Terrapin Rocket Team Project Terpulence ll

Team 9 Project Technical Report to the 2022 Spaceport America Cup

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This document presents University of Maryland's 10,000 ft COTS Motor Category rocket, Terpulence II. This project is a return to high power rocketry fundamentals within the Terrapin Rocket Team. It is the first time that the team will be attending the Cup in person since 2018 and the first time any current team members will compete at Spaceport. The design process is targeted at building off of other successful projects and manufacturing a safe and reliable competition rocket. This reports also documents the design of a novel air brake system that increases the rocket performance to reach a desired apogee. The CubeSat payload for this rocket will test liquid fuel tank geometry to gauge if capillary action can replace ullage motors in micro-gravity environments.

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Nomenclature

CFD	Computational Fluid Dynamics
CG	Center of Gravity
CNC	Computer Numerical Control
COTS	Commercial of the Shelf
CP	Center of Pressure
CSV	Comma-separated Values
D	Drag
EKF	Extended Kalman Filter
FEA	Finite Element Analysis
FRAM	Ferroelectric Random-access Memory
GPS	Global Positioning System
I2C	Inter-Integrated Circuit
IMU	Inertial Measurement Unit
MDRA	Maryland Delaware Rocketry Association
MEMS	Microelectro-mechanical Sensors
NDI	Nonlinear Dynamic Inversion
PCB	Printed Circuit Board
PETG	Polyethylene Terephthalate Glycol
PLA	Polylactic Acid
SAC	Spaceport America Cup
SF	Safety Factor
SPI	Serial Peripheral Interface
TWR	Thrust-Weight Ratio
M	Mach
SRAD	Student Researched and Developed
T	Thrust
UMD	University of Maryland
v	Velocity

I. Introduction

A. Academic Program

The Terrapin Rocket Team is a student organization at the University of Maryland, College Park. The team was established with the goal of providing students hands-on opportunities to learn about rocketry, and to gain experience designing, manufacturing, and testing engineering projects. The team is made up of over 50 undergraduate members across many disciplines such as Aerospace Engineering, Mechanical Engineering, Computer Science, Physics, and Mathematics. While this team is comprised of several different academic backgrounds, the club is sponsored by the A. James Clark School of Engineering - Department of Aerospace Engineering under the advisement of Dr. Christopher Cadou.

B. Stakeholders

There are two main types of stakeholders for our project - academic and professional. The academic stakeholders were mostly engaged with the development of the team, the members, and the team's reputation. These individuals, with their more complete understanding of rocketry, assisted the team through hours of mentorship and explanation of complex topics. These individuals are the ones who provided us the critical feedback during our design reviews, and assisted in developing new skills to better design our project. One of the most valuable of these mentors was our Tripoli advisor, Dennis Kingsley, who has been working with the team for the last couple of years and has been monumental in our success. Additional mentors include Dr. Christopher Cadou and David Nazemi.

Our professional stakeholders have been those that have helped to ensure our continual success. Their support and engagement is in the form of donations and access to engineering software. These include the A. James Clark School of Engineering, The University of Maryland Student Government Association, ABL Space Systems, The Maryland Robotics Center, Boeing, Aerojet Rocketdyne, and Siemens.

C. Team Organization

TerpRockets is a rocket organization that promotes rocketry and engineering principles. One of the ways we accomplish these goals is by participating in the SAC. The executive board of TerpRockets oversees all of TerpRockets activities included a hands-on involvement of the SAC team. This team was partitioned into natural subteams, Aerostructures, Recovery, and Payload. Aerostructures was tasked with the design, testing, and fabrication of the main rocket body as well as all subsystems not covered by recovery or payload. The Recovery subteam took responsibility for the design of our recovery system including the flight computers involved with the recovery events. Payload was tasked with the design, testing, and fabrication of the payload for Terpulence II.

One of the biggest lessons we learned during the 2020-2021 season was how debilitating the lack of rocketry experience in the team was for the progress of a competition worthy rocket. This lack of experience led to many impractical or poor design decisions based on a limited understanding of high-powered model rockets. Based on these lessons, we undertook the philosophy to build and test early and often. To accomplish this we needed to focus on proven designs with ease of manufacturing in mind. This focus necessitated a separation between competition critical systems and non-critical systems. We therefore had a base SAC team that focused on a rocket that would be able to compete in SAC and start building as soon as practical and other teams focused on exciting yet nonessential systems. Each subteam had its own non-critical projects. Aerostructures had the air brake system, Recovery had an SRAD flight computer, and Payload had Blimp payload. These non-critical teams were setup to not hinder the development of the main rocket. The air brake team managed to show preliminary success and was incorporated into Terpulence II at a late stage in the year. The Recovery SRAD team was unable to invoke confidence for this season and their progress will hopefully lead to a successful system in future years. The Payload teams consolidated their efforts to work on the Capillary Action Payload. The full breakdown can be shown in Fig. 1.

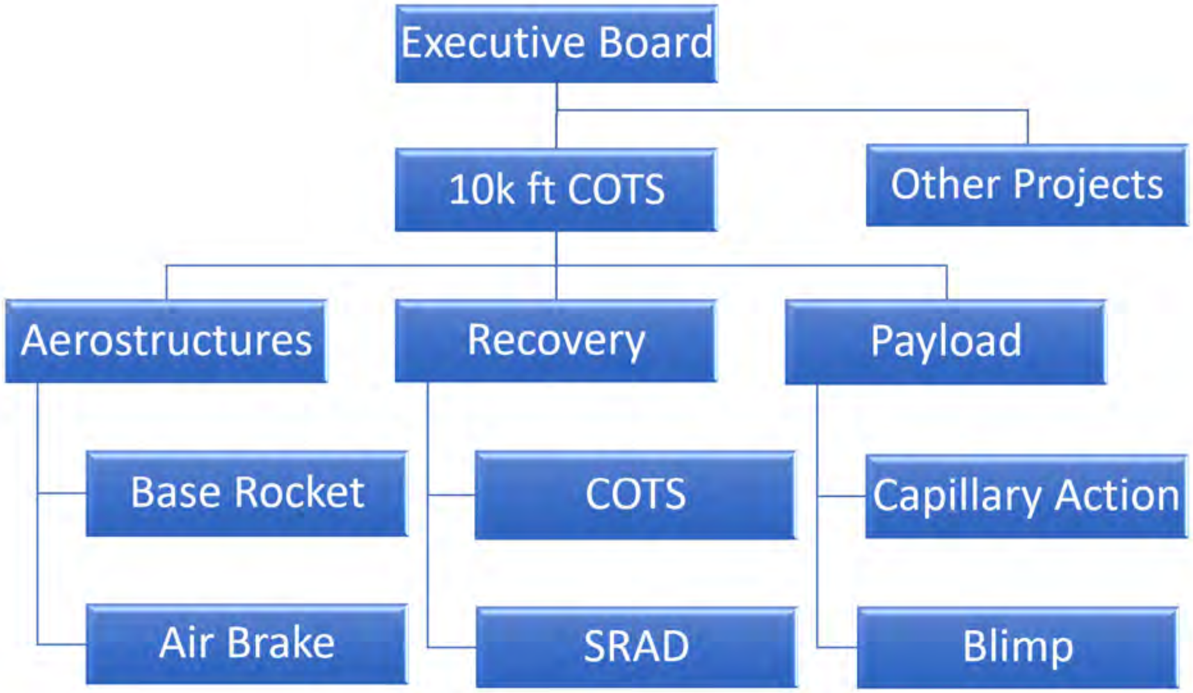

Fig. 1 Team organization

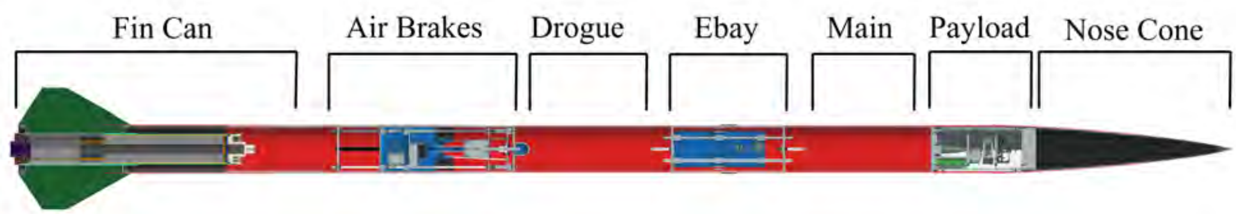

Fig. 2 *Terpulence II* layout

II. System Architecture Overview

Terpulence II is divided into seven sections: the fin can, air brake section, drogue parachute section, electronics bay, main parachute section, and the nose cone. Each air frame section is joined by a coupler tube with each coupling interface being at least one caliber in length. Figure 2 shows a basic schematic of the rocket. This configuration shows a 98/10240 casing as it was configured in its third test flight. A Loki Research 98/12500 casing with be used for the flight at Spaceport. Table 1 lists some basic parameters of the rocket.

