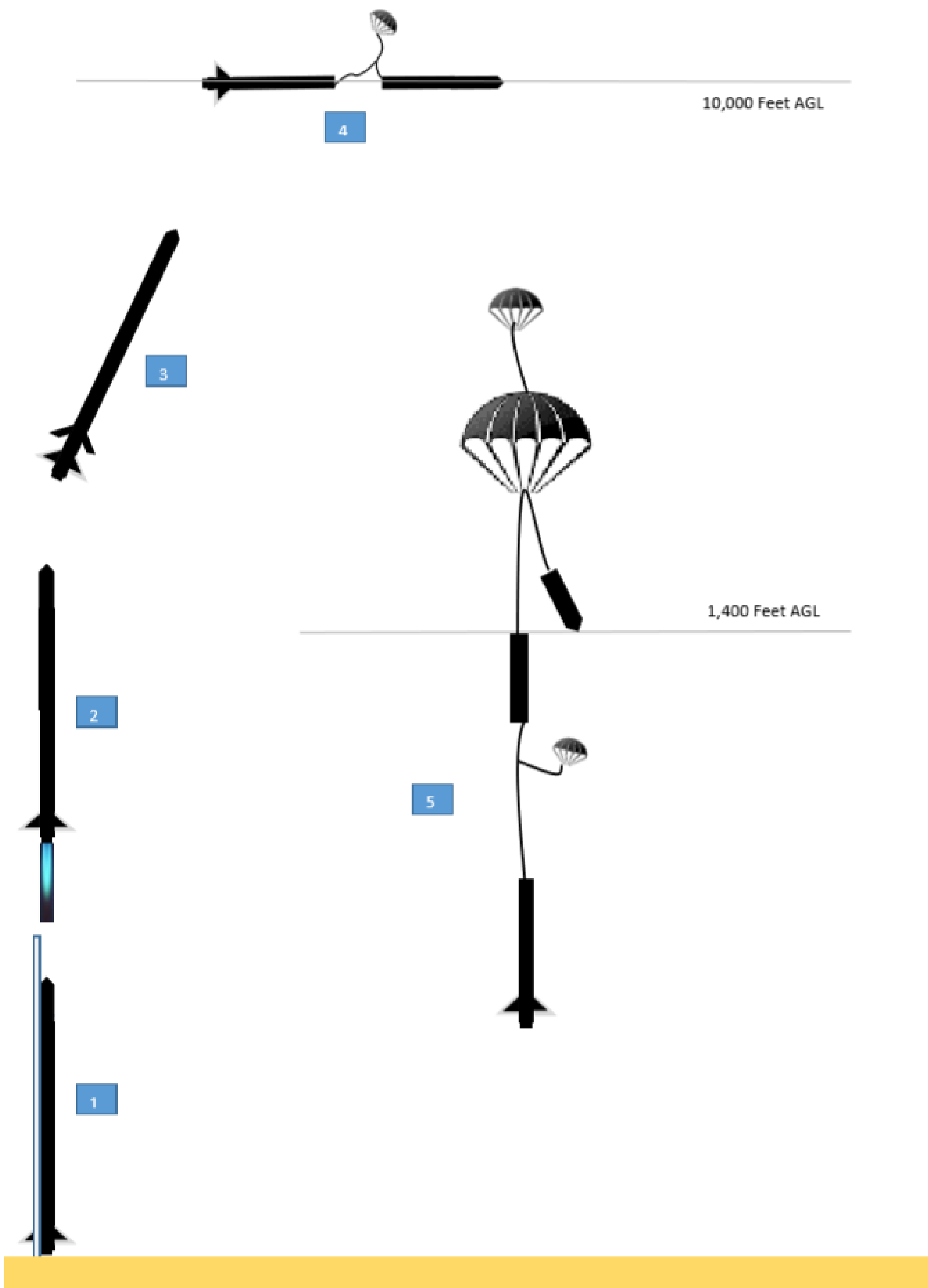

Figure 11: INVICTUS I Flight Profile

4.1 Concept of Operations

1. Vertical Integration

Once the launch vehicle is fully integrated at its respective launch angle, the team will use a small flat head screwdriver to arm four onboard switches to power on our flight computer, altimeters, and cameras.

From a safe distance, a signal will be sent to our rocket and it will ignite our motor.

2. Lift off

INVICTUS leaves the launch rail at an appropriate velocity. The N2850 motor will burn for approximately 4.5 seconds.

3. Air Brake actuation and vehicle deceleration

After burnout, the onboard flight computer is measuring the velocity of the rocket, and determines an appropriate time to actuate the vehicle's air brakes to decelerate to the target apogee of 10,000 feet.

4. Apogee drogue parachute deployment

When the rocket finally stops experiencing upward vertical velocity, our initial parachute event will occur. A 24-inch drogue parachute will deploy to slow the descent of our rocket to approximately 123 feet per second.

5. Main parachute deployment

Onboard altimeters will detect that the rocket is approximately 1,400 feet above ground level, at which point our second event will occur. At first, a pilot parachute will deploy. Upon inflation, the pilot parachute will pull out the 144-inch main parachute, slowing the vehicle down to approximately 16 feet per second.

5. Conclusions and Lessons Learned

When undertaking a project of this magnitude for the first time, a team naturally opens itself to the possibility of making mistakes, as well as an opportunity for growth and the chance to learn by doing. Many of the members of Cyclone Rocketry would agree that this method of day by day learning proved invaluable for our organizational and individual growth as engineers and rocketeers.

5.1 Design Lessons

During the design of *INVICTUS I,* many of our members were designing their first high powered rocket. The largest challenge faced in this absence of experience was finding a starting point during the design phase.

Regarding finding a starting point, our team had initial intentions of designing a system with air brakes that could achieve an altitude of 30,000 feet above ground level. After two months of working with this design, our team concluded that with our knowledge base, the only way to reach our target altitude was to use a Cesaroni O8000 motor. This option was vastly out of our budget for the year, so our team decided to change divisions and set our goal for 10,000 feet above ground level. Though some aspects of our design changed as a result, many stayed the same. For this reason, much of our rocket is overbuilt. Looking forward to future designs and the growth of our organization, our team aims to continue to improve upon our air brake design as well as cutting weight and overall bulkiness from our airframe and air brakes. In addition to working towards design optimization, our team will also work to design for the purpose of simplified manufacturing processes in the future.

5.2 Manufacturing Lessons

The biggest lesson learned throughout the manufacturing portion of this design cycle was to plan for the worst and leave plenty of time to make mistakes. This will prove a very valuable lesson for future design cycles as many team members will not have had manufacturing experience before working on a project like this. With this in mind, future teams will be able to plan more adequately for some things to not go according to plan.

In addition to planning for inconveniences, another lesson learned was to verify all aspects of the design before jumping into manufacturing. This could have saved our team some time, money, and stress. By verifying each other's work, our team could have caught errors in our design that set us back from time to time. A quote we've now adopted and try to live by as a team is, "design and verify; measure twice, cut once."

Finally, when Cyclone Rocketry makes more cylindrical carbon fiber parts in the future, such as the airframe and couplers, we plan to use a different method that allows for more accuracy. As this organization progresses and acquires more resources, we hope to make our couplers first, then lay-up a carbon fiber body tube according to the specifications of the couplers with the use of a mandrel. We learned through this year's experiences that performing carbon fiber layups to accommodate predetermined inner diameters is a very difficult task. As a result, we had to change our design from using the carbon fiber couplers we manufactured, to turned-down aluminum tubing. In the future our team plans to build and manufacture the next airframe based on the outer diameter of the couplers we manufacture. This method should make matching the inner diameter of the airframe and the outer diameter of the couplers significantly easier.

5.3 Team Management Lessons and Transfer of Knowledge

In general, our team displayed phenomenal fortitude and ability to adapt to change if anything ever didn't go according to plan. Whenever a circumstance like manufacturing errors or design oversight were encountered by our team, as whole we consistently found a way to combat them in an efficient, timely, and safe manner. As for lessons learned however, a few things could have been done on a team management level that could have prevented some of these mistakes.

Most importantly, because Cyclone Rocketry is a first-year team, there was no preliminary idea for a project timeline. That being said, when one was drafted, there was no knowledge as to how realistic it would be. As time went on, the timeline changed fluidly. In the future, Cyclone Rocketry teams that follow will have a much better idea of what a realistic timeline looks like based off of the time certain things took this year.

Next, our team ran into some minor lead time and shipping errors due to miscommunication with each other as well as material suppliers. These mistakes a led to a higher team stress level and less time for our team to complete important tasks. In the future, these errors can be mitigated be having other members of the team double check and plan further in advance in preparation for delays.

Lastly, a major change our organization looks to make in years to come, will be to introduce all new members to manufacturing processes at the beginning of their tenure with Cyclone Rocketry. Throughout the manufacturing phase of our project there was a large strain on the members that were tasked to complete many of the custom parts on *INVICTUS*. This strain on our membership can be eliminated by having more members with manufacturing experience. By transferring this manufacturing knowledge our team can operate more efficiently. This can also greatly aid the design process. When members are able to design parts that are able to be manufactured, and more easily for that matter, the design phase of the project can run more smoothly.

5.4 Conclusion

Looking back at our first run at the IREC Spaceport America Cup, our team can take away many fond memories, many unique experiences, and many valuable lessons that can be applied to not only rocketry and engineering, but to life in general. We learned how to persevere when times were tough, how to adapt quickly and effectively when time wasn't on our side, and most importantly; we learned that no matter how impossible something may seem at times, there's always a way to accomplish your goals. After a year of hard work, Cyclone Rocketry is very excited about completing and flying *INVICTUS I* and prepared to build upon this year's experiences for the years to come.

.6. Systems Weights, Measures, and Performance Appendix

System Weights, Measures, and Performance Data	
Airframe Length (inches)	182
Airframe Diameter (inches)	6.15
Fin Span (inches)	15.7
Vehicle Weight (pounds)	73.8
Propellant Weight (pounds)	14.9
Payload Weight (pounds)	8.8
Liftoff Weight (pounds)	97.5
Number of Stages	1
Propulsion type	Solid
Liftoff Thrust to Weight Ratio	7.31
Launch Rail Departure Velocity (feet/second)	83
Minimum Static Margin During Boost	3.172
Max Acceleration (G)	8.13
Max Velocity (feet/second)	912.455
Target Apogee (feet AGL)	10,000
Projected Apogee (feet AGL)	11,792

Table 3: System Weights, Measures, and Performance

7. Project Test Reports Appendix

7.1 SRAD Propulsion System Testing

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7.2 Combustion Chamber Testing

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7.3 Hybrid and Liquid Propulsion Tanking Testing

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7.4 Static Hot-fire Testing

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7.5 Recovery System Testing

Our recovery system was first tested on ground to determine sufficient amount of black powder needed to successfully separate the sections of the rocket and deploy parachutes. A full-scale flight test verified the process during descent.

7.5.1 Ground Test Demonstration

Ground testing was done in an open field with the rocket fully assembled lying horizontally off the ground on custom made PVC test stands. This was done to mimic a mid-air deployment exactly and mitigate any friction with the ground if the rocket was not on the stands. To accurately test the charges, the rocket was prepared in a post-burnout configuration with dead weight simulating a burnt-out motor. This was accomplished using iron weights securely positioned inside the motor mount. This way, the rocket weighed 82 pounds, the correct weight of the rocket right after burnout.

To begin testing, the drogue parachute was ejected first to simulate the first apogee event. Six grams of FFFF black powder was measured and poured into the PVC end cap screwed onto the side of the aft altimeter bay bulkhead. An MJG Firewire initiator e-match was inserted into the black powder and the remaining space in the end cap was filled with cellulose fiber and then covered with electrical tape to seal everything in. The ends of the e-match were screwed into the terminal block bolted onto the side of the bulkhead. Once the e-match setup was complete, the rocket was assembled using 6-32 steel tube fasteners and 6-32 nylon shear pins. Cellulose fiber was stuffed inside the drogue bay, the drogue parachute was covered with the Nomex blanket and the nylon harness was daisy-chained into a flight-ready configuration inside the rocket. Once complete, two alligator clips were attached to two wires hanging outside of the altimeter bay that lead to the e-match so that a remote ignitor with a battery could ignite the black powder. At a safe distance, the e-match was ignited to pressurize the drogue parachute bay, shear the six 6-32 nylon shear pins, and push the motor mount section and drogue parachute away from the upper section of the rocket. Using six grams of FFFF black powder was successful as it sheared all six shear pins, deployed the parachute to where it could catch air and inflate if the rocket was launched, and pushed the lower section of the rocket a distance of about 15 feet which is a good rule-of-thumb.

As for testing the main and pilot chute, the drogue parachute and lower section of the rocket was kept on the ground but out of the way to best simulate the main parachute being deployed in real-life. The main PVC end cap charge was prepared the same way as the drogue but with 10 grams of FFFF black powder and then assembled with the upper section of the rocket. The main parachute was packed correctly in the deployment bag, cellulose fiber was stuffed inside the rocket near the charge, shock cords were daisy-chained and neatly placed inside the bay, and the remaining nose cone section was screwed on using six 6-32 nylon shear pins. The alligator clips were hooked up to the wires and once the team was at a safe distance from the rocket, the main charge was ignited. The shear pins were sheared off, the deployment bag with the main parachute and pilot parachute were pushed out of the main tube, and the nose cone was ejected at a good rule-of-thumb distance of 15 feet, so the test was a success. These tests proved that for an actual flight, six grams for the drogue parachute and 10 grams for the main parachute would deploy all parachutes successfully, but as a backup, the redundant charges would carry seven and 10.5 grams of black powder respectively to account for extra variables such as horizontal velocity or wind speed in an actual flight.

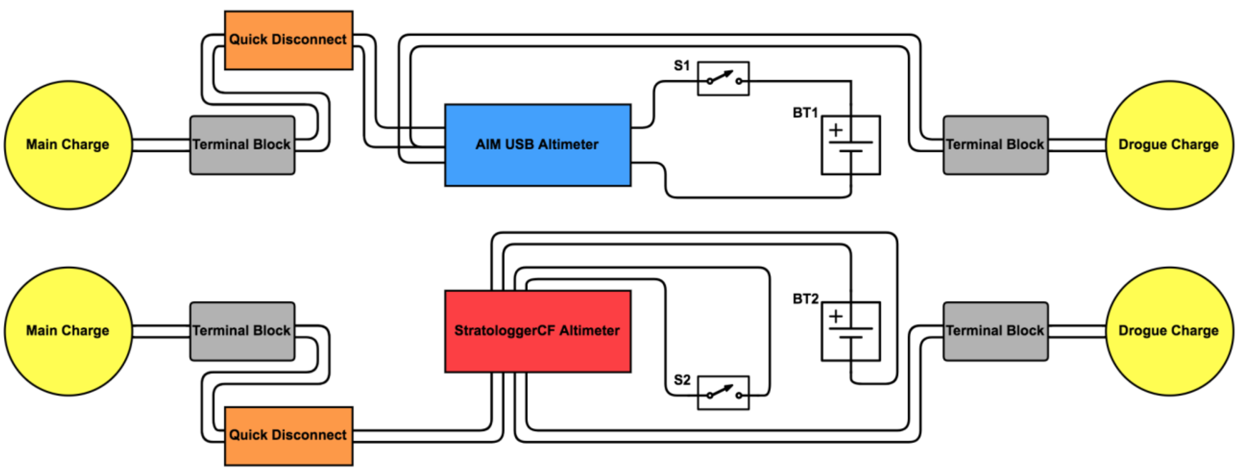

Figure 12: Altimeter Bay Electronics Diagram

7.6 Optional Flight Test Demonstration

Our team conducted a full flight test demonstration on May 13th. Members traveled to North Branch, Minnesota to go through pre-launch procedure and witness our rocket take flight. *INVICTUS I* was vertically integrated on a 17-foot rail angled at 88 degrees from horizontal. Winds were approximately 3-5 miles per hour. The rocket flew straight and true. Upon main parachute deployment, we were able to receive active GPS signal. Fortunately, we were able to see the rocket land approximately 4,000 feet away. The launch vehicle sustained no internal or external damage and was deemed re-flyable. The team confirmed that both dual redundant ejection charges went off. Below is a graphical depiction of the flight test flight profile (*Figure 13*). Given these circumstances, our team has reason to believe *INVICTUS* should fly in a similar fashion at Spaceport America.