Table 1 Vehicle Parameters

Predicted Apogee (ft)	11,664
Total Impulse (N-s)	12,500
Peak Thrust (N)	4,965
Takeoff Mass (lb)	80.6
Takeoff TWR	10.85
Velocity off Rail (ft/s)	116
Max. Velocity (ft/s)	1,040
Max. Acceleration (g)	13.6
Stability Margin (Calibers)	2.51

A. Propulsion Subsystems

The motor being used for Terpulence II is a Loki Research N3800-LW. Details about the performance of the motor are listed in Fig. 3 and Table. 2.

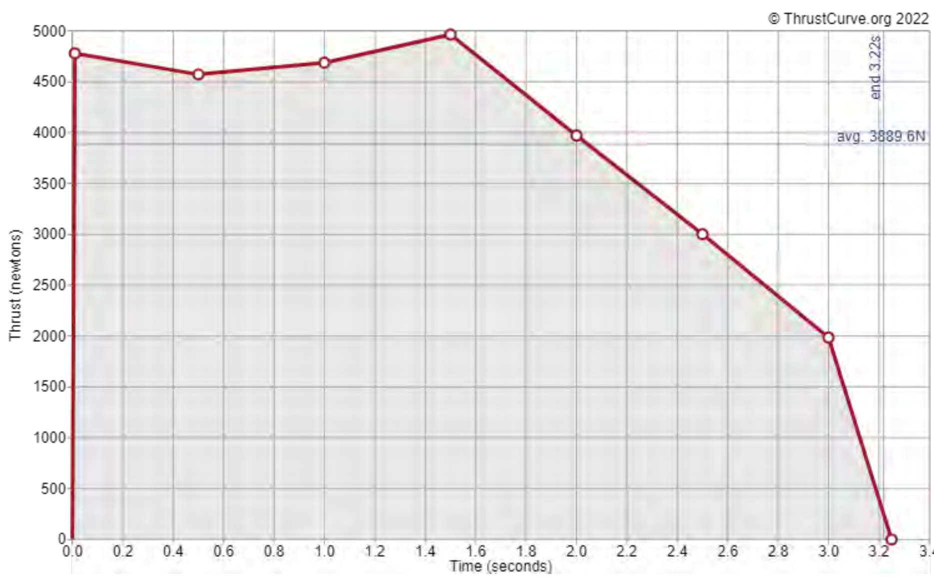

Fig. 3 Loki N3800 motor characteristics [7]

B. Simulations

Flight simulations were done primarily in OpenRocket. OpenRocket provided an easy way for the team to develop the rocket and estimate masses before construction. After the rocket was built, we updated our OpenRocket simulations with the updated total mass and center of gravity. This let us better inform our motor choices as we ended up around six pounds heavier than predicted. Originally, we planned to use an Aerotech M2500 however, the addition of the airbrake module increased the mass substantially. The heavier rocket required a larger motor and the only motor that was powerful enough to take the rocket to altitude and have a safe rail exit velocity was the Loki N3800. Other similar options from Aerotech or Cesaroni either did not have enough initial thrust or would not send the rocket high enough or much higher than necessary. With the N3800, shown in Fig. 4, OpenRocket estimates an altitude of 11286 ft at Spaceport America and a rail exit velocity of 116 ft/s. At a maximum speed of Mach .9, OpenRocket is still fairly reliable, however Terpulence II was also simulated in RasAero II. RasAero II provides more accurate flight estimates than OpenRocket, especially at faster speeds. Using the settings for All Turbulent Flow, Rogers Modified Barrowman,

Table 2 Loki N3800 Motor Characteristics [7]

Loaded Weight (g)	11,600
Propellant Weight (g)	6,125
Burnout Weight (g)	5,475
Total Impulse (Ns)	12,500
Average Thrust (N)	3,851
Burn Time (s)	3.3

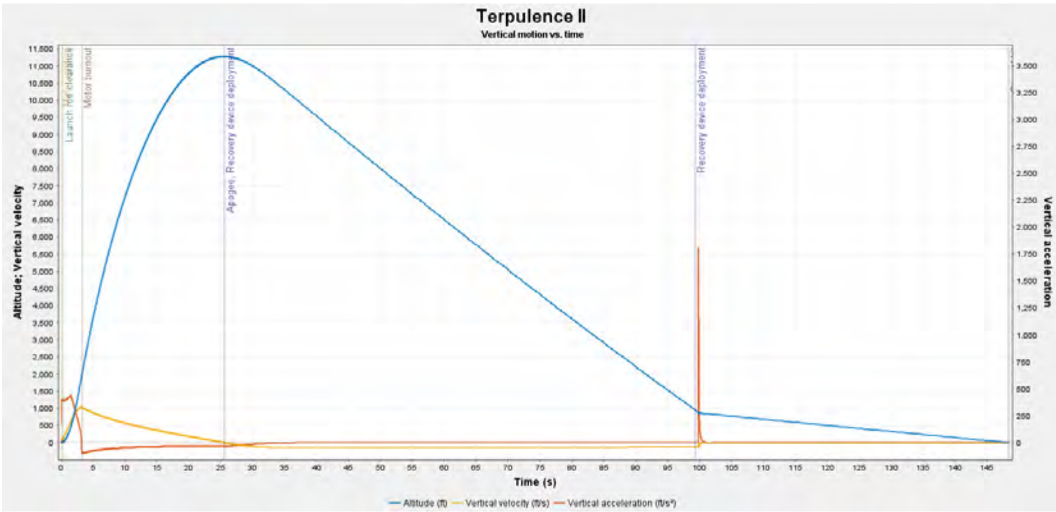

Fig. 4 OpenRocket simulation for Spaceport America conditions

and a Rough Camouflage surface finish, RasAero II predicted an apogee of 11,664 ft. at Spaceport America as shown in Fig. 5. Rough Camouflage paint was chosen based on our previous test flights. Terpulence II underperformed its simulations by a fair amount in the previous three test flights, so it is safe to assume that its actual altitude will be lower. Changing the skin friction of the rocket is an easy way to adjust for this.

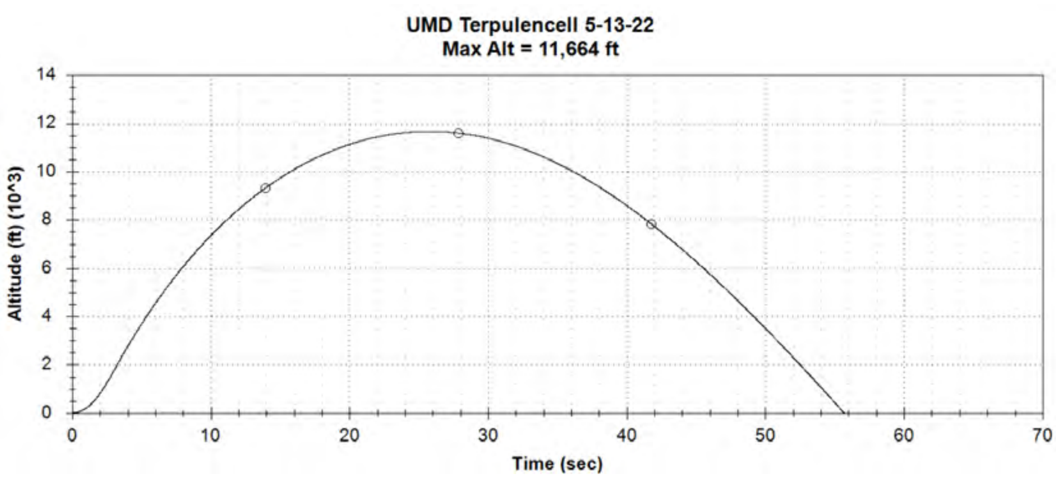

Fig. 5 Altitude simulation from RasAero II. Note: parachutes are not considered in this simulation.