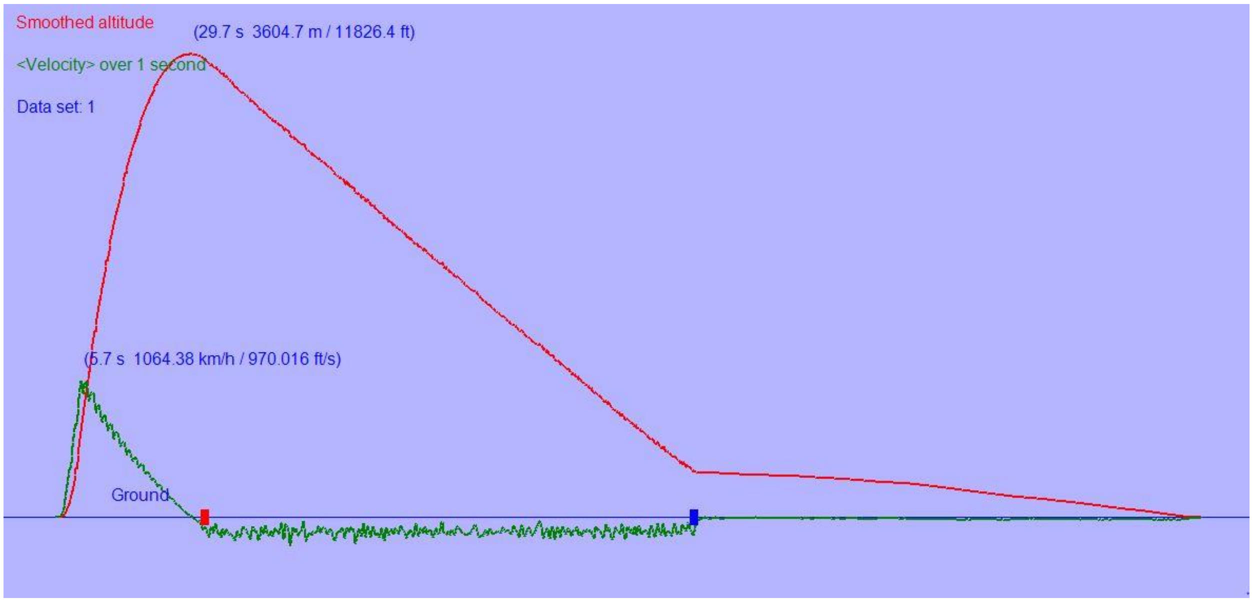

Figure 13: Optional Test Demonstration Flight Profile

7.7 SRAD Pressure Vessel Testing

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7.8 Proof Pressure Testing

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7.9 Optional Burst Pressure Testing

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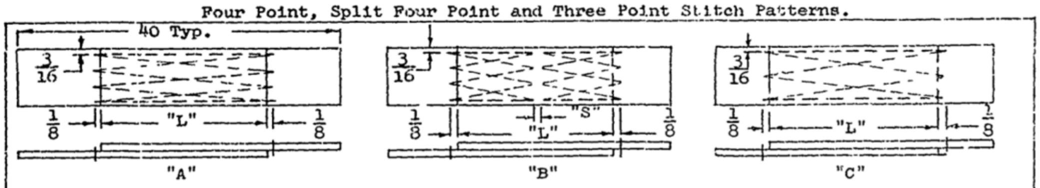
7.10 Shock Cord Tensile Testing

WADC TR 56-313 Pt II

TABLE VIII

Four Point, Split Four Point and Three Point Stitch Patterns.



NYLON WEBBING	TH'D. SIZE	ST./IN.	OVER-LAP TYPE	"L"	"S"	SERIES NO.	BREAKING STRENGTH (AVERAGE)	EFF. %	COMMENT
MIL-W-5625, ½"W.,1000 lbs.	"E"	8	"C"	6	-	III	1316	89	One stitch failure. Webbings failed at stitch ends on the rest.
MIL-W-5625, ½"W.,1000 lbs.	"F"	8	"C"	6	-	III	1432	97	Webbing failed at end of stitching.
MIL-W-5625, ½"W.,1000 lbs.	"FF"	8	"C"	6	-	III	1470	99.6	Webbing failed at end of stitching.
MIL-W-5625, 1"W.,3000 lbs.	"F"	8	"C"	6	-	IV	2090	52	Stitching failed on all specimens.
MIL-W-5625, 1"W.,3000 lbs.	"FF"	8	"C"	6	-	IV	2646	66	Stitching failed on all specimens.
MIL-W-5625, 1"W.,3000 lbs.	3 cord	8	"C"	6	-	IV	3746	93	Webbing failed at end of stitching.
MIL-W-5625, 1"W.,3000 lbs.	5 cord	6	"C"	6	-	IV	3307	81.9	Webbing failed at end of stitching.
MIL-W-5625, 1"W.,3000 lbs.	3 cord	11	"C"	6	-	IV	3833	94.9	Webbing failed at end of stitching.

MIL-W-5625, 1/2", 1000 lbs. Control = 1476 lbs.
MIL-W-5625, 1' W., 3000 lbs. Control = 4040 lbs.

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Figure 14: Four Point, Split Four Point and Three Point Stitch Patterns

In 1956, Pioneer Parachute Company Inc. of Manchester, Connecticut, under the direction of the U.S. Air Force, conducted tests on varying harness materials with varying stitching patterns and thread characteristics to study the effect they have on seam efficiency. These tests varied the type of joint, the size of thread and sewing needle, the pattern of stitching, and the number of stitches per inch. Taken from their report as shown in table VIII above, is data obtained from using 1-inch width, MIL-W-5625 tubular nylon harness with varying thread sizes and threads per inch. Note that other combinations of possible changes to affect the seam efficiency from the report are not shown due to these results having lower seam efficiencies than shown above. Looking at the bottom test; a 1-inch width, 4,040 pound rated tubular nylon shock cord with a three-cord thread size (207 size equivalent), an 11 threads per inch seam, a three-point cross stitch pattern, and a six inches length seam yielded the highest average breaking strength of 3,833 pounds giving the combination a 94.9 percent seam efficiency. This seam efficiency was the highest out of all tests conducted on the 1-inch width, 4,040 pound rated tubular nylon shock cord, so the team naturally used these results and based the design of the recovery harness after this test. Looking into other tests, it was apparent that in every single test done with a split three-point cross stitch, there was an increase in seam efficiency compared to a regular three-point cross stitch, so the team used this to further increase the seam efficiency and breaking strength. This overall combination currently constructs the entirety of the nylon webbing on *INVICTUS* yielding a much stronger bond than if the recovery team chose to knot the shock cord which would give the cord a lower seam efficiency of around 40 to 75 percent, depending on the knot used.

7.11 Non-Destructive Evaluation

To ensure the structural integrity of the fuselage, two non-destructive evaluation (NDE) techniques were used. The two NDE techniques utilized were air coupled ultrasonics and pulse thermography. Air coupled ultrasonics testing involves transmitting a frequency through a material. The transmission in a piezoelectric transducer sends a signal out and the receiver picks up the signal. This transmission in collected and displayed with defects shown as attenuations of the ultrasonic signal. In the setup of the experiment, a robotic fixture is used to minimize error. The data is then collected on a computer and digitized. Once completed, defects in the test subject can be identified. The set up for the lamb-wave air coupled ultrasonics is displayed in *Figure 12* and *Figure 13*.

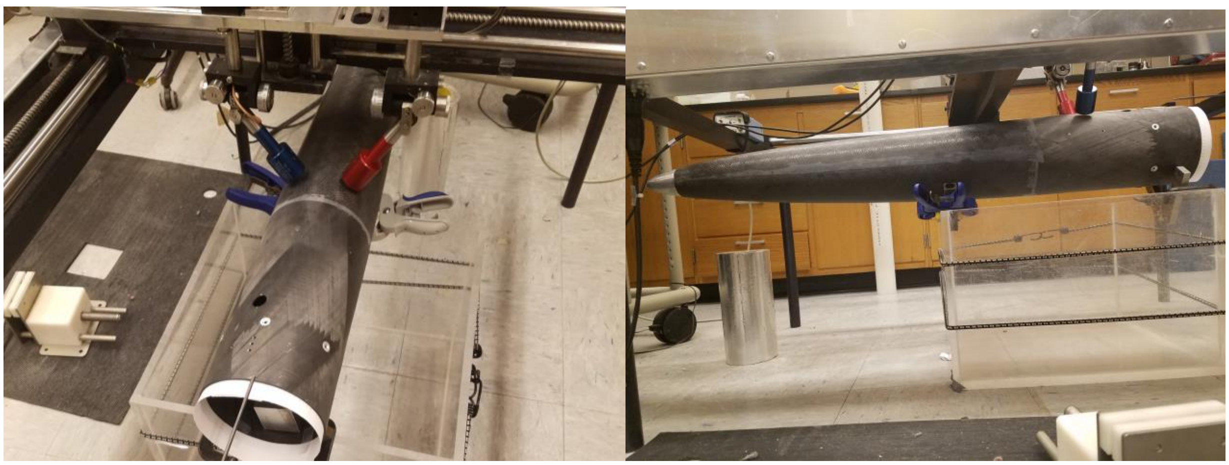

Figure 15 & 16: Air Coupled Lamb-Wave Ultrasonic Test Set Up

The data collected from the air coupled ultrasonic tests identified delaminations ranging from two to six square millimeters in area. With the use of finite element analysis, it was determined that these delaminations had no bearing on the structural integrity of the rocket. On the lower section of the fuselage, a single four square millimeter ovular delamination was identified from ultrasonic testing as well. This delamination was also determined to not be a structural hazard to the integrity of the air frame.

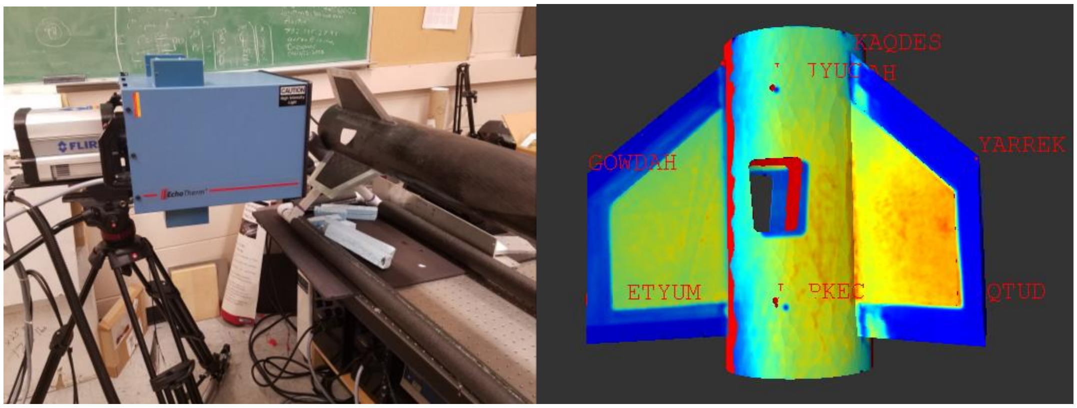

Figure 17 & 18: Fin Section Pulse Thermography Set Up

When performing pulse thermography tests, two flash lamps are used to transmit a high level of thermal energy into a material for a short period of time. After this pulse of energy is transmitted, a thermal camera records the differences in temperature observed. Over the respective time period, the data is overlaid on a 3D CAD model of the test subject shown in *Figure 15*. When a material has an internal defect, said defect has a different response to temperature due to variations in its geometric and/or material properties. Common defects within carbon fiber are delaminations; and these delaminations behave as voids. These voids can be seen by way of infrared camera. If there are no defects present, then the thermal waves propagate into the material without disturbances. In *Figure 17*, the thermal image is overlaid on a CAD model of our fin section. This figure displays a small delamination on the right-hand side of the structure. This is the same defect identified with the air coupled ultrasonic tests stated earlier. As aforementioned, it was determined that the depth of this delamination is not a structural concern.

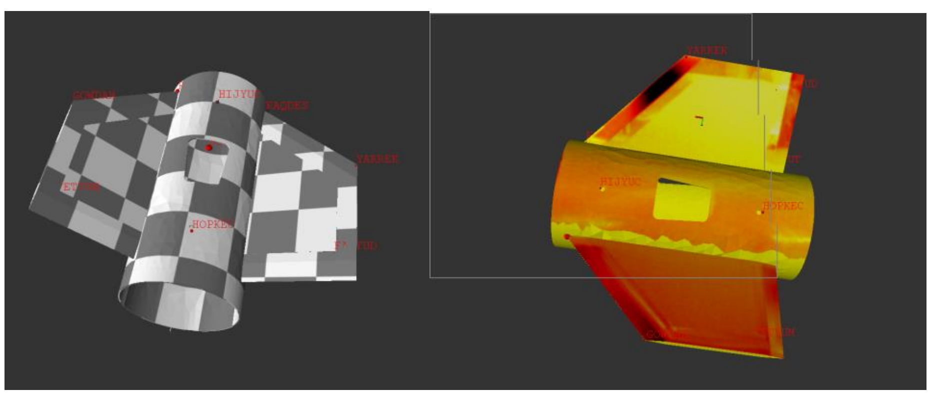
Figure 19 & 20: Fin Section Pulse Thermography Delamination Identification

8. Hazard Analysis Appendix

Hazard	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Rocket falls from launch rail during pre-launch preparations, causing injury.	Rail buttons are not securely attached to *INVICTUS I*.	Low; Industry-grade launch rails in combination with a successful use of rail buttons (during first test launch).	Ensure that rail buttons are fastened to the rocket and apply stress test to ensure.	Low
	Launch rail was not assembled properly.		Inspect launch rail when assembled and apply a stress test to determine if it is properly assembled.	
Rocket does not ignite when command is given ("hang fire"), but does ignite when team approaches to troubleshoot	Transmitters and ignition system are not properly set up.	Low; The range is opened up after time has passed after a misfire so a motor igniting after that time is unlikely to start.	Inspect system before launch to ensure that it was properly assembled and set up.	Low
	The fuse is blown or faulty.		Ensure that fuse has no damage and is free of any other defects.	
Explosion of solid-propellant rocket motor during launch with blast or flying debris causing injury	Cracks in propellant grain.	Low; certified COTS motor with testing and verification.	Visually inspect motor grain for cracks, de-bonds, and gaps during and after assembly.	Low
	De-bonding of propellant from wall.		Use ductile (non-fragmenting) material for motor case.	
	Gaps between propellant sections and/or nozzle.		Inspect motor case for damage during final assembly before launch.	
	Chunk of propellant			

	breaking off and plugging nozzle.			
	Motor case unable to contain normal operating pressure.			
Rocket deviates from nominal flight path, comes in contact with personnel at high speed	Fin separates from rocket during launch.	Low; Fins are currently attached to *INVICTUS I* with carbon fiber strips and high-grade resin. Also, *INVICTUS I* did not deviate from its flight path much during its test flight.	Inspect fins to make sure that they are secured properly.	Low
	Fin flutter may cause the rocket to become unstable.		Ensure that carbon fiber layups on fins are secure and the fins are not loose.	
	Protrusions on rocket cause instability of rocket.		Ensure protrusions are secured and no other parts may leave the rocket.	
	Abnormal burn of propellant.		Inspect motor and propellant for any cracks or abnormalities.	
Recovery system fails to deploy, rocket or payload comes in contact with personnel	Recovery system is not secured tightly or properly.	Low; Recovery system has been tested numerous times without any deployment failures.	Inspect recovery system to ensure that all parts are fastened tightly and engaged properly before and during assembly.	Minimal
	Not enough black powder to shear off shear pins.		Pack all parachutes neatly and properly.	
	Parachutes get tangled and don't inflate.		Carefully place harness inside the tube loosely with a proper daisy-chain.	
	Parachutes were not folded correctly.		Use redundant black powder charges to shear nylon shear pins.	
	Parachute gets stuck in tube or is too tight.			

Recovery system partially deploys, rocket or payload comes in contact with personnel	Recovery system is not secured tightly or properly.	Low-Medium; Main parachute is of concern due to its large size	Inspect recovery system to ensure that all parts are fastened tightly and engaged properly before and during assembly.	Low
	Not enough black powder to shear off shear pins.		Pack all parachutes neatly and properly.	
	Parachutes get tangled and don't inflate.		Carefully place harness inside the tube loosely with a proper daisy-chain.	
	Parachutes were not folded correctly.		Use redundant black powder charges to shear nylon shear pins.	
	Parachute gets stuck in tube or is too tight.			
Recovery system deploys during assembly or pre-launch, causing injury	Altimeters are faulty or have errors from last launch.	Low; Altimeter bay is RF-shielded from any signal misfiring the altimeters and igniting the black powder charges	Test beep codes of altimeters before integrating them on the rocket.	Minimal
	A strong RF signal triggers the altimeter to ignite the black powder charges.		Remove all RF signal devices near the rocket besides those specifically needed.	
Main parachute deploys at or near apogee, rocket or payload drifts to highway(s)	Wiring is reversed or connected the wrong way.	Low; Pre-flight checklists will be double checked to verify wiring is correct	Two team members sign off on each pre-flight checklist item to ensure all setup and wiring steps are completed accurately and correctly.	Minimal
	Altimeter is faulty and ignited the wrong the charge.		Test beep codes of altimeters before integrating them on the rocket.	

Recovery bulkhead, U-bolt, quick-link, harness, parachute, etc. breaks upon deployment causing sections of the rocket to fall without a parachute	Harness leading to the motor mount section doesn't go taut and produces a strong shock load when the main parachute inflates.	Medium; Shock loadings are still present and could be substantial to break any component	Use a pilot parachute and deployment bag to ensure a "lines-first" deployment method so the lines go taut and shock loads are therefore reduced significantly.	Low
	Strong snatch load occurs with the main parachute being ejected out of the main parachute bay.		Pack all parachutes neatly and properly.	
	Nose cone experiences a strong shock load when pilot parachute inflates.		Accurately measure out the correct amount of black powder.	
			Inspect recovery system to ensure that all parts are fastened tightly and engaged properly before and during assembly.	
Rocket catches on fire due to the black powder charges on deployment	Parachute/harness is stuck inside the tube causing the fire to be contained inside.	Low; FFFF black powder burns very fast so it's unlikely fire-retardant materials will burn quickly	Use a fire-retardant harness near the black powder charges.	Minimal
	Cellulose insulation is forgotten to be put inside the rocket.		Use a Nomex blanket and stuff cellulose fiber in near the black powder charges to protect the parachutes.	

	Embers quickly cut through the Kevlar to the foam/tape and start a fire.		Accurately measure out the correct amount of black powder.	
			Pack parachutes and harnesses into the parachute bays loosely.	

Table 4: Hazard Analysis Matrix

9. Risk Assessment Appendix

The risks in the matrix below can negatively affect the CONOPS of *INVICTUS I.* Our team has identified these risks beforehand, and done everything in terms of design, manufacturing, and assembly to mitigate these potential issues.

Risk	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach
Flight computer begins to detect flight prematurely.	Onboard accelerometers detect accelerations that trigger flight.	Low-Medium- The COTS accelerometers tend to leak acceleration.	Arm system only after it is fully vertical and ready for launch. Set trigger threshold to higher acceleration.
Flight computer wires detach from PCB, H-board, or battery.	Inserting avionics sled into coupler strains wires and causes detachment.	Low-Medium - The wires are securely fastened but if pulled on hard enough they can come undone.	Team members will exercise care and precaution when handling all components of the rocket to prevent user error.
Altimeters read incorrect altitude and deploy parachutes early.	Setting the altimeters incorrectly/not calibrating the altimeters.	Low - The COTS altimeters have been flight tested and performed as expected.	Use caution when setting deployment altitude i.e. double check before arming and flying.
Altimeters read incorrect altitude and deploy parachutes late/do not deploy parachutes.	Setting the altimeters incorrectly/not calibrating the altimeters.	Low - The COTS altimeters have been flight tested and performed as expected.	Use caution when setting deployment altitude i.e. double check before arming and flying.
Air brakes deploy too early/for too long resulting in a low miss in target apogee.	Incorrect reading from flight computer.	Medium - System is based off a predetermined flight profile and a test profile, leaving room for error.	Ensure the correct flight profile is uploaded to the onboard flight computer and arm launch vehicle in the upright position.

Air brakes do not deploy for long enough resulting in a high miss in target apogee.	Incorrect reading from flight computer.	Medium - System is based off of a predetermined flight profile and a test profile, leaving room for error.	Ensure the correct flight profile is uploaded to the onboard flight computer and arm launch vehicle in the upright position.
Electronics' power supply (battery) shakes loose from its housing.	Snatch load from first recovery event.	Low - Launch vehicle undergoes a large snatch load when the drogue parachute is ejected.	Zip ties are in place around the batteries to secure from disconnecting during recovery.
Payload experiment does not read electrostatic charge during flight.	Initial acceleration during launch tampers with connection to payload electronics.	Medium - The launch vehicle is expected to undergo 8 G's of acceleration which could shake components loose from the payload experiment.	Secure all components of payload system before flight.

Table 5: Risk Analysis Matrix

10. Assembly, Preflight, and Launch Checklists Appendix

10.1 Step by Step Vehicle Assembly and Arming Checklist:

[ ] - Verify all bolts are secured in upper portion of Air-brake system and rods are in full actuation position.
[ ] - Insert Air-brake system into main body, utilizing the pre-installed securing plate inside the main body tube.
[ ] - Attach and fasten the thrust plate and motor retainer assembly.
[ ] - Install Air-brake pads.
[ ] - Using the power supply, close the Air-brakes.
[ ] - Verify two screws are securing the top and bottom portions of the avionics sled
[ ] - Secure batteries (Two different ones make sure to specify which is which) to avionics sled using zip-ties
[ ] - Connect batteries to their respective boards
[ ] - Reference & Complete Avionics Checklist
[ ] - Insert and secure camera in avionics bay
[ ] - Insert two 9-volt batteries into altimeter bay
[ ] - Attach two rail buttons within their respective couplers, and attach 3rd to main body tube.
[ ] - Check to see if powder container wires are disconnected and power is switched off
[ ] - Measure out six grams of black powder and insert into primary PVC container on drogue parachute bulkhead. Secure with electrical tape.
[ ] - Measure out seven grams of black powder and insert into secondary PVC container on drogue parachute bulkhead. Secure with electrical tape.
[ ] - Measure out 10 grams of black powder and insert into primary PVC container on main parachute bulkhead. Secure with electrical tape.
[ ] - Measure out 10.5 grams of black powder and insert into secondary PVC container on main parachute bulkhead. Secure with electrical tape.
[ ] - Connect powder container charges
[ ] - Assemble avionics coupler
[ ] - Connect linear actuator to the h-bridge wires of avionics coupler
[ ] - Insert avionics coupler into main body tube
[ ] - Fasten avionics coupler to main body tube with tube fastener screws (every other screw, then all screws).
[ ] - Verify tube fastener screws are tight and tube is aligned.
[ ] - Assemble altimeter coupler
[ ] - Fasten altimeter coupler to drogue parachute tube with tube fastener screws. (Every other Screw, then all screws).
[ ] - Attach drogue parachute quick-link to aft U-bolt on altimeter coupler
[ ] - Pour in half of the cellulose fiber insulation bag for drogue parachute

[ ] - Ensure anti-zipper ball is halfway protruding from airframe lip
[ ] - Z-fold Kevlar shock cord and stuff into the drogue bay
[ ] - Fold drogue parachute with lines inside canopy and cover with Nomex blanket. Ensure the shroud lines are not tangled.
[ ] - Pack the drogue parachute inside the drogue bay
[ ] - Daisy chain nylon shock cord for drogue parachute
[ ] - Fasten drogue parachute tube to avionics coupler with shear pins (every other screw, then all screws).
[ ] - Feed Kevlar shock cord through main tube and attach main parachute quick-link to U-bolt on altimeter coupler
[ ] - Fasten main parachute tube to altimeter coupler with tube fastener pins (every other screw, then all screws).
[ ] - Attach main parachute quick-link to forward U-bolt on altimeter coupler
[ ] - Pour in remaining half of the cellulose fiber insulation bag for main parachute
[ ] - Ensure anti-zipper ball is halfway protruding from airframe lip
[ ] - Z-fold Kevlar shock cord and stuff into the main bay
[ ] - (*This step is recommended to be done inside before launch*) Fold main parachute carefully in a z-fold manner at each gore and returning to the center. Ensure that the shroud lines are not tangled. Z-fold last gore to keep lines remaining in the center of the canopy and stuff into the deployment bag in a z-fold fashion starting with the apex.
[ ] - (*This step is recommended to be done inside before launch*) Once the main parachute is housed in the deployment bag, separate the left, center, and right shroud lines and z-fold each accordingly into their respective elastic straps on the deployment bag. Make sure the main parachute bridle is hanging outside the deployment bag with the steel swivel and that the deployment bag cover is over all shroud lines. Tape around deployment bag if this is done inside before launch to prevent any shroud lines from moving.
[ ] - Remove tape around deployment if needed
[ ] - Connect main parachute quick-links accordingly
[ ] - Insert the deployment bag with the main parachute into the bay with the Nomex blanket covering the bag
[ ] - Fold pilot parachute with lines inside canopy. Ensure the shroud lines are not tangled and put next to the deployment bag inside the bay
[ ] - Daisy chain pilot parachute Kevlar shock cord and stuff into the main bay
[ ] - Daisy chain nylon shock cord and stuff into the main bay
[ ] - Insert and secure three cameras onto the camera sled for payload coupler.
[ ] - Fasten main parachute tube to payload coupler with shear pins (every other screw, then all screws).
[ ] - Fasten payload tube and nose cone section to the payload coupler with tube fasteners (every other screw, then all screws).
[ ] - Ensure launch site is ready for vehicle mating (launch system is assembled and rail tie downs in place).
[ ] - Slide vehicle onto launch rail horizontally.
[ ] - Raise vehicle to desired launch angle
[ ] - Using a small flat-head screwdriver, power on all four cameras onboard
[ ] - Using a small flat-head screwdriver, power on all four rotary switches

10. 2 Preflight Checklist:

[ ] - Vehicle Assembly and Arming checklist completed
[ ] - Rocket positioned on launch rail correctly
[ ] - Flight Computer Bay electronics ON
[ ] -Avionics electronics ON
[ ] -Verify altimeter beep codes
[ ] - Onboard cameras ON and Recording
[ ] - Motor igniter inserted and secure
[ ] - Team positioned safely
[ ] - Hand off to RSO