OpenRocket calculates a minimum stability margin of 2.51. RasAero Predicts a minimum static margin of 3.7

increasing to 4.87 after burnout. A plot of stability over time can be found in Fig. 6. While this may be higher than usual for high power rockets, a higher caliber of stability is necessary for rockets with a high fineness ratio like Terpulence II. Many in the hobby, and even OpenRocket, have begun to calculate stability in terms of percentage of total airframe length. This value should nominally be between 8%-18%. OpenRocket calculates our stability percentage at 10.7% which is acceptable. A high caliber of stability is also helpful for our airbrake system as it provides a larger factor of safety before it becomes unstable, which we do not predict will happen.

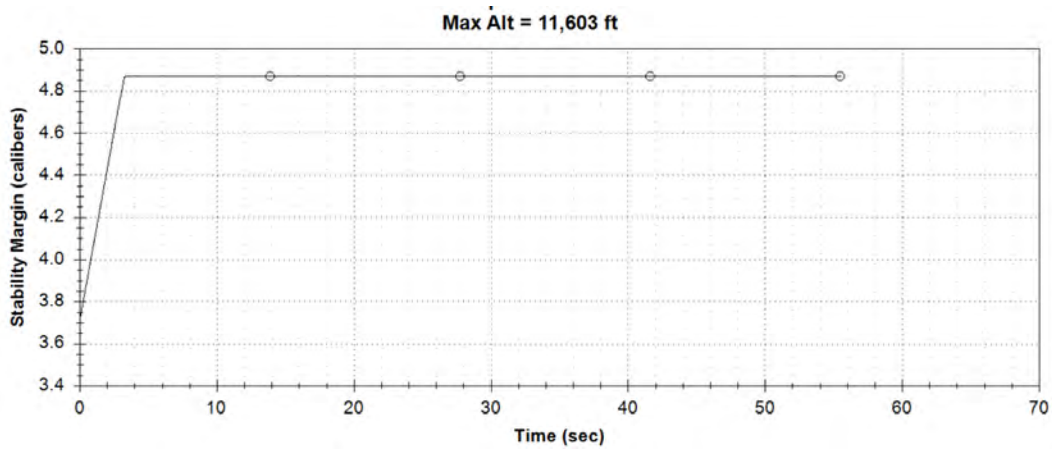

Fig. 6 Stability margin simulation from RasAero II

C. Aero-Structures Subsystems

The purpose of the Aerostructures team is to design and manufacture Terpulence II to be lightweight, cost-efficient, and manufacturable. Terpulence II is nominally six inches in diameter and stands approximately 12 feet tall. The nose cone, recovery section, upper fin can, and switch band are made of fiberglass. The fin can is a student made hand rolled carbon fiber airframe and the fins and centering rings are made of G10 fiberglass. Our main parachute is housed in the recovery section, whereas the drogue is housed in the upper fin can above the airbrake. Fiberglass was chosen as the primary structural material as it is lightweight and very strong, which makes it very popular in high power rocketry. Fiberglass is also transparent to radio frequencies, which is important for receiving telemetry from the flight computer. Carbon fiber was chosen for the fin can as it is very strong and stiff while being lightweight. Minimizing weight at the aft end of the rocket is important for stability purposes and its strength is useful for keeping the rocket together when it touches down.

Fig. 7 Layup of the carbon fiber airframe

1. Body Tubes & Couplers

Airframe Manufacturing Our fin can airframe was made from four wraps of carbon fiber cloth on a 6” BlueTube coupler as a mandrel. The mandrel is first waxed using car wax and then a mylar sheet is wrapped around the mandrel. Because we are using couplers from Wildman, extra wraps of Mylar were necessary to make up for the differences between the Bluetube and Wildman outer diameters. The ends and seam in the layer of Mylar are then sealed with flash tape to prevent the epoxy from leaking under the plastic and bonding to the mandrel. The cloth was then carefully wrapped and impregnated with epoxy using brushes and squeegees. Once the carbon had been wrapped, a layer of peel ply was applied in order to remove excess epoxy and provide a surface for post processing. After the tube had fully cured, it was removed from the mandrel and the peel ply was removed. Two coats of laminating epoxy were then applied to the tube and set to cure. This epoxy layer was then wet sanded and polished to a shiny surface finish.

Fig. 8 Airframe after removal from the mandrel

Fig. 9 Airframe with light coats of epoxy

While we originally planned to manufacture all of the airframe tubes ourselves, we ran into multiple issues. First, our BlueTube coupler was very sensitive to changes in the environment. We made multiple tubes using the same layup process and the Inner diameter of the tubing was variable. With the carbon fiber tube, a Wildman coupler slides easily with little binding. In the two fiberglass tubes we made, the coupler would not initially fit and required hours of sanding to slide easily. Before we implemented our airbrake, the booster section was made up of a student made carbon fiber tube and a student made fiberglass tube. With the airbrake, the booster section is now a carbon fiber fin can with a section of commercial fiberglass tubing to accommodate the longer motor followed by the airbrake and then a 30" section of commercial filament wound tubing.

To hold sections of airframe together, 1/4" adhesive mount nuts are epoxied to the inside of the coupler as shown in 10. We can then use 1/4" button screws to fasten the the air frame to the coupler. This method is used for the fin can extension, air brake, and recovery tube. In these locations it is impractical to permanently fix these airframes together. This technique is also used to secure both rail buttons to the airframe.

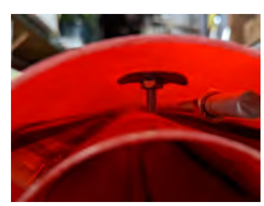

Fig. 10 Adhesive mount nut epoxied to the inside of an airframe

Airframe Testing After constructing the body tubes, we then compression tested these tubes at a facility at UMD. Figure 12 shows the stress-strain curve of the fiberglass tube while Fig. 11 shows the stress-strain curve of the carbon fiber tube. The fiberglass tube failed at a force of 9754 lbf while the carbon fiber tube failed at 2611 lbf. The conditions we were attempting to simulate with this test were the vertical loads imparted by the motor. With a peak thrust of 3821 N, or 859 lbf, both of these airframes were adequate for the flight vehicle. Even though the carbon tube had fewer layers of cloth than the fiberglass tube, it still failed

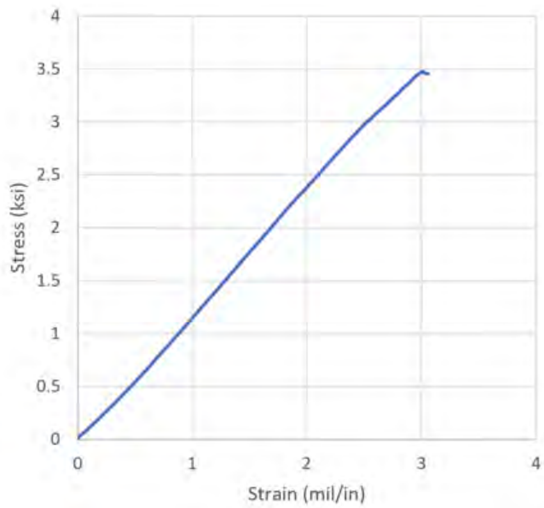

Fig. 11 Stress - Strain for carbon fiber tube

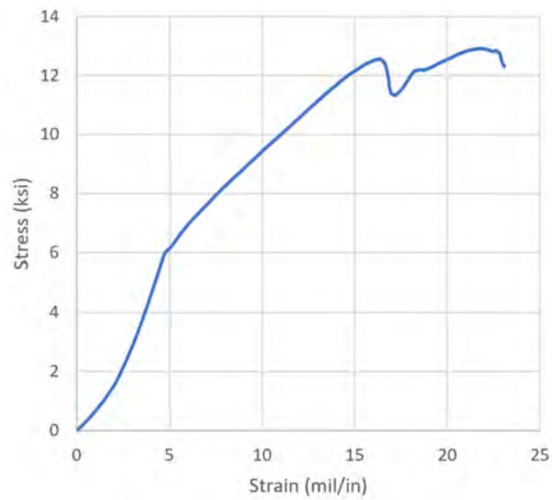

Fig. 12 Stress - Strain for fiberglass tube

much earlier than expected. As we were starting the test, we realized that the ends of the tube were not parallel to one another. This meant that there was a greater moment arm during the compression and buckling is very sensitive to this moment. If the ends were parallel we expect the tube to fail closer to the standard Euler load. Another factor that would improve these tube's strength in the future is better composites procedures and techniques. During mixing, many air bubbles were added to the resin, and even though we attempted to removed them with a plastic squeegee, many still remained. We will likely attempt to degas the epoxy in the future to minimize this as vacuum bagging tubes can be difficult.