11. Engineering Drawing Appendix

11.1 Aero-structures Drawings

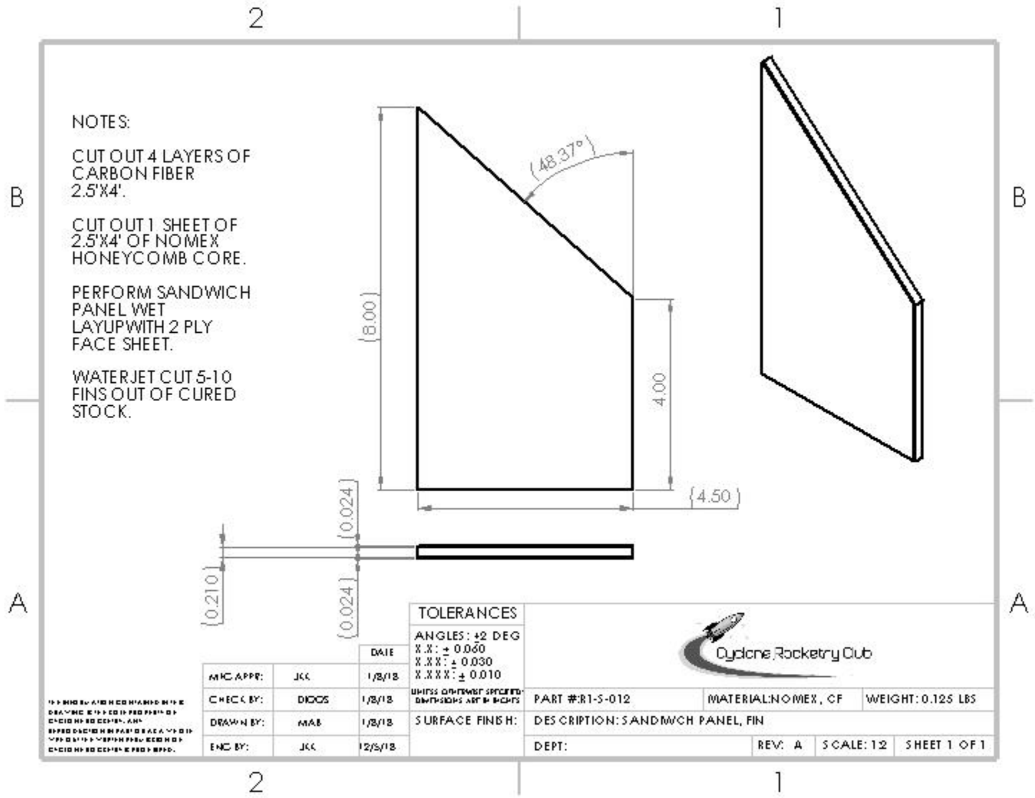

Figure 21: Sandwich Panel Fin Drawing

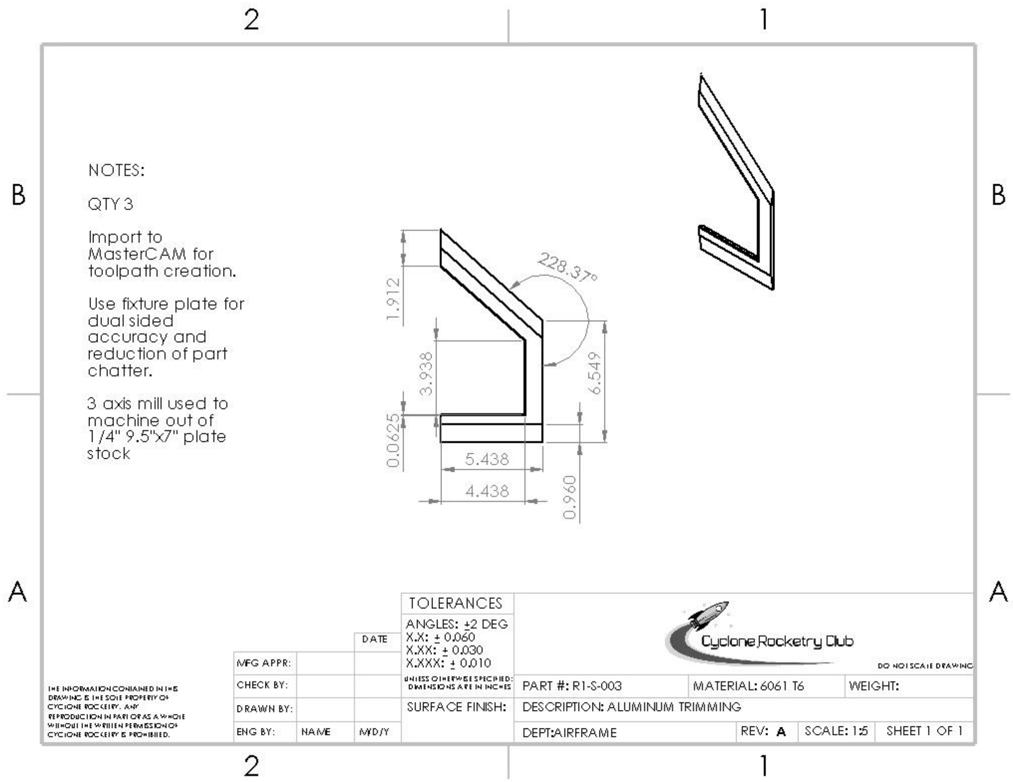

Figure 22: Fin Trimming Drawing

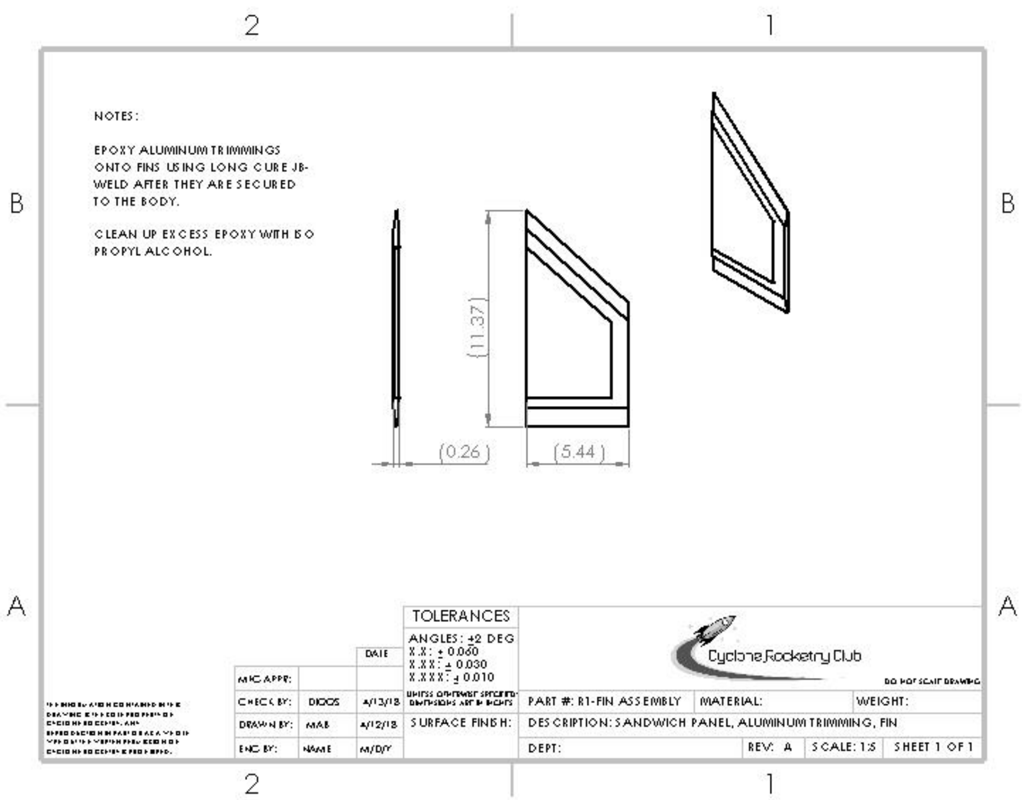

Figure 23: Full Fin Assembly Drawing

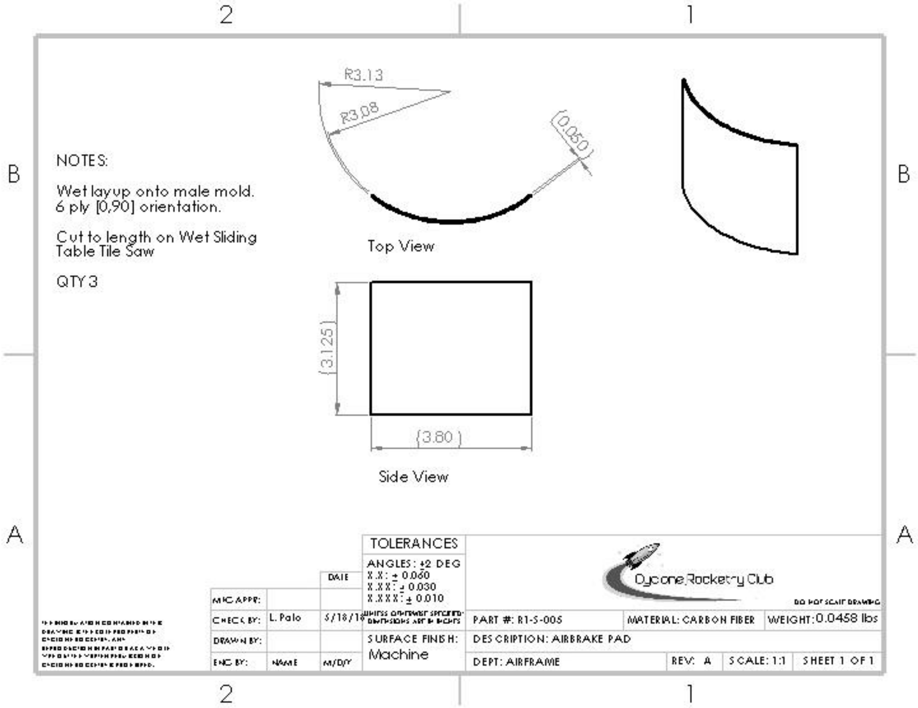

Figure 24: Air Brake Pad Drawing

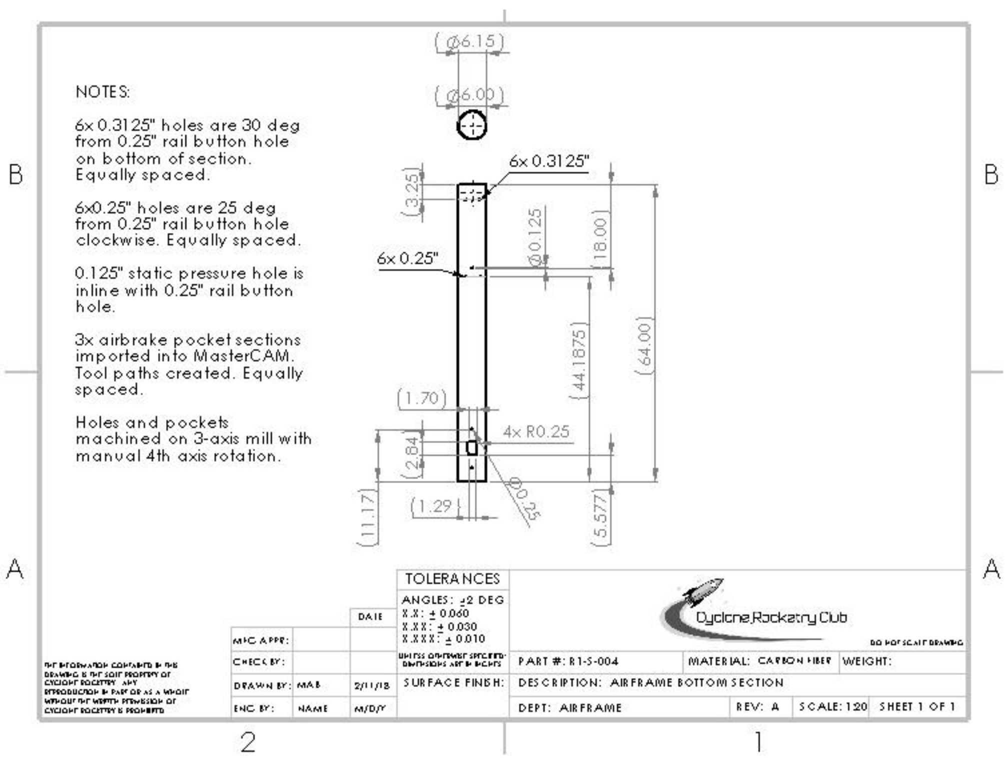

Figure 25: Lower Airframe Section Drawing

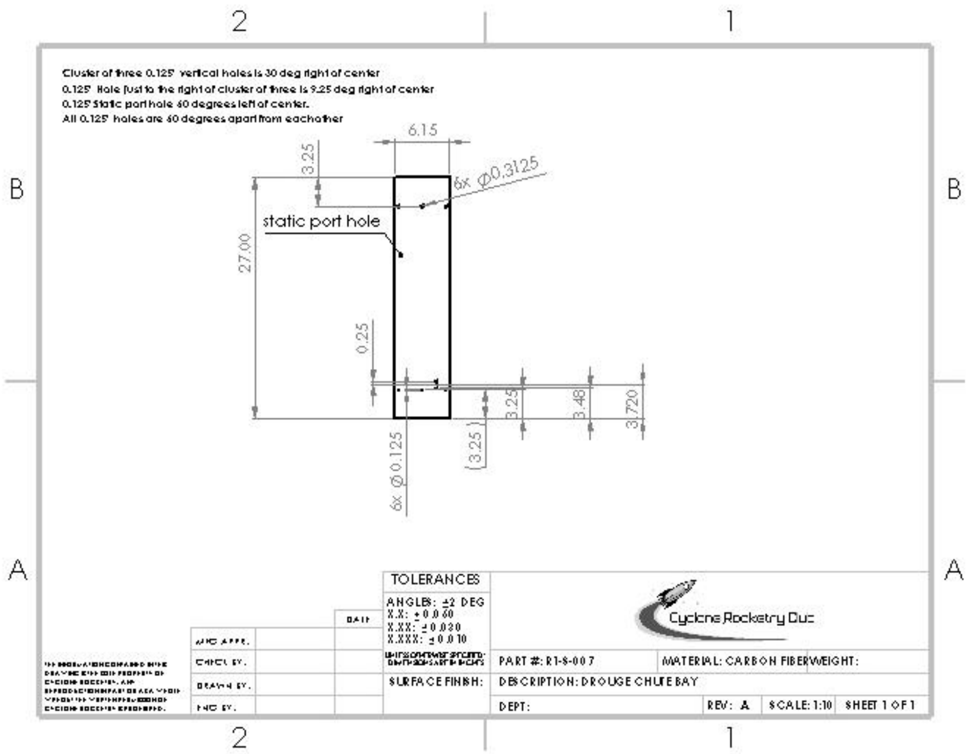

Figure 26: Drogue Parachute Bay Drawing

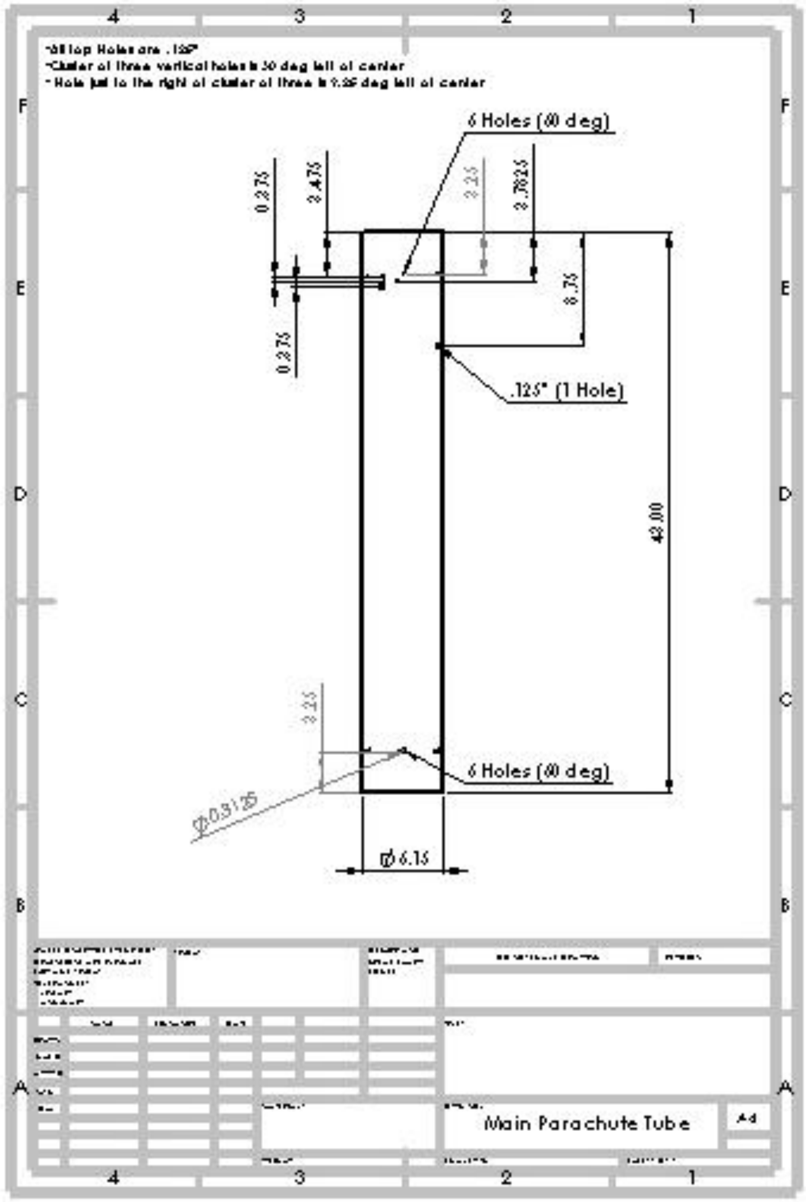

Figure 27: Main Parachute Tube Drawing

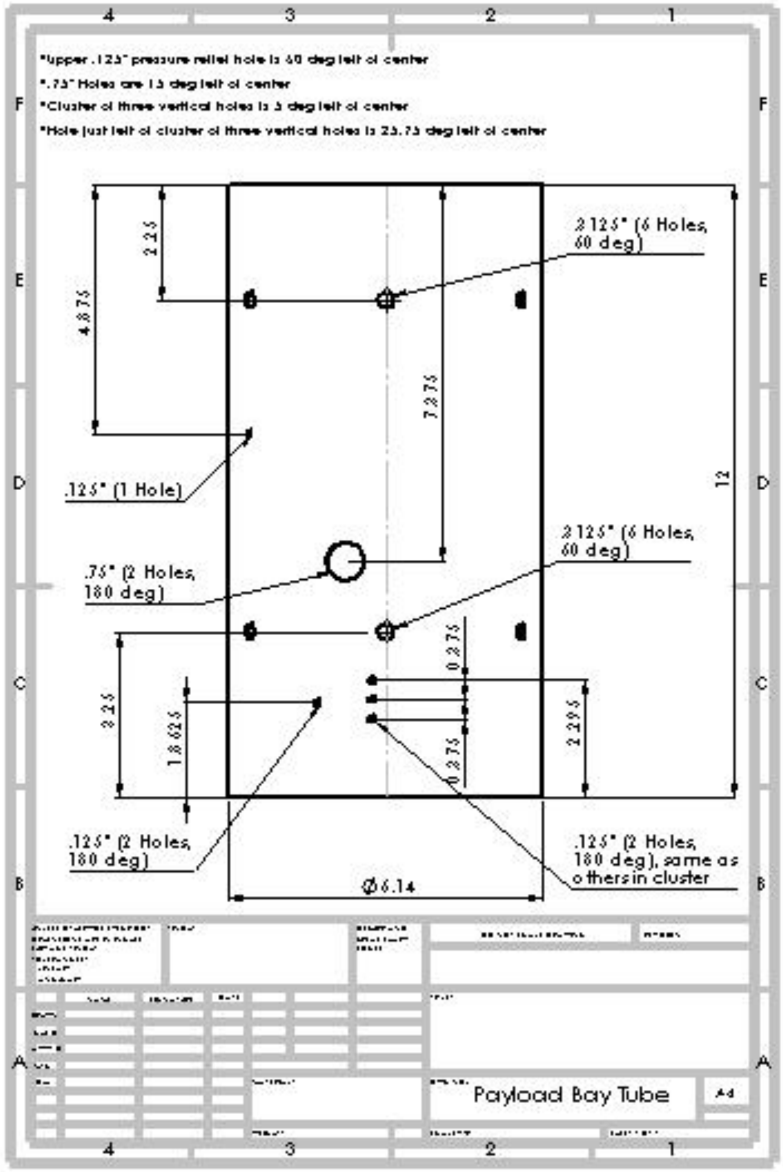

Figure 28: Payload Tube Drawing

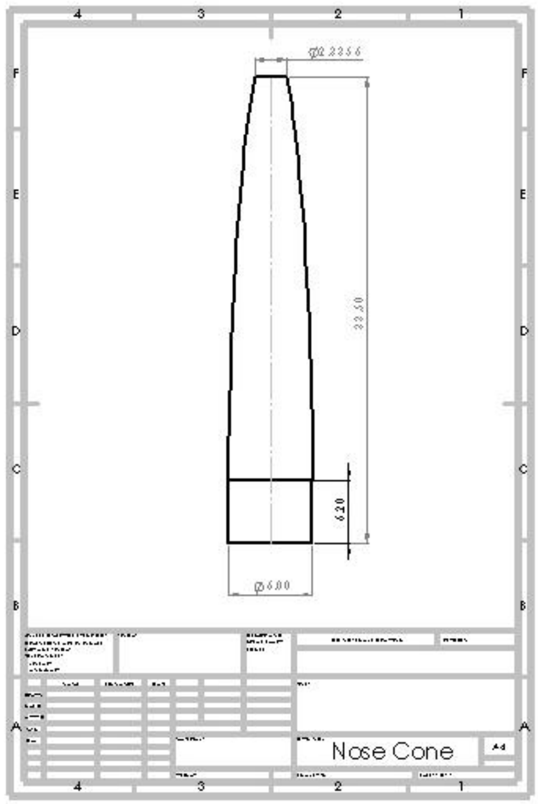

Figure 29: Nose Cone Drawing

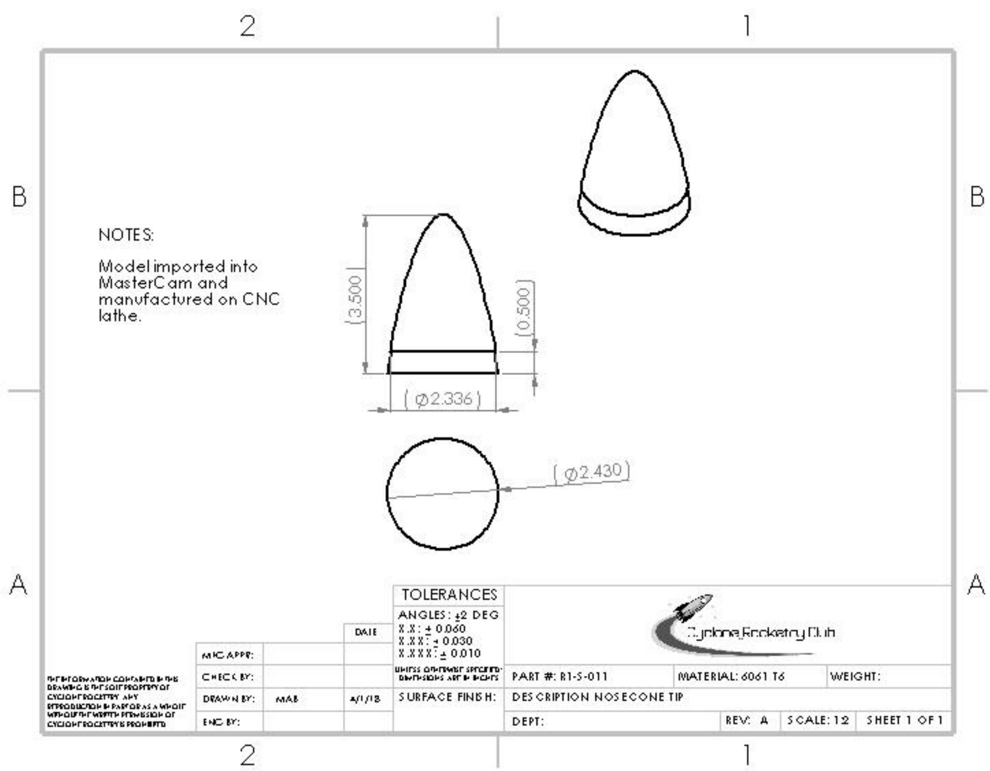

Figure 30: Nose Cone Tip Drawing

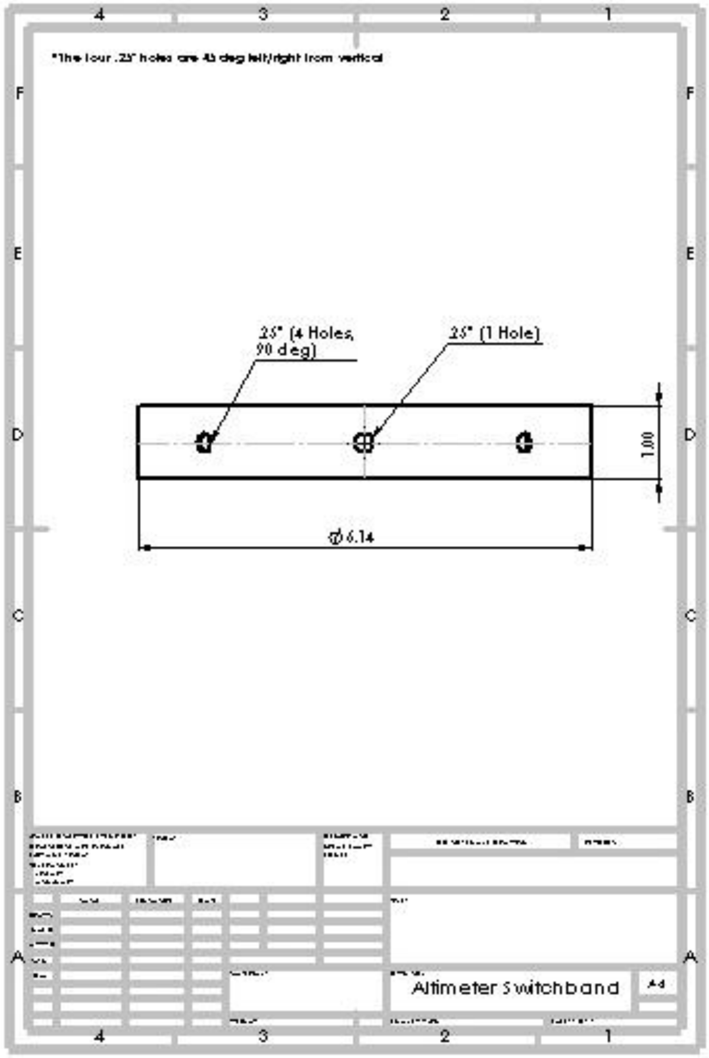

Figure 31: Electronic Switchband Drawing

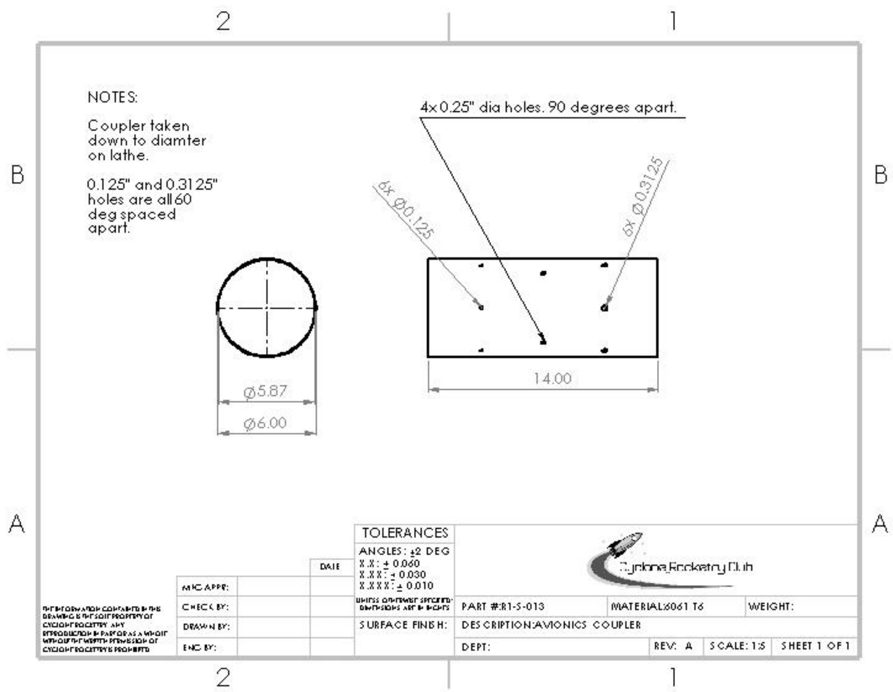

Figure 32: Avionics Coupler

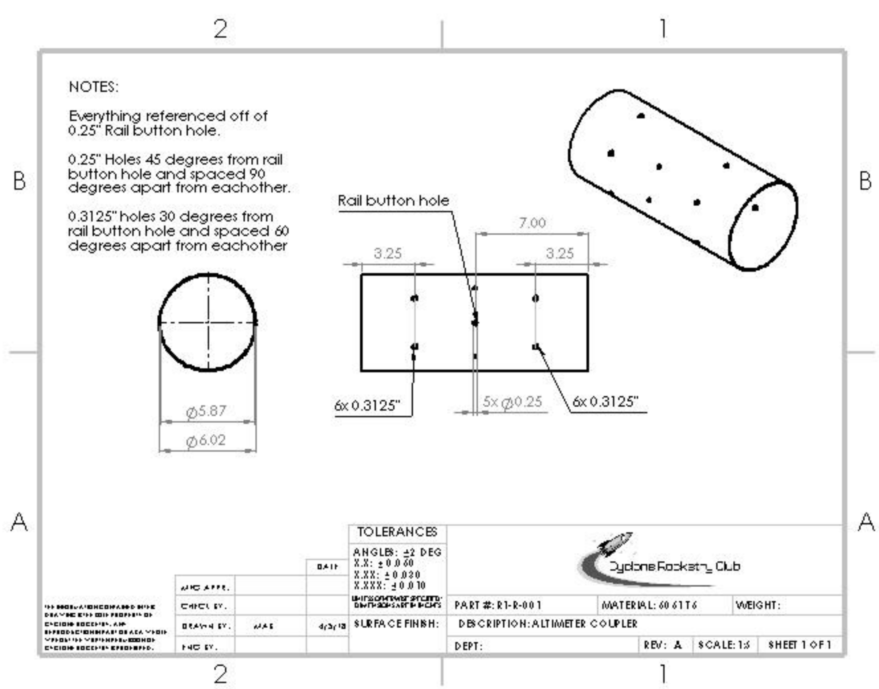

Figure 33: Altimeter Coupler

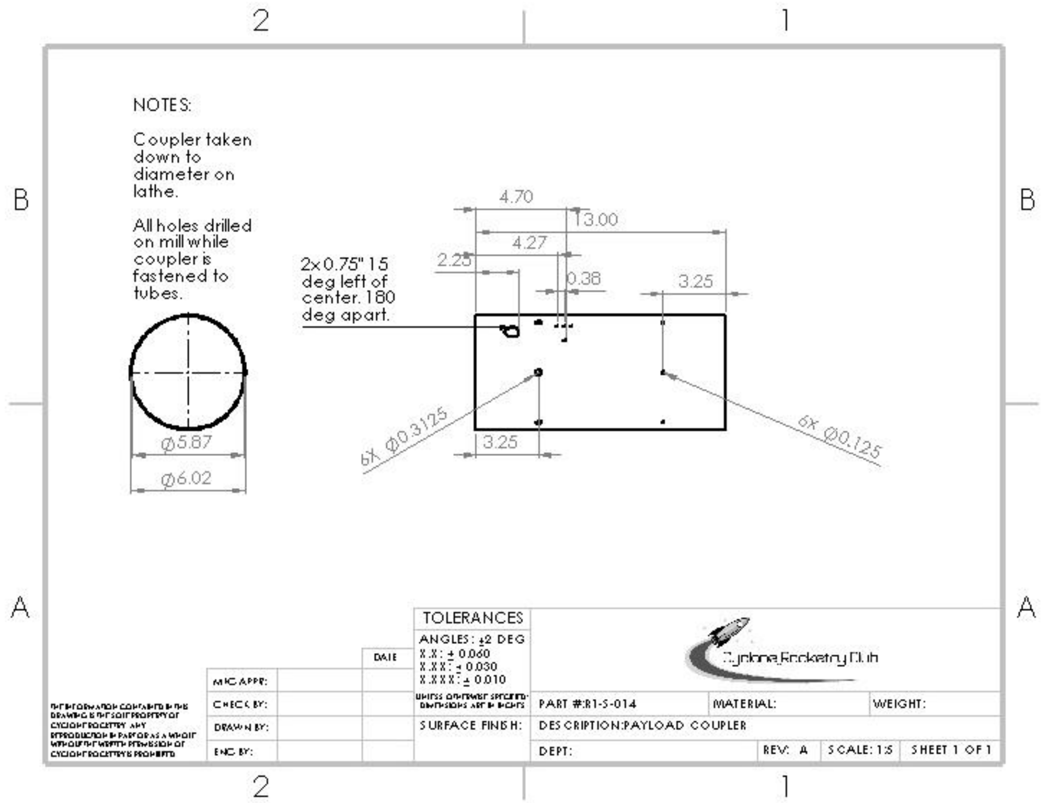

Figure 34: Payload Coupler

11.2 Mechanical System Drawings

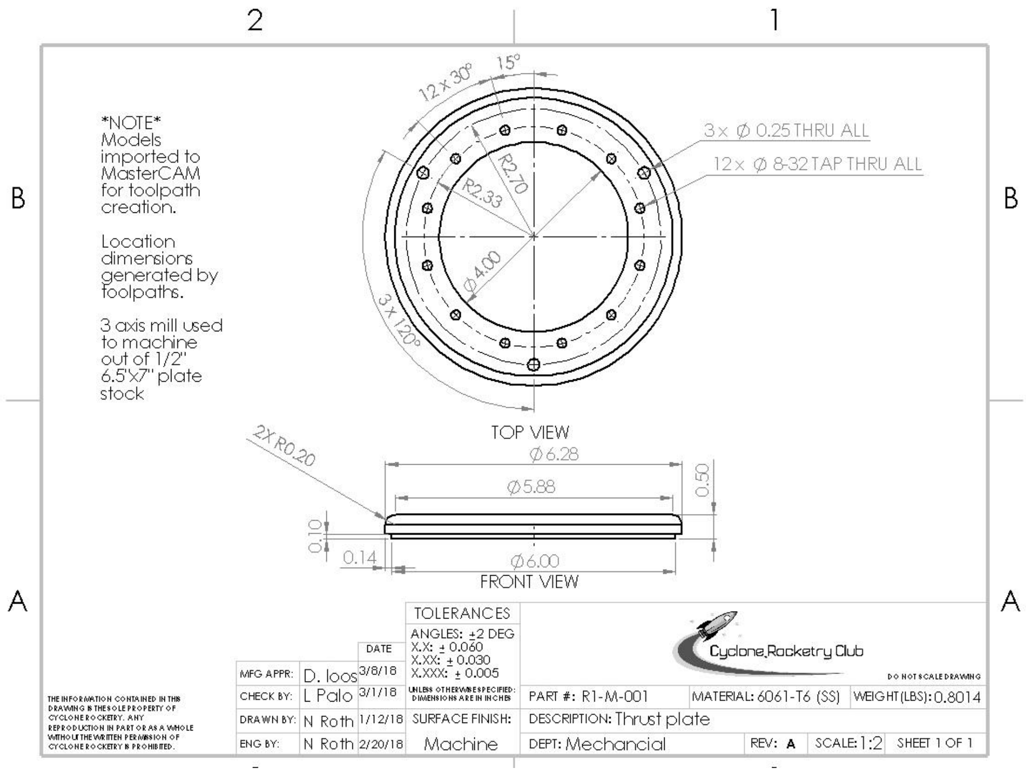

Figure 35: Thrust Plate Drawing

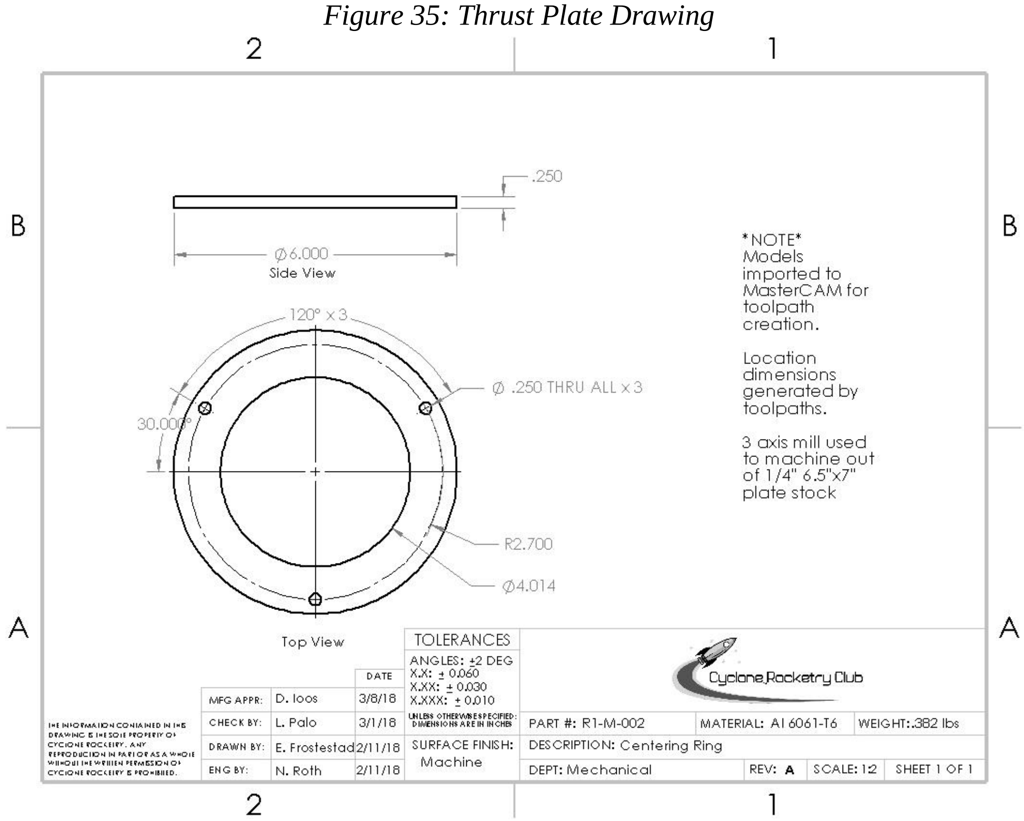

Figure 36: Centering Ring Drawing

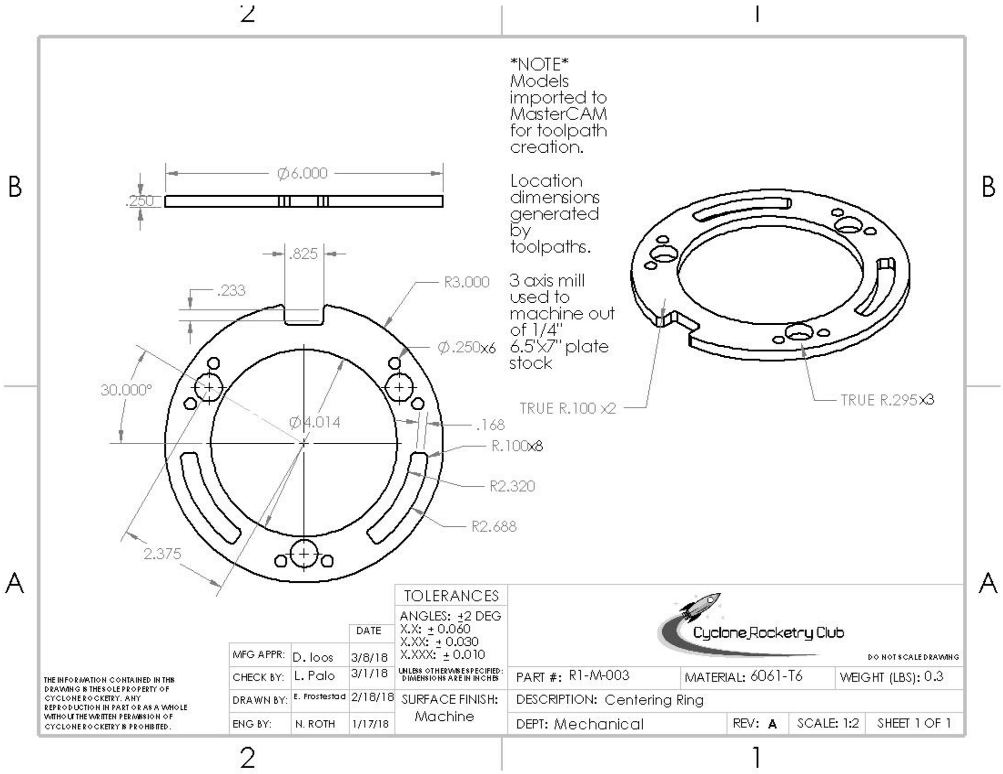

Figure 37: Centering Ring/Airbrake Mount Drawing

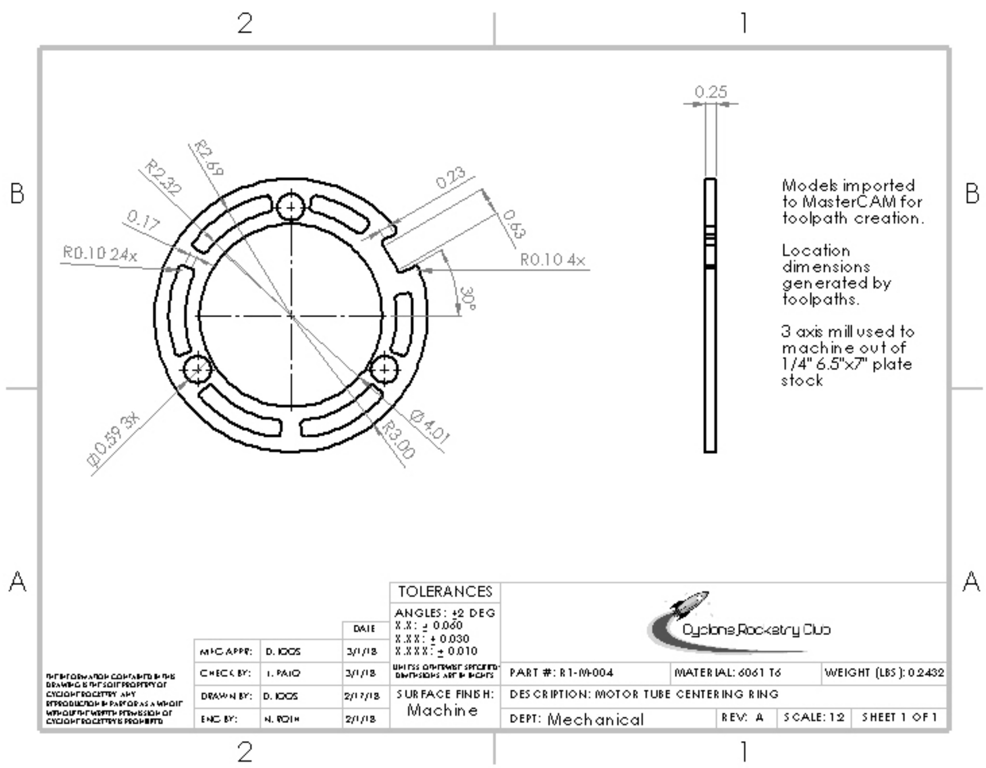

Figure 38: Centering Ring Drawing

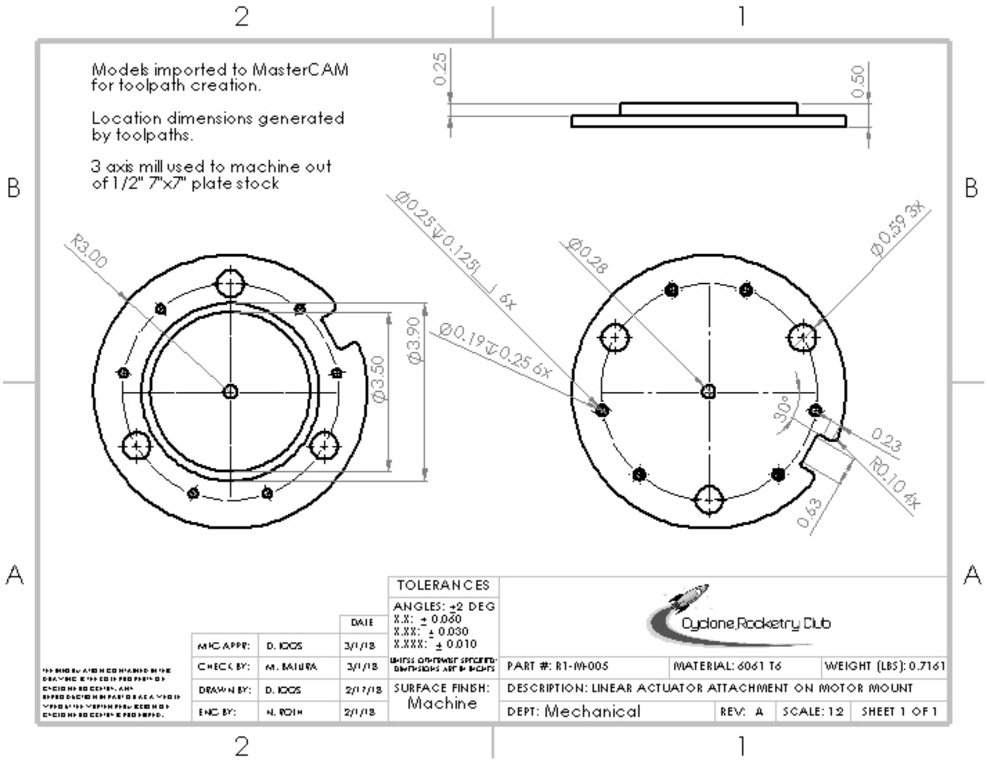

Figure 39: Linear Actuator Attachment Drawing

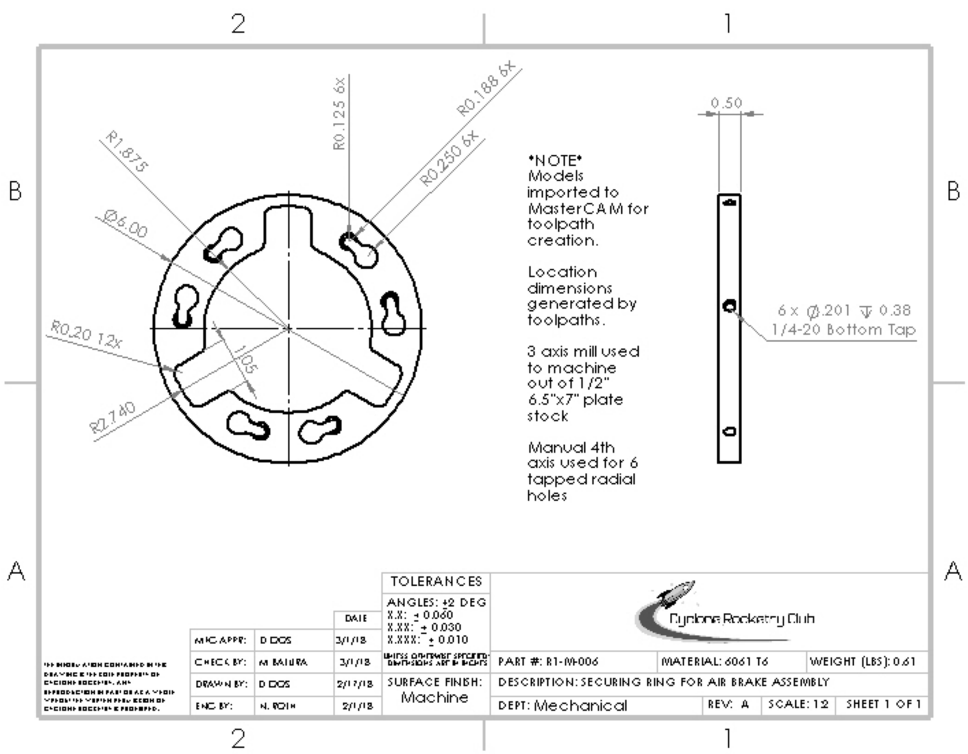

Figure 40: Securing Ring for Air Brake Assembly Drawing

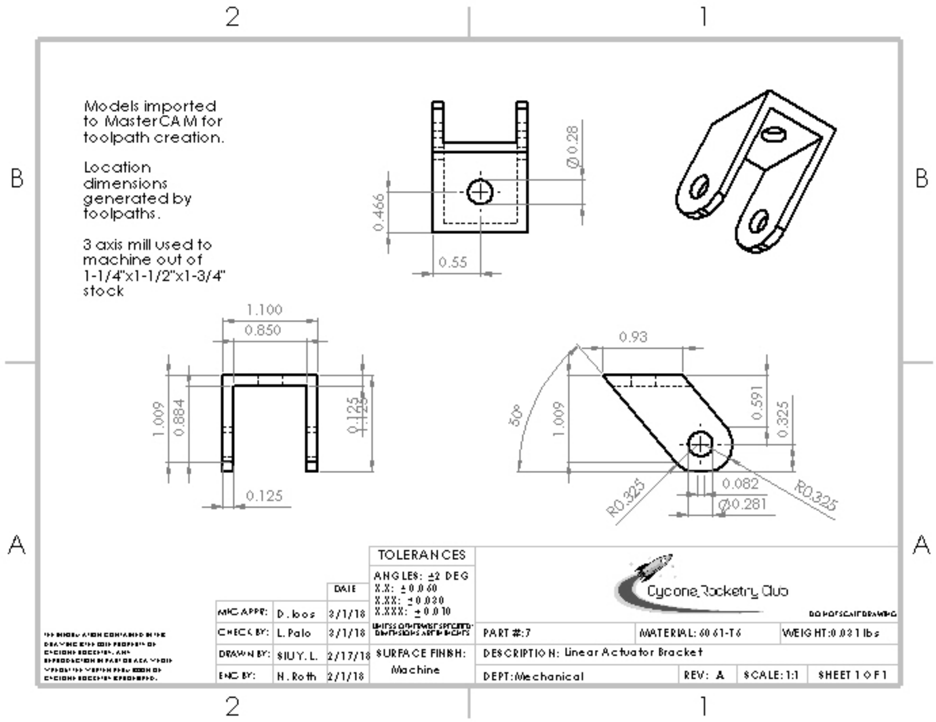

Figure 41: Linear Actuator Bracket Drawing

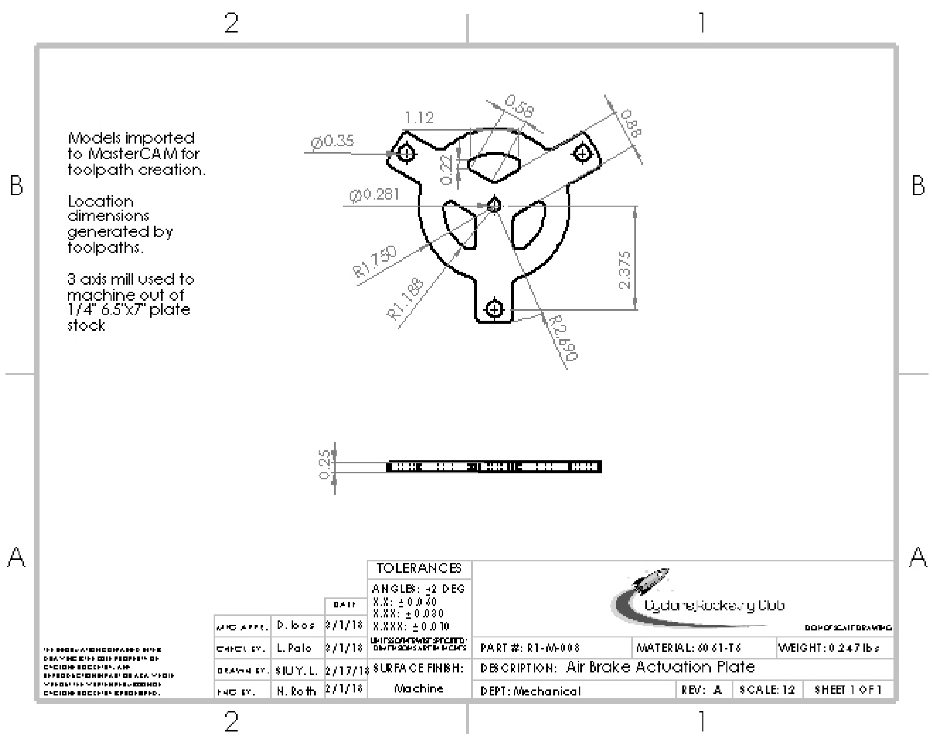

Figure 42: Air Brake Actuation Plate Drawing

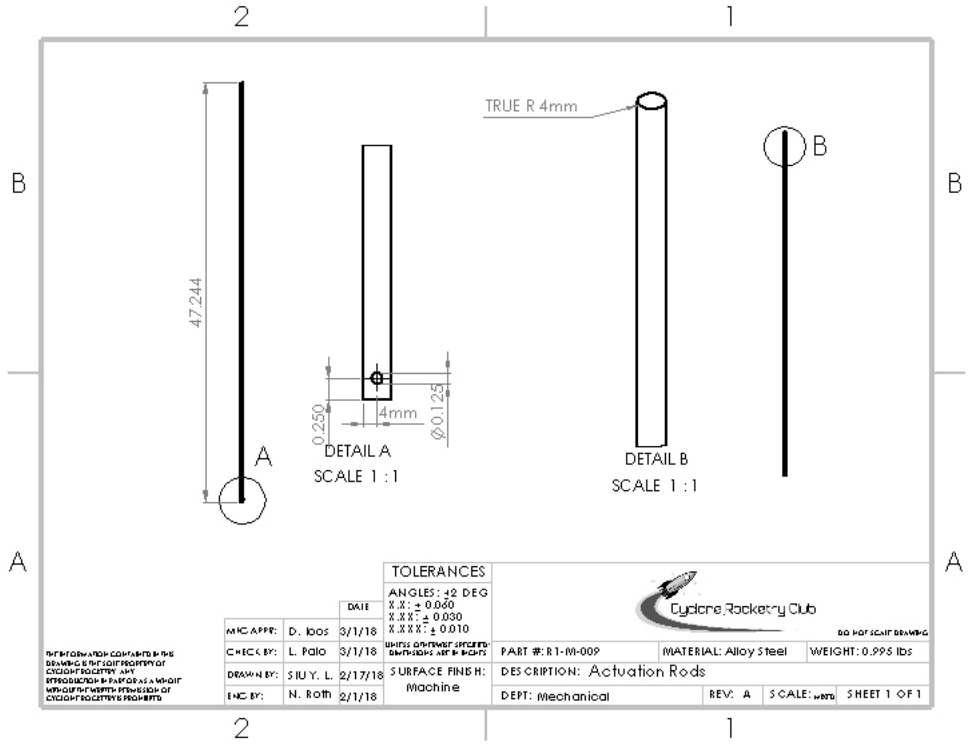

Figure 43: Air Brake Actuation Rod Drawing

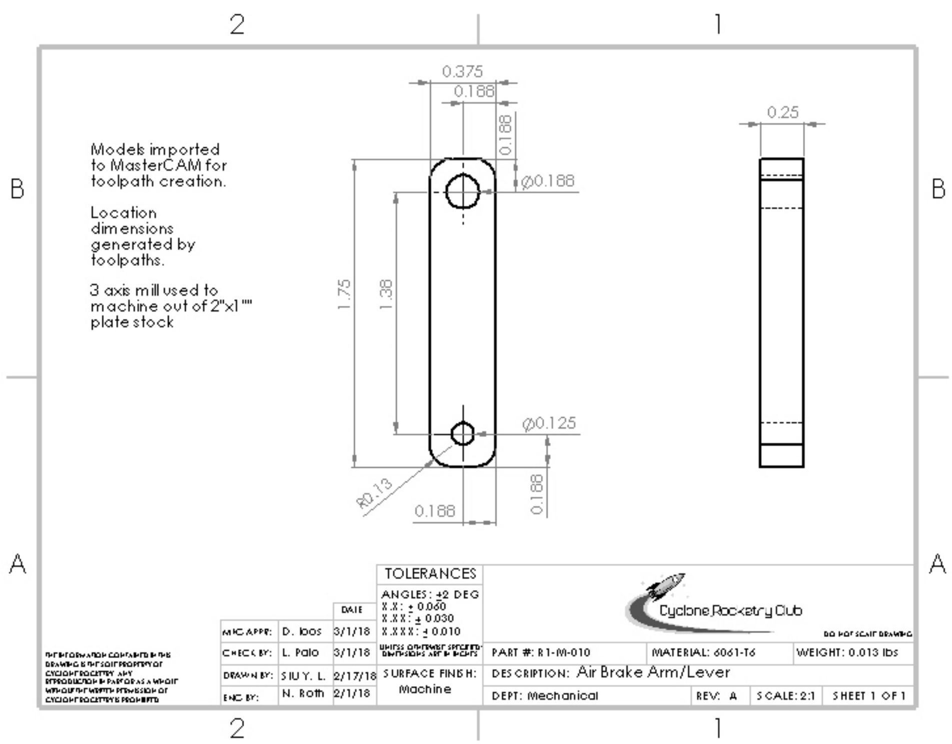

Figure 44: Air Brake Arm/Lever Drawing

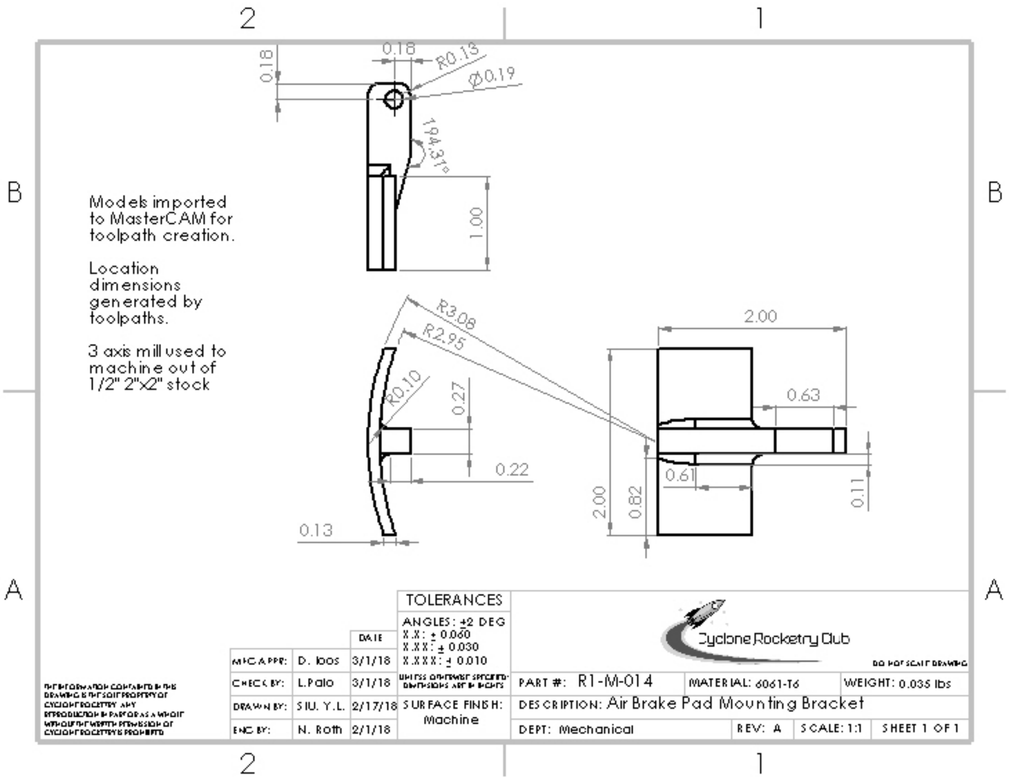

Figure 45: Air Brake Pad Mounting Bracket Drawing

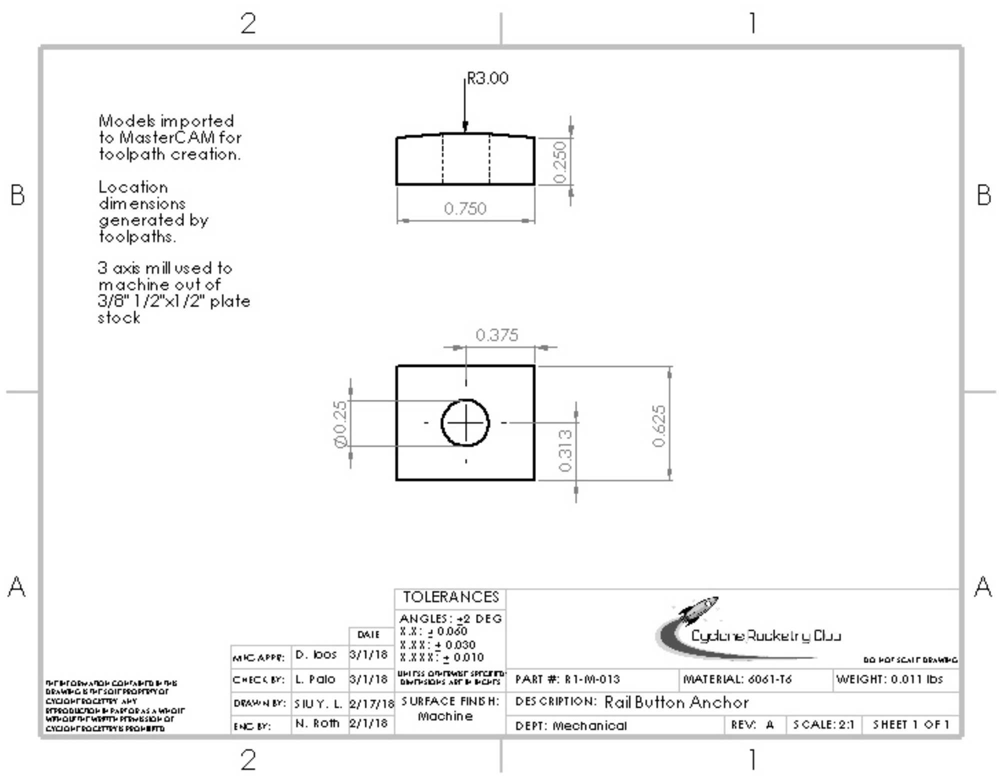

Figure 46: Rail Button Anchor Drawing

11.3 Avionics System Drawings

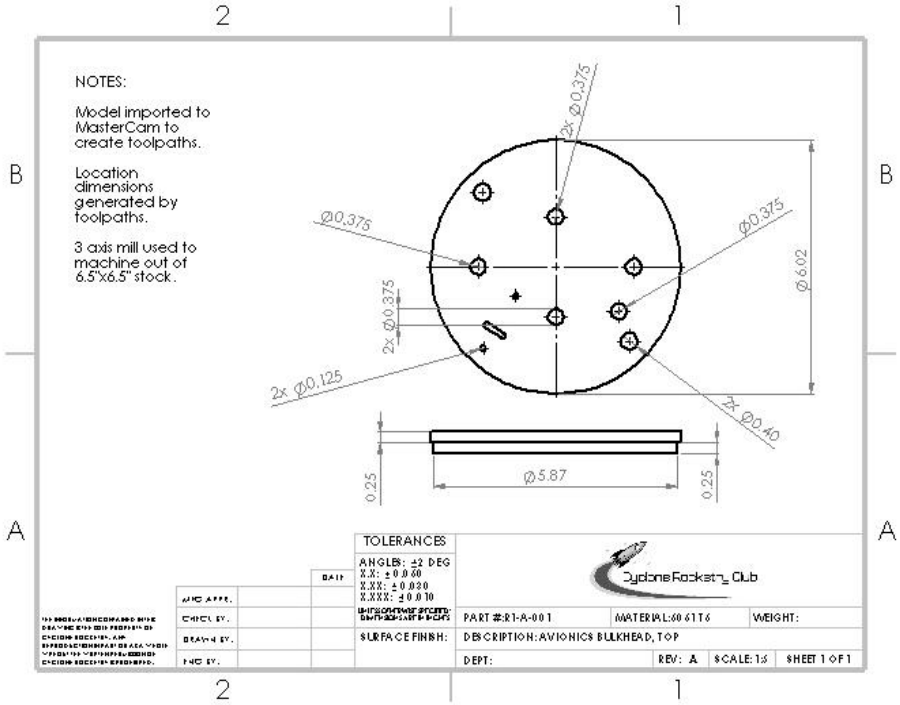

Figure 47: Avionics Upper Bulkhead Drawing

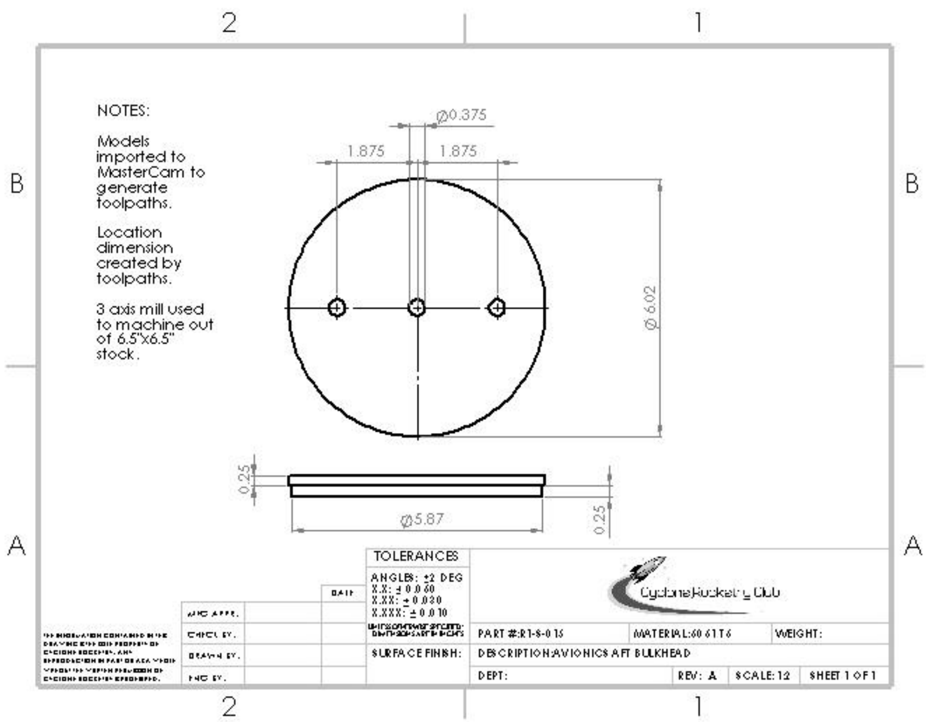

Figure 48: Avionics Lower Bulkhead Drawing

11.4 Recovery System Drawings

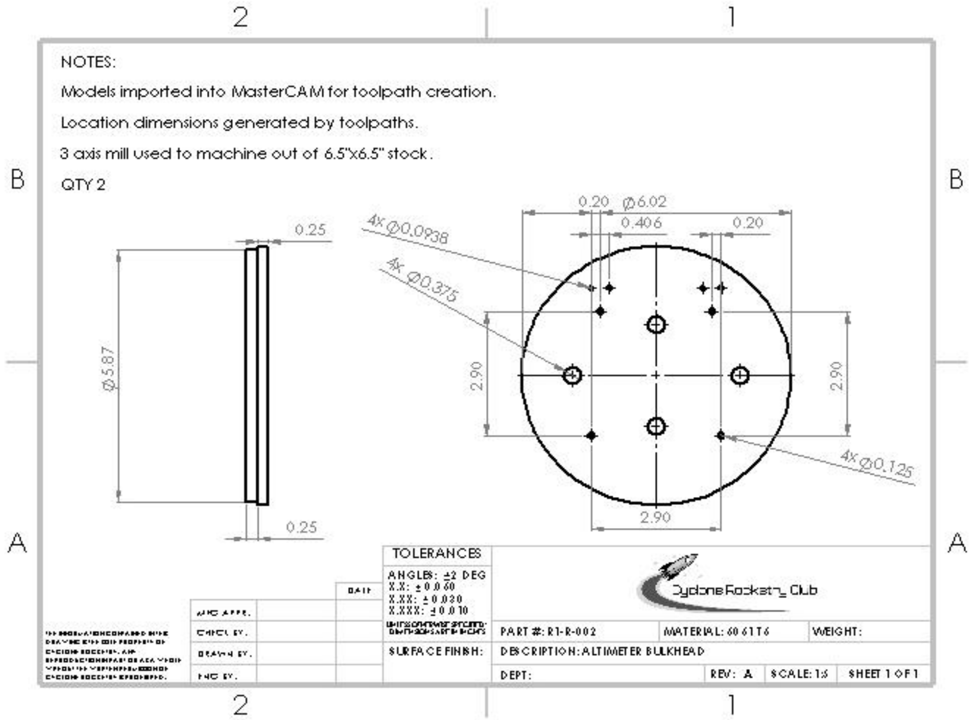

Figure 49: Altimeter Bay Bulkhead

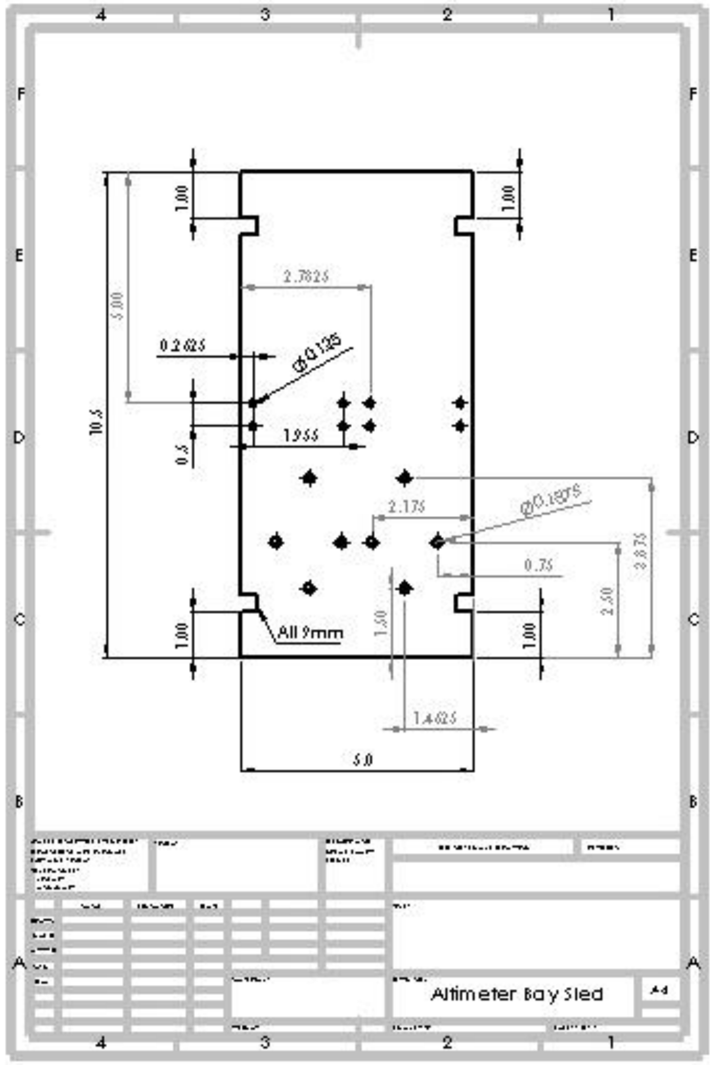

Figure 50: Altimeter Sled Drawing

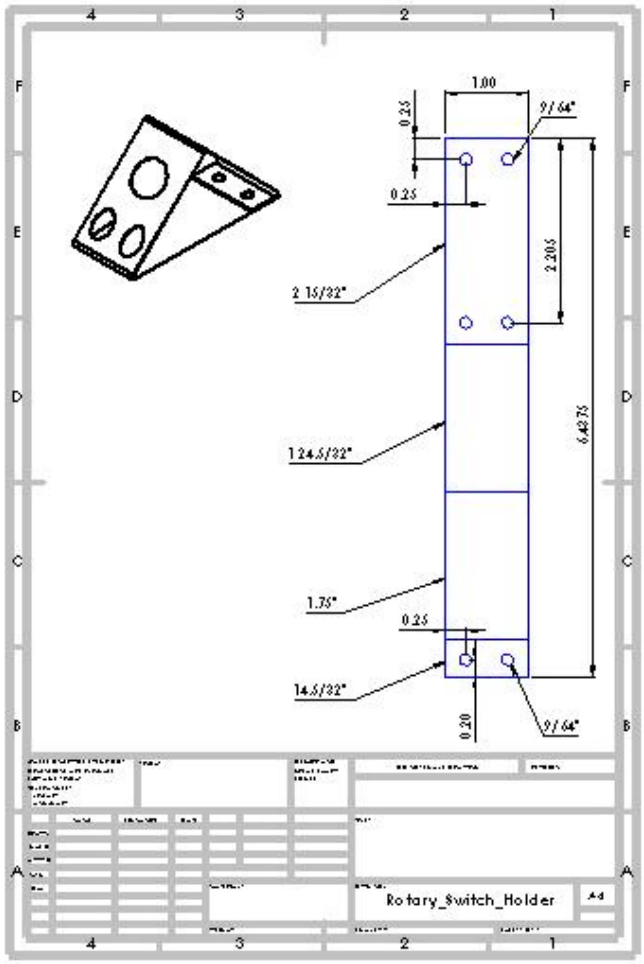

Figure 51: Rotary Switch Fastener Drawing

11.5 Payload Drawings

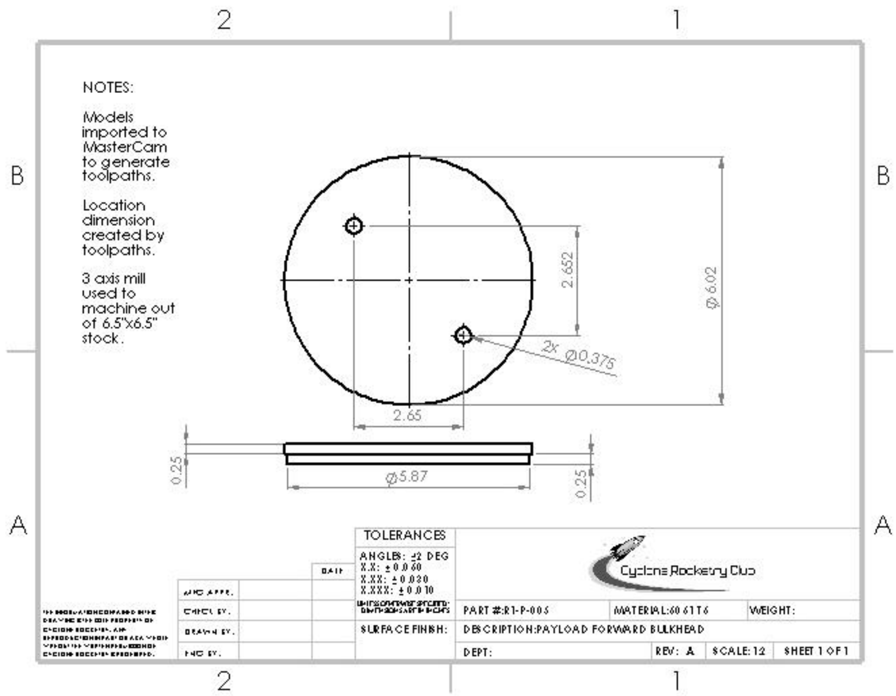

Figure 52: Forward Payload Bulkhead Drawing

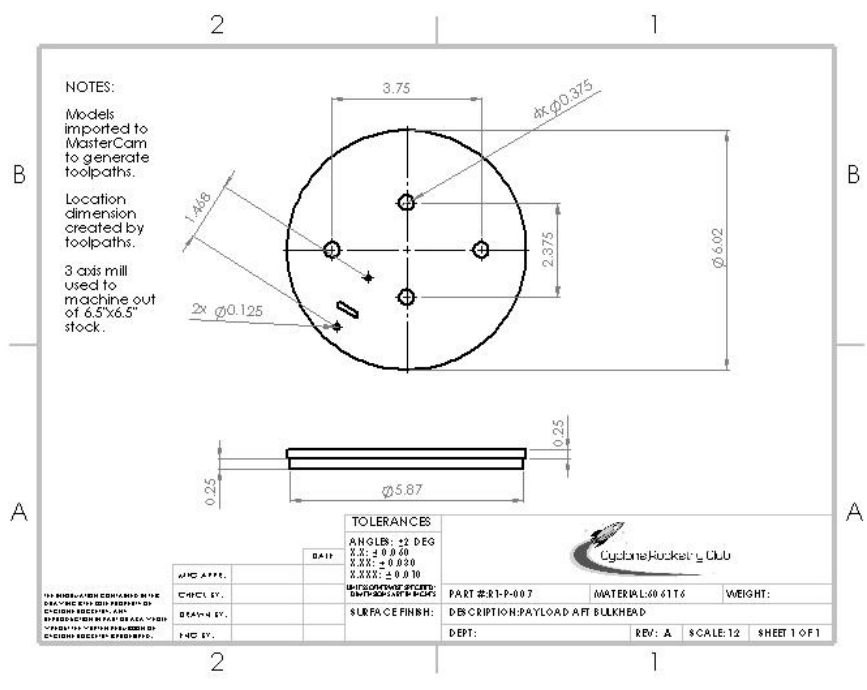

Figure 53: Aft Payload Bulkhead Drawing

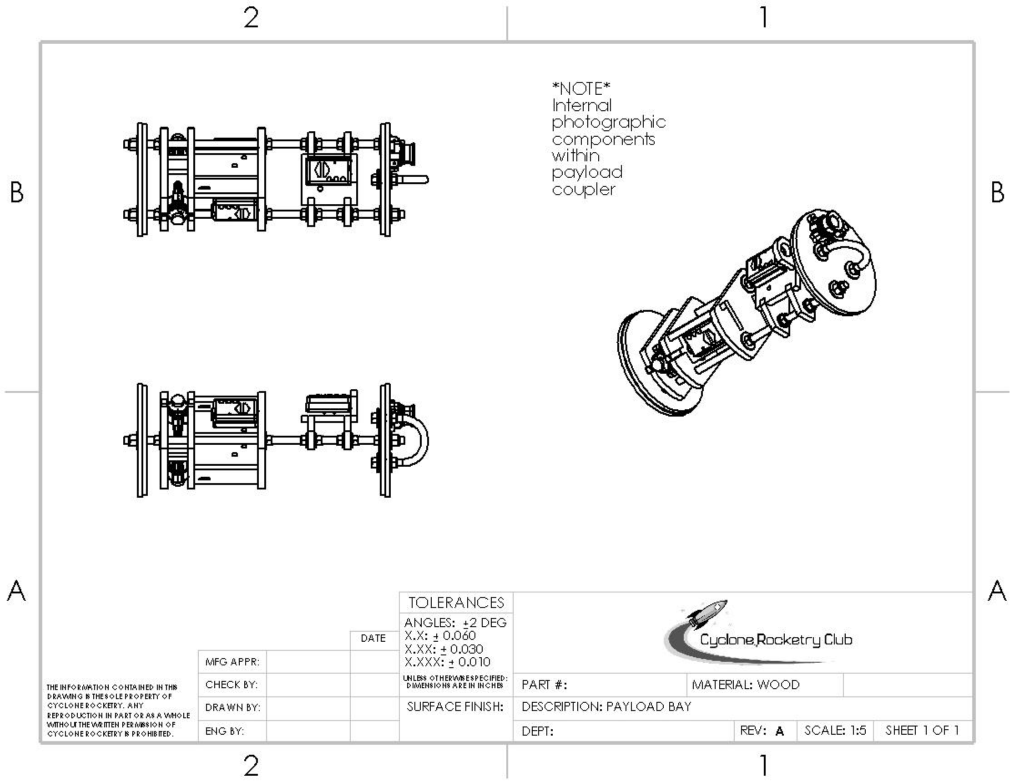

Figure 54: Payload Bay Camera Assembly

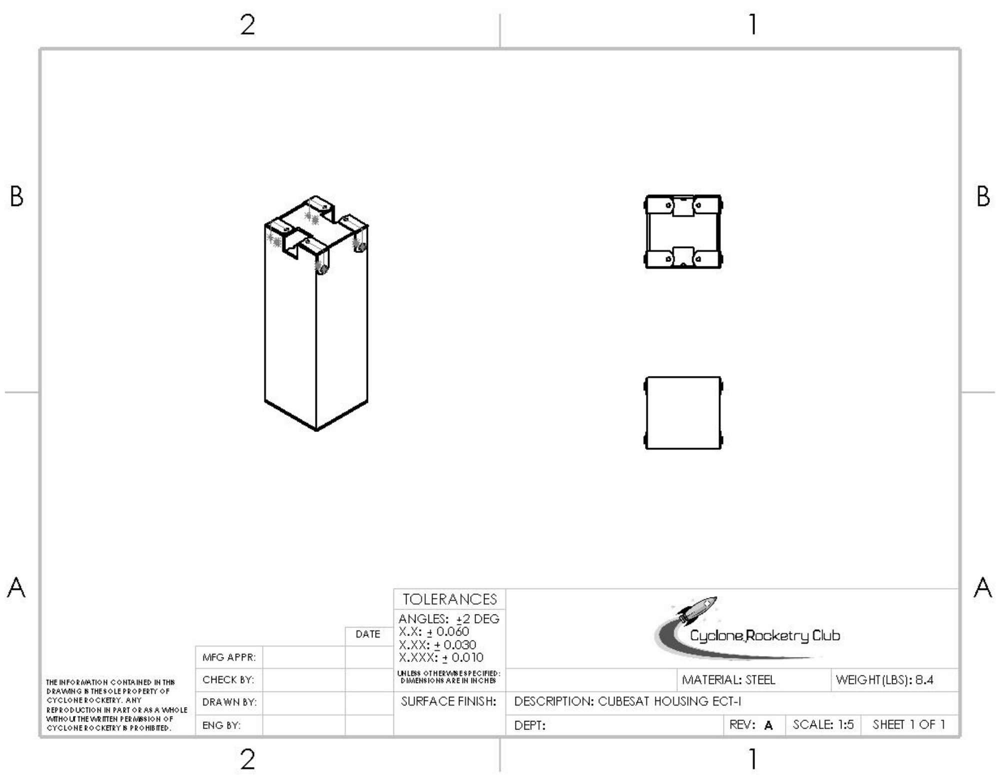

Figure 55: CubeSat Assembly

12. Reference Code Appendix

12.1 Payload Code:

```
#include <SPI.h>
#include <SD.h>

const int chipSelect = 10;
String testString = "Payload";

void setup() {
  // Open serial communications and wait for port to open:
  Serial.begin(9600);
  while (!Serial) {
    ; // wait for serial port to connect. Needed for native USB port only
  }


  Serial.print("Initializing SD card...");

  // see if the card is present and can be initialized:
  if (!SD.begin(chipSelect)) {
    Serial.println("Card failed, or not present");
    // don't do anything more:
    return;
  }
  Serial.println("card initialized.");
  File dataFile = SD.open("datalog.txt", FILE_WRITE);
  if(dataFile) {
    Serial.println("File");
    dataFile.println(testString);
    dataFile.close();
    // print to the serial port too:
    Serial.println(testString);
  }
  else {
    Serial.println("No File.");
  }
}
```

```
void loop() {
  // make a string for assembling the data to log:
  String dataString = "";

  // read three sensors and append to the string:
  for (int analogPin = 0; analogPin < 2; analogPin++) {
    int sensor = analogRead(analogPin);
    dataString += String(sensor);
    if (analogPin < 2) {
      dataString += ",";
    }
  }

  // open the file. note that only one file can be open at a time,
  // so you have to close this one before opening another.
  File dataFile = SD.open("datalog.txt", FILE_WRITE);

  // if the file is available, write to it:
  if (dataFile) {
    dataString += (millis());
    dataFile.println(dataString);
    dataFile.close();
    delay(10);
    // print to the serial port too:
    Serial.println(dataString);
  }
  // if the file isn't open, pop up an error:
  else {
    Serial.println("error opening datalog.txt");
  }
}
```

Figure 56: Payload Code

12.2 Avionics Code

AirbrakeMatrix.m

```
clear, clc % clears previous values
tic % starts time counter
G = 9.81; % acceleration due to gravity in m/s^2
SeaDensity = 1.225; % air density at sea level
TimeDelta = .01; % itteration time for flight path
CDBrake = 1.28; % coefficient of drag of the airbrakes
CDRocket = .42; % coefficient of drag of the rocket
AreaRocket = .0182414692; % drag area of the rocket
AreaBrake = .00692; % drag area of the airbrakes
StartAlt = 274; % launch altitude
WeightF = 354.256; % weight after burnout
Mass = WeightF / G; % mass after burnout
Matrix = zeros(300,2449); % matrix of appogee heights
x = zeros(1,2449); % vector of brake heights
y = zeros(1,300); % vector of brake velocities
HeightGood = zeros(1,523); % vector of brake heights that are "good"
VelocityGood = zeros(1,523); % vector of brake velocitiess that are "good"
HeightVelocityGood = zeros(2,523); % matrix of both brake height and velocities that are "good"
HeightGood1 = zeros(1,333);
VelocityGood1 = zeros(1,333);
HeightVelocityGood1 = zeros(2,333);
HeightGood2 = zeros(1,200);
VelocityGood2 = zeros(1,200);
HeightVelocityGood2 = zeros(2,200);
c = 1; % its just a counter for later matrices
d = 1;
```

```
for i = 600:3048 % 2449 values for brake heights
    for j = 1:300 % 300 values for brake velocities
        Velocity = j; % brake velocity
        Time = 0; % time since brake deployment
        Altitude = StartAlt + i; % altitude from sea level