Fig. 13 Fiberglass tube in testing jig

Fig. 14 SRAD tubes after failure

Table 3 Fin parameters

Root Chord (in)	13
Tip Chord (in)	3
Sweep (in)	8
Height (in)	5

2. Fins

Our fin shape was determined by the required stability margins as well as ease of manufacturing. After trying multiple fin shapes in OpenRocket, we decided on the fins with the parameters shown in Table. 3 The fins also include fin tabs that go through fin slots in the airframe and are epoxied to the motor mount tube. These are 11" by 1.075" centered along the root chord of the fin.

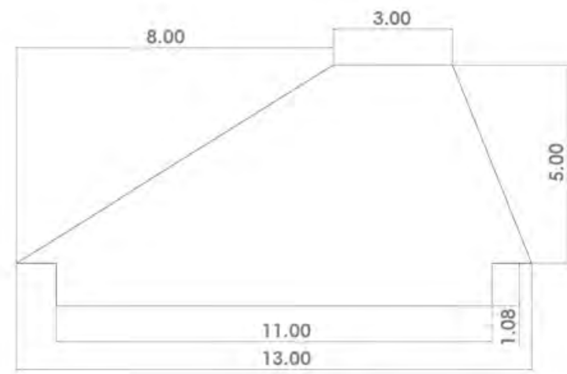

Fig. 15 Fin dimensions

Flutter analysis From the OpenRocket simulations, Terpulence II has a maximum speed of 1000 ft/s at 2000 ft above ground level. Using these parameters and dimensions of the fins in Aero FinSim gives a flutter velocity of 1113 ft/s and a divergence velocity of 1825 ft/s with the U-G method. This gives a margin of 100 ft/s before flutter is estimated. Even if the rocket somehow goes past the flutter velocity, we are not concerned as similarly sized rockets with larger fins have flown faster than Terpulence II without issue. We have also flown Terpulence II three times and have not encountered any issues with flutter thus far. The Aero FinSim simulation is shown in Fig. 16

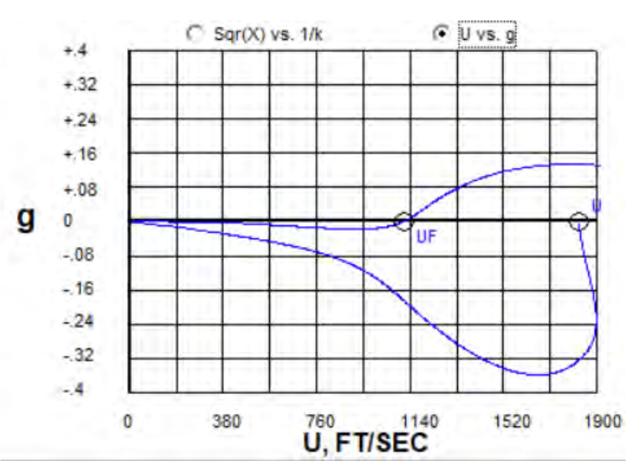

Fig. 16 Data plot from Aero FinSim

Manufacturing The fins were made out of 3/16" G10 sheet. A fin template was cut out of paper and traced on the stock G10 plate. The rough profile was then cut out using a band saw, leaving .5" around the edge. After each fin was cut, they were all clamped together and sanded on a belt sander. This was done to ensure uniformity between all of the fins. Even if the shape varied slightly from our simulations, it was important that they were all the same. After being sanded together, the edges were cleaned up individually on the belt sander. We decided against bevelling the fins as the process is very time intensive. We do not own a table saw or router table and would have had to spend many hours sanding the fins down. Bevels added marginal improvement to our altitude, and as we are already overshooting the altitude target, they were deemed unnecessary.

Fin Attachment The fins are attached using the standard through-the-wall method common in high power rocketry. All surfaces were first prepared using 400 grit sandpaper and cleaned with acetone. First, the fins were tacked to the motor tube using Rocketpoxy as shown in Fig. 17. Rocketpoxy was applied to the fin tab, and then the fin was pushed onto the motor tube and wiggled back and forth to spread the epoxy. This was done twice to ensure there was enough epoxy and a strong bond was formed. Foam fin guides were then slid onto the rocket in order to make sure that each fin was perpendicular to the body tube and motor tube. This method was repeated for the 3 remaining fins. Once the Rocketpoxy cured, West Systems Laminating epoxy thickened with chopped carbon tow was injected from the aft end of the rocket and allowed to run along the root edge of the fin tab. The airframe was then rocked back and forth to make sure that the epoxy spread evenly along the root chord of the fin. Internal fillets are shown in Fig. 18. Two sets of internal fillets were done at once to allow them to settle at an angle and form the fillet. After each set of internal fillets cured, the aft centering ring was epoxied into the airframe after being tightened via nuts on the threaded rods. External fillets of Rocketpoxy were then applied and pulled with a 1" diameter

Fig. 17 All four fins tacked to the motor tube

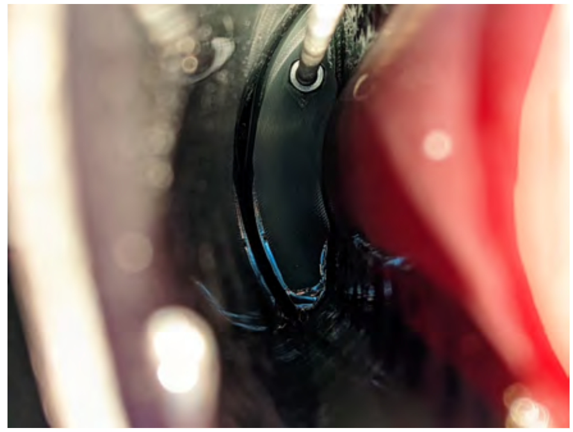

Fig. 18 Internal fillets after injection from the aft end

popsicle stick for consistency. This method of fin can construction is well proven within the hobby and ensures that the forces from the motor and recovery are transferred to the airframe. Fig. 19 shows a set of external fillets curing. Fig. 20 shows the aft centering ring epoxied onto the bottom of the fins.

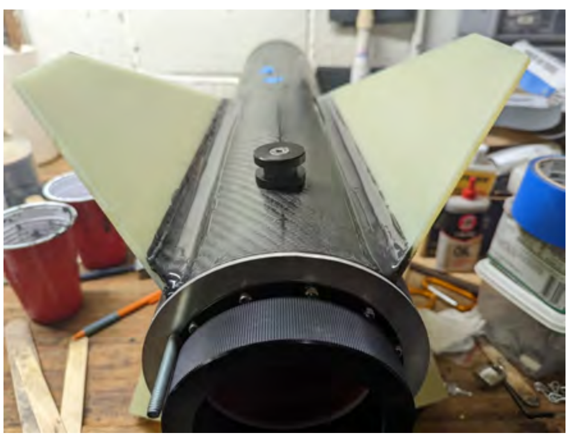

Fig. 19 A set of external fillets curing

Fig. 20 The aft centering ring epoxied into the airframe

3. Nose Cone

Nose Cone Design The type of nose cone we chose to use is a COTS Fiberglass 5:1 Von Karman nose cone. A Von Karman nose cone was chosen due to its high efficiency in the transonic regime [3]. As our simulations have Terpulence II flying at a max speed of Mach .9, this was our best option. It is also the most common profile available for commercial filament wound fiberglass nose cones. The nose cone is 30” long cone with a 6.17” diameter. An aluminum bulkhead will be mounted to the base of the nose cone coupler and secured to the payload frame which is connected to the nose cone tip via a threaded rod.