        while Velocity >= 0 % loops until apogee
            Altitude = Altitude + (Velocity * TimeDelta); % calculates altitude based one velocity
            Height = Altitude - StartAlt; % calculates height from altitude
            Density = SeaDensity * (1 + (-.0065 * Altitude / 287))^(4.25363734); % calculates density at altitude
            Drag = .5 * Density * Velocity * Velocity * CDRocket * AreaRocket; % calculates rocket drag
            Brake = .5 * Density * Velocity * Velocity * CDBrake * AreaBrake; % calculates air brake drag
            if Time < 3 % if the airbrakes are still opening
                Brake = (Brake / 3) * Time; % the drag force of the airbrakes is a fraction of its full force
            end
            Force = -Drag - (.66 * Brake) - WeightF; % calculates force from the components
            Velocity = Velocity + (Force * TimeDelta / Mass); % calculates velocity due to force
            Time = Time + TimeDelta; % time since airbrake deployment
        end
        Matrix(j,i-599) = Height; % stores the apogee value
        y(1,j) = j; % stores the velocity at time of airbrake deployment
        if (Height>3047) && (Height<3049) % if the apogee was within goal values
            HeightGood(1,c) = i; % stores the airbrake deployment value
            VelocityGood(1,c) = j; % stores the airbrake deployment velocity
            HeightVelocityGood(1,c) = i; % stores the airbrake deployment value
            HeightVelocityGood(2,c) = j; % stores the airbrake deployment velocity
            if (i<=2500)
                HeightGood1(1,c) = i;
                VelocityGood1(1,c) = j;
                HeightVelocityGood1(1,c) = i;
                HeightVelocityGood1(2,c) = j;
            end
            if (i>2500)
                HeightGood2(1,d) = i;
                VelocityGood2(1,d) = j;
                HeightVelocityGood2(1,d) = i;
                HeightVelocityGood2(2,d) = j;
                d = d + 1;
            end
            c = c + 1;
        end
    end
    x(1,i-599) = i; % stores the height at time of airbrake deployment
end
%HeightGood(250:581) = []; % Cuts the HeightGood Matrix down to 950 values to give a better linear fit for the data
%VelocityGood(250:581) = []; % Cuts the VelocityGood Matrix down to 950 values to give a better linear fit for the data
mesh(x,y,Matrix) % plots all of the apogee values
colorbar
xlabel('brake height'); % labels the  axis
ylabel('velocity'); % labels the y axis
zlabel('end height'); % labels the z axis
title('end height as a function of brake height, and velocity'); % titles the graph
figure % makes a new figure
plot(HeightGood,VelocityGood) % plots the "good" pairs of deployment height and velocity
xlabel('Brake Height m'); % labels the x axis
ylabel('Brake Velocity m/s'); % labels the y axis
title('Height & Velocity Flight profile'); % titles the graph
figure % makes a new figure
plot(HeightGood1,VelocityGood1) % plots the "good" pairs of deployment height and velocity
xlabel('Brake Height m'); % labels the x axis
ylabel('Brake Velocity m/s'); % labels the y axis