Nose Cone Manufacturing We also began the process to manufacture our own SRAD nose cone, however it will not be ready for the 2022 Spaceport America Cup. First, we 3D printed a positive mold from PLA and sanded it smooth. Then we applied several layers of PVA Release and Partall Paste #2 to keep the epoxy from bonding to the plastic. We then used two fiberglass sleeves in a wet layup over the mold. As we were applying the fiberglass to the mold, we had issues getting it to conform properly which led to imperfections in the final product. Finally, we covered the layers in peel-ply and breather cloth to remove excess epoxy and vacuum-bagged the assembly for 45 minutes. Fig. 21 shows one of the nose cone layups. However, it was necessary to keep vacuum pressure low to prevent the mold from caving in as a low infill percentage was used to minimize filament usage. After curing, the breather and peel ply were removed from the fiberglass. The issues mentioned earlier with the sleeves became apparent as there were large creases that would need to be sanded off.

Fig. 21 Fiberglass layup using a PLA mold and vacuum bagging

4. Bulkheads

Electronics Bay Bulkheads The electronics bay (ebay) bulkhead shown in Fig. 22 is a circular plate made from aluminum 6061-T6. The overall dimensions of the bulkhead are as follows: the outer diameter is 5.995" and the total thickness of 1/4". The bulkhead is separated into two layers with a 1/8" thick and 5.995" diameter outer lip and a 1/8" thick and 5.775" diameter ribbing pattern to strengthen the bulkhead while also minimizing weight. The ribbing pattern consists of a thin outer circle with an x-shaped pattern in the middle. Two sets of holes were made: one set of two small holes (0.164" diameter) opposite each other for wiring and a set of four larger holes (0.375" diameter) placed directly on the ribbing. Of the larger four holes, the two sets of holes opposite each other are used to thread a u-bolt and the ebay rods. Two ebay bulkheads will be mounted to the ends of the ebay coupler and attached in place by the ebay rods that go through the entire assembly. The bulkheads were manufactured in two components (the outer lip plate and the inner ribbing) by waterjet. No adhesive was used to join the two components, instead relying entirely on the u-bolts and ebay rods. Fig. 23 shows a CAD of the bulkhead and Fig. 24 shows a FEA of the bulkhead.

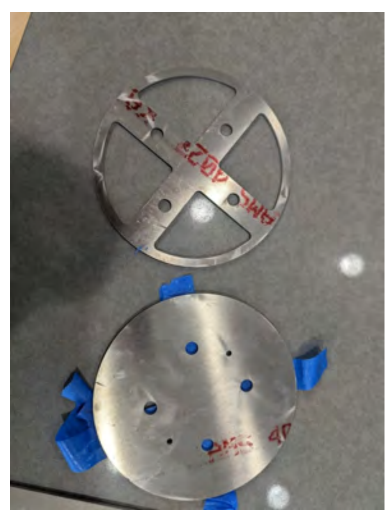

Fig. 22 Ebay bulkhead

Finite Element Analysis (FEA) was conducted on the ebay bulkhead. The

Fig. 23 **CAD of ebay bulkhead**

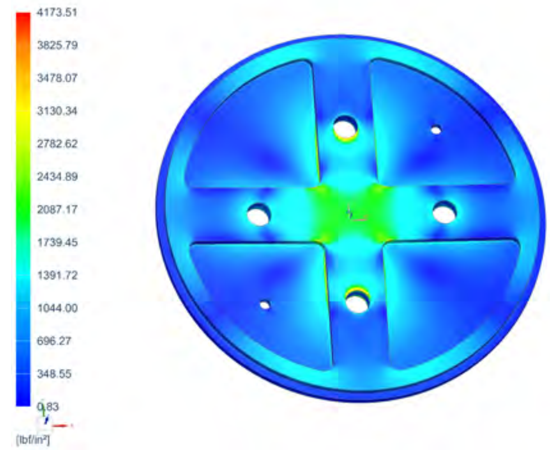

Fig. 24 **FEA of ebay bulkhead**

peak loading condition was based on accelerometer data collected from a test
flight. It was determined that the maximum force applied to the bulkhead was 86 lbf from the deployment of the main parachute. Two separate analyses were conducted with slightly different methodologies. The analysis shown in Fig. 25 progressively increased the overall mesh density of the entire bulkhead. Based on the FEA and the subsequent convergent analysis, maximum stress values reached approximately 4.0 ksi. The analysis shown in Fig. 26 decreased mesh size on high stress locations. This resulted in a slightly higher maximum stress value of approximately 4.2 ksi. Aluminum 6061-T6 has an ultimate strength of at least 45 ksi and a yield strength of at least 40 ksi [**matweb 6061**]. Thus, our bulkheads have a safety factor of ten and will be able to handle the peak loading condition.

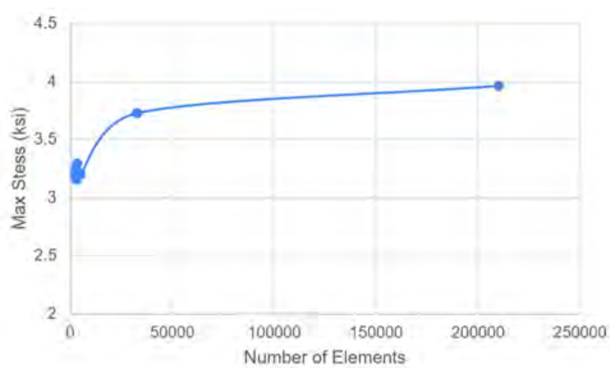

Fig. 25 Convergent analysis by refining the mesh over entire part

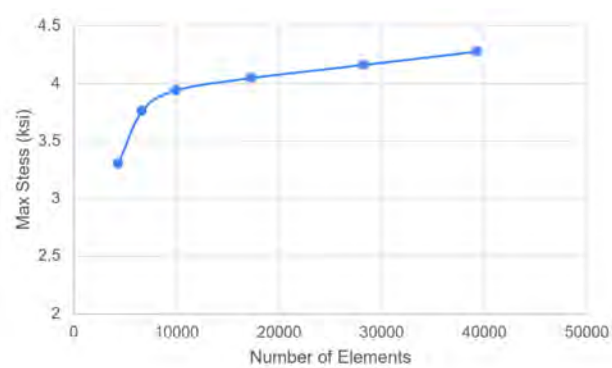

Fig. 26 Convergent analysis by refining mesh around concentrated loads

Nose Cone Bulkheads

Thrust Plate To retain the motor casing, a 98mm Flanged Aeropack retainer is being used. To mount this to the rocket, a thrust plate was manufactured shown in Fig. 27,from two stepped pieces of aluminum, similar to our bulkheads. This thrust plate contains mounting holes for the retainer as well as holes for the threaded rod to secure the assembly to the rocket. Fig. 28 shows the thrust plate integrated with the retainer. The thrust plate was mostly manufactured to make the process of mounting the retainer simpler since the holes would be precisely machined. It has the added benefit of transferring the force of the motor directly to the airframe instead of through the motor tube into the centering rings and fins, even though either way works well.

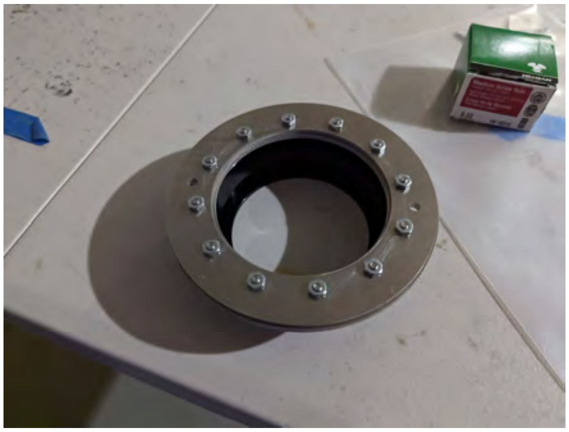

Fig. 27 Thrust plate

Fig. 28 Thrust plate integrated with rocket

D. Recovery Subsystems

For this year's competition, the team decided to keep recovery as simple as possible and stick to the methods that we have already implemented. In the past, we have attempted to utilize single break recovery using CO2 charges to separate the rocket and Tinder Rocketry Tender Descenders to deploy the main. We had multiple issues getting the system to work correctly including having the main come out at apogee or tangling with the drogue lines. This year, we switched to standard two break dual deploy using black powder charges. This is a much simpler and cheaper method that works just as well, if not better.

1. Recovery Devices and Shear Pins

Parachutes for the competition rocket were chosen based on manufacturer rated descent rates and reliability. Almost all commercial parachutes are very reliable, but we focused on how easy they were to pack and how likely they were to tangle. This led us to choose the Recon Recovery 24" drogue and the SkyAngle Cert3XXL. These are both simple parachutes with only 4 shroud lines each which helps prevent tangling. They also each come with swivel links to prevent tangling from the rocket spinning below it. The Cert3XXL is rated for descent rates of 17-25 ft/s on rockets weighing between 60 and 130 pounds. Interpolating between these values with a burnout weight of 67 lbs gives an estimated descent rate of 18 ft/s [8]. The Recon Recon recovery drogue was chosen based on flights of similarly sized rockets. Determining the descent rate for the drogue is difficult since the airframe of the rocket induces lots of drag, slowing it down substantially. OpenRocket gave descent rates in the range of 120 ft/s under drogue, however in reality this was close to 90 ft/s during our test flights.

To prevent premature separation and deployment of either of the parachutes, both separation points are held in with 4-40 shear pins. The Booster is held in with 2 shear pins while the nose cone is held with 6. Each of these provides a shear force of around 50 lbs, which means that the nose cone requires 300 lbs of force to separate. The shear pins are inserted into the airframe and then a continuous strip of electrical tape is wrapped around each of them to make sure they do not fall out in flight.

2. Parachute Protection

Each of the parachutes is protected from the hot ejection gasses by 24"x24" nomex blankets. The parachute is tightly folded into a square, making sure all air is pushed out, then wrapped in the blanket using the burrito method. We make sure the shroud lines are not around the parachute itself in order to prevent tangling. This method ensures that the parachute is tightly packed and will come out of the airframe easily when the ejection charge is activated.

Fig. 29 The main parachute folded and shroud lines loosely folded over the nomex blanket.

Fig. 30 The main parachute tightly wrapped in the nomex blanket and ready for launch

3. Recovery Harness

Terpulence II has three sets of harnesses, the Y harness from the fin can to the drogue harness, the drogue harness connected to the Y harness and electronics bay, and the main harness connected from the electronics bay to the nose cone bulkhead. The Y harness is made from two 8 ft. lengths of $1/2$" tubular kevlar rated for 7800 lbs [4] with figure 8 knots on either end. These are attached to eye nuts in the fin can via quicklinks rated for 1100 lbs. This harness is then connected to the drogue harness via a $\frac{3}{8}$ in quick link rated for 2200 lbs. The drogue harness is made from two 35 ft. lengths of $\frac{7}{16}$ in tubular kevlar in series. These are commercially available from OneBadHawk and rated for 5600 lbs [2]. The drogue parachute is attached at the second loop from the top of the harness, which helps keep both sections of the airframe apart during descent. These are connected to one another via another 3/8" quick link and then to the electronics bay U-bolt. The Main harness is a single 35' section of 7/16" tubular kevlar from OneBadHawk connected with 3/8" quick links to the U-bolts on the top of the electronics bay and nose cone bulkhead.

The drogue harness is particularly long to deal with the heavy payload in the nose. Such a long cord gives time for the rocket to come apart and slow down instead of inducing a shock from going taught quickly after ejection. This is important to keep the nose cone from separating early, even with the shear pins holding it in place. This also reduces stress on the rocket overall which is important for the longevity of the airframe.

4. Recovery Attachment

Attachment for the drogue recovery harness begins in the fin can. There are 4 steel threaded rods running along the length of the fin can through the three fiberglass centering rings. Each of the threaded rods is tightened to the centering rings with nuts and then held in place with Rocketpoxy. The two 3/8" in threaded rods have eye nuts on top of them for attachment to the Y harness. The two 3/8" in threaded rods do not extend past the forward end of the motor tube and instead extend out the aft end of the rocket to hold the thrust plate in. While this method of attachment adds weight to the aft of the rocket, which isn't desirable as it hurts stability, it helps spread out the recovery loads across the centering rings instead of just the top one. Each of the electronics bay bulkheads as well as the nose cone bulkhead have a 3/8" in U-Bolt rated for 1075 lbs [1]. These are secured to the bulkheads

Fig. 32 Nose cone bulkhead

Fig. 31 Terpulence II descending under drogue. Both sections are descending far from one another to prevent collisions.

using 3/8" nuts and secured with Loctite Red Threadlocker. The electronics bay is held together with two 3/8" threaded rods. The forward ebay bulkhead is held in via a nylon lock nut and a 3/8" nut on the other side of the bulkhead secured with threadlocker. The aft bulkhead is attached after all electronics have been prepared and is held on via two 3/8" nuts on each threaded rod in order to prevent them from unscrewing in flight. All of these nuts are tightened with a wrench when possible to prevent any premature separations. The nose cone bulkhead is similar to the electronics bay bulkheads except it has holes for mounting the payload instead of the electronics sled. The payload is bolted to the bulkhead and then inserted into the nose cone. The top of the payload has a 1/4” threaded rod which extends up into the aluminum nose tip. The tip is then tightened and secured with threadlocker to keep the whole nose cone assembly together. The payload frame is structural and transfers the recovery forces from the bulkhead to the threaded rod. This configuration has flown three times and has worked as expected.

E. Parachute Deployment System

Both parachutes are deployed with black powder charges using the glove figertip method. The finger of a nitrile glove is cut off and then filled with the desired amount of black powder. An igniter is then inserted and the charge is wrapped tightly in electrical tape. It is wrapped until the charge feels hard and cannot be squished anymore. The charge sizes are as follows:

- Primary Drogue: 6g 4F GOEX Black Powder
- Backup Drogue: 8g 4F GOEX Black Powder
- Primary Main: 5g 4F GOEX Black Powder
- Backup Main: 6g 4F GOEX Black Powder

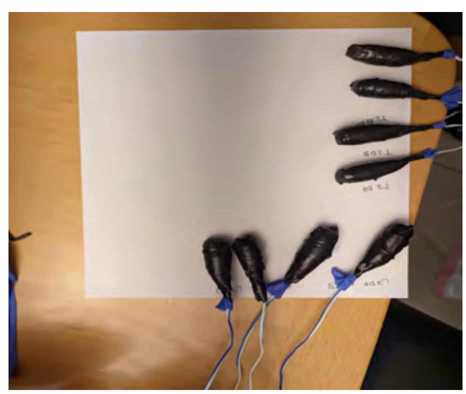

Fig. 35 Black powder charges

Since our rocket did not originally contain the air-brake module, the booster had a lot more volume which required more powder to properly work. With the module included, this volume was significantly decreased so the primary drogue charge was also decreased. The backup charge was kept at a similar level in order to ensure the rocket came apart. While the best case is to have two successful deployment events, the bare minimum is to have the drogue deploy. If the rocket does not separate at apogee, it will come in ballistically, and even if the main does deploy, it will likely shred. This is safer for any spectators and property as well as for the rocket itself. During our testing campaign,

Fig. 33 A view of the motor mount before installation into the airframe

Fig. 34 The motor mount after being epoxied into the airframe.

Fig. 36 Immediately After Main Deployment Test

Fig. 37 Drogue deployment test

we had one flight where the main failed to deploy. Our drogue had deployed as expected and the rocket came in faster than usual, far away from any people. While two of the fins had broken off, it was minor compared to what would have happened had it come in ballistically.