title('Height & Velocity Pairs That Get Us Close section 1'); % titles the graph
figure % makes a new figure
plot(HeightGood2,VelocityGood2) % plots the "good" pairs of deployment height and velocity
xlabel('Brake Height m'); % labels the x axis
ylabel('Brake Velocity m/s'); % labels the y axis
title('Height & Velocity Pairs That Get Us Close section 2'); % titles the graph
toc % ends time counter
```

Figure 57: Flight Profile Code

Altitude_Calculations - Notepad

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```
//Comment description herevoid get_Alt_BNO() {
  imu::Vector<3> euler = bno.getVector(Adafruit_BNO055::VECTOR_EULER);
  imu::Vector<3> acc = bno.getVector(Adafruit_BNO055::VECTOR_ACCELEROMETER);
  imu::Vector<3> linear = bno.getVector(Adafruit_BNO055::VECTOR_LINEARACCEL);
  imu::Vector<3> gravity = bno.getVector(Adafruit_BNO055::VECTOR_GRAVITY);
  VerticalAccelBNO = ((linear.x() * gravity.x()) + (linear.y() * gravity.y()) + (linear.z() * gravity.z())) / 9.81;
  Serial.print("VerticalAccel:, ");
  Serial.println(VerticalAccelBNO);
  if (VerticalAccelBNO >= 4.5) {    LaunchValue = true ;  }
  if (VerticalAccelBNO <= -4.5) {    LaunchValue = true ;  }
  if (LaunchValue == false) {    VerticalAccelBNO = 0;      }
  HeightBNO = AvgHeight + (AvgVelocity * TIME_DELTA) + (.5 * VerticalAccelBNO * TIME_DELTA * TIME_DELTA);
  VelocityBNO = AvgVelocity + (VerticalAccelBNO * TIME_DELTA);
  if (LaunchValue == false) {    HeightBNO = 0;    VelocityBNO = 0;  }    int ADXL377_X_axis = analogRead(A2);
  int ADXL377_Y_axis = analogRead(A1);  int ADXL377_Z_axis = analogRead(A0);
  // Convert raw values to 'milli-Gs"  long xScaled = map(ADXL377_X_axis, 512, 517, -1000, 1000);
 // Acceleration in the x direction in milli G's  long yScaled = map(ADXL377_Y_axis, 512, 517, -1000, 1000);
 // Acceleration in the y direction in milli G's  long zScaled = map(ADXL377_Z_axis, 511, 517, -1000, 1000);
 // Acceleration in the z direction in milli G's
float yAccel = yScaled / 1000.0;
  float zAccel = zScaled / 1000.0;
  float ADXLRatioPart1 = (acc.x() * acc.x()) + (acc.y() * acc.y()) + (acc.z() * acc.z());
  float ADXLRatioPart2 = (xAccel * xAccel) + (yAccel * yAccel) + (zAccel * zAccel);
  if (LaunchValue == true) {    VerticalAccelADXL = VerticalAccelBNO * 9.81 * sqrt(ADXLRatioPart2) / sqrt(ADXLRatioPart1);
    HeightADXL = AvgHeight + (AvgVelocity * TIME_DELTA) + (.5 * VerticalAccelADXL * TIME_DELTA * TIME_DELTA);
        VelocityADXL = AvgVelocity + (VerticalAccelADXL * TIME_DELTA);  }
  if (LaunchValue == false) {    VerticalAccelADXL = 0;
    HeightADXL = 0;
    VelocityADXL = 0;  }}/

* * Function Summary: *    This function gets the altitude from the barometric pressure sensor through a x-point averager *    as defined by the PRESSURE_AVERAGING_ITERATIONS defined value. *
 * Parameters: *    Input: Void *    Output: (float) altitude_from_pressure,  *
 */void get_Alt_Pressure(){    for (pressure_avg_counter = 0; pressure_avg_counter < PRESSURE_AVERAGING_ITERATIONS; pressure_avg_counter++) {        mpl115a2.getPT(&pressureKPA, &temperatureC);