F. Avionics

1. Avionics and Battery Selection

Electronics selection was based on simplicity and flight computers already available to the team. In previous years, the team has utilized the TeleMega flight computer from AltusMetrum and it has worked very reliably. It has a very rich feature set including onboard GPS, telemetry, and many sensors for data logging, which can be helpful for post flight analysis. This was chosen to be our primary flight computer. For our backup computer, we are using an EasyMini, also from Altus Metrum. This is a very simple and reliable flight computer that isn't too expensive. It also uses the same battery type and connector for programming as the TeleMega which makes it very easy to set up. While dissimilar redundancy was considered for both flight computers, it was decided that modern flight computers are very reliable and often failures are because of user error rather than a hardware or software error. Both flight computers are using 900 mAh single cell lithium polymer batteries specifically for use with Altus Metrum flight computers. At maximum power draw, Apogee Components estimates a battery life of around 6hrs for the TeleMega [9]. This is more than enough for standard pad idle times, however, just in case, the EasyMini will also have the same 900mAh battery. Since the EasyMini does not have to deal with GPS or Telemetry, its battery life should be much longer than the TeleMega's.

2. Tracking and Telemetry

Tracking of the rocket is primarily done with the GPS built into the TeleMega. Telemetry is received using a 70cm Yagi antenna connected to an Altus Metrum TeleDongle. The Altus Metrum software on a laptop then automatically updates the coordinates of the rocket on a map in software. In case the flight computer loses connection to satellites or the TeleMega stops working for some reason, we are also including a ComSpec radio beacon in the rocket. This beacon is taped to the drogue shock cord and has a battery life that can last as long as a week [6]. This is especially helpful for finding the rocket once we get closer to it as we can sweep with the receiver to get a heading instead of looking at a screen. Including this beacon has already helped us during one of our test flights where the telemetry we received was being combined with the telemetry from another flight. While the GPS coordinates led us in the wrong direction, the beacon led us directly to the rocket. Unlike the Telemega radio which can change channels within software, the beacons have preset frequencies. If there is an overlap with another team's trackers, we have multiple transmitters that we can use with different frequencies.

Device	TeleMega	version 1.9.9	serial 8193
Flight	2		
Date/Time	2022-04-02	20:18:36 UTC	
Maximum height	2401.8 m	7880 ft	
Maximum GPS height	2376.0 m	7795 ft	
Maximum speed	239.2 m/s	785 fps	Mach 0.7
Maximum boost acceleration	103.6 m/s²	340 ft/s²	10.56 G
Average boost acceleration	71.5 m/s²	235 ft/s²	7.30 G
Ascent time	3.6 s boost	18.8 s coast	
Drogue descent rate	27.7 m/s	91 ft/s	

Fig. 38 Telemetry data from our third test flight

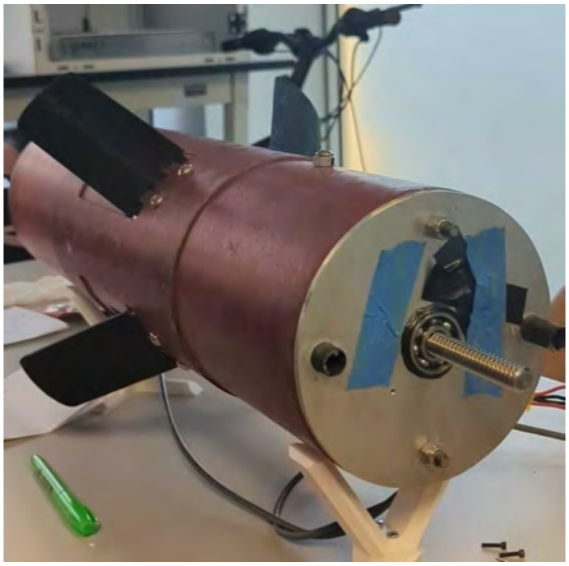

Fig. 39 Air brake module

Fig. 40 Air brake module installed in Terpulence II

3. Sled and Mounting

All electronics are mounted to a 3D printed PETG sled. This sled has guides for the two threaded rods to keep it stationary within the electronics bay. The flight computers are mounted with brass standoffs to the sled and batteries have printed enclosures to keep them from moving. The screw switches are mounted to the sides of the sled on shelves and also have their own standoffs. The switches are placed so that they are close to the coupler wall and they are easy to turn on once the rocket is on the pad. PETG was chosen for the sled as it is more temperature resistant than PLA and we have seen PETG work well for rockets in high temperature environments.

4. Avionics Testing

While avionics were primarily tested via flight tests, the TeleMega and EasyMini went through some ground tests to verify their functionality. The TeleMega was tested by placing it outdoors and walking far away with a laptop and the telemetry antenna. A continuous connection was kept the whole time over 1000ft. This test also had many obstructions, unlike a flight in clear air, which built confidence that we would have telemetry throughout the flight. The second test was to verify the altimeter could detect continuity of igniters. Igniters with no charges attached were connected to the screw terminals and both altimeters were turned on to verify they would complete their startup sequence. This was taken further with the TeleMega as it was used to fire ejection charges wirelessly. Further altimeter testing was conducted via a test rocket and our competition rocket, which will be discussed later in the report.

G. Air Brake

TerpRockets has explored adding active braking to the competition rocket to increase the rockets performance to hit a desired apogee. For the 2020-2021 academic year the team spent time exploring different designs, doing some preliminary tests, and discussing various designs with our mentors. This effort did not ultimately stumble across a working prototype but there were plenty of lessons learnt about how not to design an air brake. The 2021-2022 season brought new motivation, funding, and experience. We first designed and fabricated an air brake integrated into a 4" cardboard rocket. This rocket was launched at MDRA with an onboard camera and we were able to successfully deploy and retract the air brake in flight. Unfortunately, the recovery system failed and we lost the rocket. With this success, TerpRockets continued to design an air brake for Terpulence II. We were able to utilize all information gained from building a small scale version to inform the final air brake design.

Fig. 41 External CAD of the air brake module.

Fig. 42 Internal CAD of the air brake module.

1. Overview

Since it was unclear that the air brake would be flight ready for the 2022 Spaceport America Cup, the requirement was for Terpulence II, with only minor modifications, to be able to fly without the air brake. It was therefore designed as a module that can be added to Terpulence II or removed easily.

The air brake module utilizes similar construction techniques as a standard electronics bay. A 22" Wildman coupler with aluminum bulkheads and all thread make up its structural rigidity. An 10" "switch band" is placed at the middle section and the flaps which are flush with the switch band rest against the coupler. They are housed in cutouts of the switch band and are deployed based on a state feedback control loop. The flap motor and electronics are all housed inside of the module. There is a single stepper motor that controls all four flaps and uses a mechanical lock so that each flap is deployed to the same angle, which ensures continual stability.

There are four flaps, each is 45 degrees of the circumference of the airframe and 5" long. The flaps are the thickness of the airframe and stay flush until deployed. The flaps rotate about the hinge located towards the top of the flap into the airflow. We chose this configuration so that if the control horn that controls the angle of the flap fails, the flap will be pushed back to its original position, flush with the rocket. The flaps are powder sintered with the material Onyx produced by Mark Forged and infilled carbon fiber for extra rigidity. This material was chosen for its strength and performance under thermal loads since it would be encountering the high temperatures common in New Mexico.

An Arduino Zero is used to process the data from the sensors, estimate the state using an Extended Kalman Filter, and calculate the required angle based on a P.I. controller. This angle desired is sent to a Teensy 4.1 microcontroller that delivers the steps required to the stepper motor. The state is determined using a barometer, IMU, and GPS. Before launch and after the first recovery event the data is logged to a micro SD card. During the powered and unpowered ascent, the data is written to an FRAM, this doubles the sensor measurement frequency. After apogee, this data is dumped into the SD card. The electronics package is wired using a SRAD PCB board. A 9V is used to power the electronics. Three 550mAh 90C 4s Lipo batteries are wired in series to power the actuator. These batteries were flown on one of our test flights to ensure they could survive the launch loads.