    pressure += pressureKPA;     tempC += temperatureC;  }  pressure = pressure / PRESSURE_AVERAGING_ITERATIONS;  tempC = tempC / PRESSURE_AVERAGING_ITERATIONS;
  pressure = pressure / 10.0; //Convert to hPa
//Calculating Altitude from Pressure and Temperature Equation  altitude_from_pressure = ((pow(SEA_LEVEL_PRESSURE / pressure, 1 / 5.257) - 1) * (tempC + 273.15)) / (0.0065);
   HeightPress = altitude_from_pressure - START_ALT;  if (current_status == 0) {    START_ALT = altitude_from_pressure;  }}void get_Avg_Alt()/*
 * this function averages the height and velocity values,  * calculates AvgHeight and AvgVelocity,  *
 * INPUTS(global): * OUTPUTS(global): AvgHeight and AvgVelocity */{  AvgHeight = (HeightBNO + HeightPress + HeightADXL) / 3;  AvgHeightWithoutPressure = (HeightBNO + HeightADXL) / 2;
  //AvgVelocity = (AvgHeightWithoutPressure - AvgHeightPrevious) / TIME_DELTA;  AvgVelocity = (VelocityBNO + VelocityADXL) / 2;
```

Figure 58: Altitude Calculation Code

GPS_on_Nano - Notepad

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```
#include <TinyGPS++.h>#include <SoftwareSerial.h>/*
This sample sketch demonstrates the normal use of a TinyGPS++ (TinyGPSPlus) object.
It requires the use of SoftwareSerial, and assumes that you have a   4800-baud serial GPS device hooked up on pins 4(rx) and 3(tx).
*/static const int RXPin = 8, TXPin = 9;
static const uint32_t GPSBaud = 9600;
// The TinyGPS++ objectTinyGPSPlus gps;
// The serial connection to the GPS deviceSoftwareSerial ss(RXPin, TXPin);void setup(){  Serial.begin(9600);
  ss.begin(GPSBaud);
  Serial.println(F("Cyclone Rocketry.ino"));}void loop(){  // This sketch displays information every time a new sentence is correctly encoded.
  while (ss.available() > 0)
if (gps.encode(ss.read()))
displayInfo();  if (millis() > 5000 && gps.charsProcessed() < 10)  {
    Serial.println(F("No GPS detected: check wiring."));
    while(true);
  }}void displayInfo(){  Serial.print(F("Location: "));
   if (gps.location.isValid())  {
    Serial.print(gps.location.lat(), 6);
    Serial.print(F(", "));
    Serial.print(gps.location.lng(), 6);  }
else  {    Serial.print(F("INVALID"));  }
    Serial.print(F("  Altitude: "));
    if (gps.location.isValid()) {      Serial.print(gps.altitude.meters());      Serial.print(F("Meters"));    }
    else {      Serial.print(F("INVALID"));    }  Serial.print(F("  Date/Time: "));
if (gps.date.isValid())  {    Serial.print(gps.date.month());
Serial.print(F("/"));
Serial.print(gps.date.day());
Serial.print(F("/"));
Serial.print(gps.date.year());  }
else  {    Serial.print(F("INVALID"));  }
Serial.print(F(" "));
if (gps.time.isValid())  {    if (gps.time.hour() < 10) Serial.print(F("0"));
Serial.print(gps.time.hour());
Serial.print(F(":"));
if (gps.time.minute() < 10) Serial.print(F("0"));
Serial.print(gps.time.minute());
Serial.print(F(":"));
if (gps.time.second() < 10) Serial.print(F("0"));
Serial.print(gps.time.second());
Serial.print(F("."));
if (gps.time.centisecond() < 10) Serial.print(F("0"));
Serial.print(gps.time.centisecond());  }  else  {    Serial.print(F("INVALID"));  }  Serial.println(" INVICTUS I.");}
```

Figure 59: GPS Code