Fig. 44 Flaps fully retracted

Fig. 45 Flaps deployed to 45°

Fig. 46 Flaps fully deployed

2. Module Placement

During flap deployment the flaps will shift the CP significantly towards the location of the flaps. To ensure this does not create an unstable rocket, the flap module should be placed as far aft as possible. The farthest aft option without modifying the rocket would be just above the fin can. This placement puts the air brake in between the CP and CG. An OpenRocket simulation was performed to calculate the CG after motor burnout. This was done by simulating the stability margin during a flight and then this margin was then used to calculate the CG using the assumption the CP did not move during the simulation. The distance between this new CG and location of the flaps divided by the diameter of the rocket was determine as the stability margin. The stability margin was calculated in this configuration as 2.17. Note that this assumes the extremely conservative estimate that the CP is now moved forward to exactly the location of the flaps. This is a safe stability margin and it is concluded it is the best configuration under the current constraints.

3. Deployment Mechanism

The deployment is achieved by a stepper motor. The motor displaces an actuator disk which is connected to four threaded rods. The actuator disk has two channels that restrict the disk to only move in the vertical direction. The rods are connected on their other end to a control horn connected to the flaps. As the disk is displaced down it rotates the flaps into the airflow. The entire assembly is connected so that the flaps are mechanically locked to each other and are therefore deployed to the same angle; figs. 44 to 46 shows various deployment configurations.

Fig. 43 FEA of actuator rod

The CAD module places another hinge where the actuator rod is fixed to the actuator disk. The actual design has the rod fully fixed to the disk and for the rod to deflect in the transverse direction to allow for flap deployment. The radial placement of the actuator rod to the actuator disk was chosen to minimize the magnitude of the rod deflection over the ranges of flap deployment. An FEA analysis was performed on the maximum deflection of 0.58" to ensure an adequate safety factor. Fig. 43 shows the analysis. One end is held fixed and the other is forced to 0.58" displacement. This resulted in an ultimate SF of 1.3, although this is low the module was tested with the hardware and was able to sustain the loads.

Since the input to the control loop is the desired angle of the flap. We need a function to convert angle into number of steps for the stepper motor. Fig. 47 shows the geometry of the problem. Here the constraint is that the length of the actuator rod is constant. The length of the rod for any angular

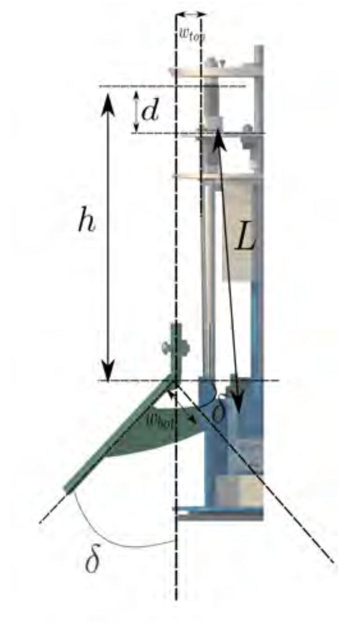

Fig. 47 Geometry Of deployment mechanism

displacement can be written as,

$$L = \sqrt{(h - d + w_{bot}\sin\delta)^2 + (w_{bot}\cos\delta - w_{top})^2}, \tag{1}$$

where h is the vertical distance from the actuator rod in the fully retracted position to the flap hinge, δ is the displacement of the actuator plate, w_{bot} is the width of the control horn to the hinge, w_{top} is the width from the place the actuator rod is fixed to the actuator disk to the vertical line passing through the hinge, and δ is the flap deployment angle. This equation simplifies if we assume small angle but since the range of deployment angle is $[0, \pi]$ we cannot make that approximation. Since we know that at $\theta = 0 \rightarrow \delta = 0$,

$$L = \sqrt{h^2 + (w_{bot} - w_{top})^2}. \tag{2}$$

We can set set Eq. 1 equal to Eq. 2 and solve for δ which gives us,

$$d = h + w_{bot}\sin\delta - \sqrt{h^2 + (w_{bot} - w_{top})^2 - (w_{bot}\cos\delta - w_{top})^2}. \tag{3}$$

From the manufacturer we know that there are 200 steps per 0.24" of vertical displacement of the stepper motor, so the final form of the steps as a function of angle is,

$$steps = 847(h + w_{bot}\sin\theta - \sqrt{h^2 + (w_{bot} - w_{top})^2 - (w_{bot}\cos\theta - w_{top})^2}). \tag{4}$$

The values for h, w_{bot}, w_{top} were measured on the air brake module. This formula was bench tested and was found to deploy the flaps to very close to the desired angle.

4. Selection of Linear Actuator

In order to achieve precise actuation and handle high torque, a stepping motor was our choice for linear actuator. The specifications of the motor were decided based on expected load, required precision and actuation speed. We use STP-LE23-3H06ANN motor manufactured by AutomationDirect for actuating the flaps. It can handle a maximum load of 193 lbf, has a linear travel of 0.24” per revolution, and can achieve linear speeds up to 2.5 in/sec. It has a 4” effective screw length to get the full-range of flap-deflection ($0° - 90°$).

From flight simulations for our rocket, braking force due to the flaps at h = 6000 ft with v = 656 ft/s is 147 lbf. Accounting for a factor of safety of 1.2~1.3, the actuator should be able to handle a *load* of 190 lbf, which is within the rated load capacity. The actuator is capable of precisely moving by a step which corresponds to 0.0012” of linear movement, or alternatively a flap-deflection *precision* of at most 0.05°. Hence, the actuator is capable of meeting our design requirement for flap-defection precision of 1° (20 steps).

Fig. 48 STP-LE23-3H06ANN stepper motor

The load capacity and the linear travel speed follow an inverse relation, with load capacity decreasing with increasing actuating speed. We had to consider a design trade-off between load capacity, rate of flap-deflection and precision. Based on simulated loads and desired brake-performance, it was decided to actuate at 1 in/sec or equivalently a flap-deflection rate of 30°/sec, with rated load capacity of 154 lbf.

Stepping motor driver and DC power supply: The input voltage to the motor is 24 − 48VDC. The stepper motor is driven by STP-DRV-4845 driver from AutomationDirect. The power input to the driver is from three 550mAh 90C 4s LiPo batteries connected in series − effectively a 12s battery cell, and the output voltage is 44.4V with a peak amperage of 3A.

5. Air Brake Structure

The structure of the air brake module is inspired by standard electronics bays in high-powered model rockets. The main body is a 22" Wildman fiberglass 6" coupler. Two $\frac{1}{4}$" steel rods connected to a bulkheads placed at the top and bottom of the module providing an anchor for the various systems. The switchband is a 10" section of the 6" diameter Wildman fiberglass airframe. The cuts in the switch band which house the flap and screw holes for the upper section of flap assembly were cut on a manual mill using an indexing head to allow for precise radial cuts. This switch band then acted as a guide for the cutouts on the coupler which were cut using a dremel.

Upper Section The upper part of the module houses the stepper motor and related parts as well as the upper bulkheads. Fig 54 shows this part of the module.

The linear guard screw is 3d printed using PETG and serves to protect the exposed part of the screw from the shock cord. We left part of the screw exposed to be able to turn the screw by hand to reset the flaps to be fully retracted. Just below are the two upper bulkheads which are both 1/8" aluminum 6061 and manufactured on a water jet. The Top Upper Bulkhead serves to seal the air brake from the recovery charges and to have a place for the threaded rods to attach. The Bottom Upper Bulkhead serves to center the upper bulkhead to ensure that it can slide into the upper air frame. The actuator disk is made from stock 6061 aluminum and was manufactured using a CNC mill. It is bolted to the flange nut and is what is displaced vertically by the stepper motor. Aluminum guiding spacers were necessary to allow smooth movement and to make sure the disk does not get caught on the threads of the rods. The actuator mounting plate, also 1/8" 6061, is secured to the threaded rods via bolts and spacers and serves as a place to secure the stepper motor. Lastly two carbon fiber shock cord tubes are shown. These serve as to protect the shock cords since they run from the fin can to the main electronics bay. Since the air brake was designed to be non critical to the safety of the rocket the shock cords need to pass by the module so no recovery forces are applied to the air brake. A FEA analysis was performed on the actuator mounting plate since it experiences non trivial forces during the flight. The stepper motor weighs 4 lb and with an assumed 13 g max acceleration, a 52 lbf is used. A factor of safety of 2.3 was determined with this analysis.

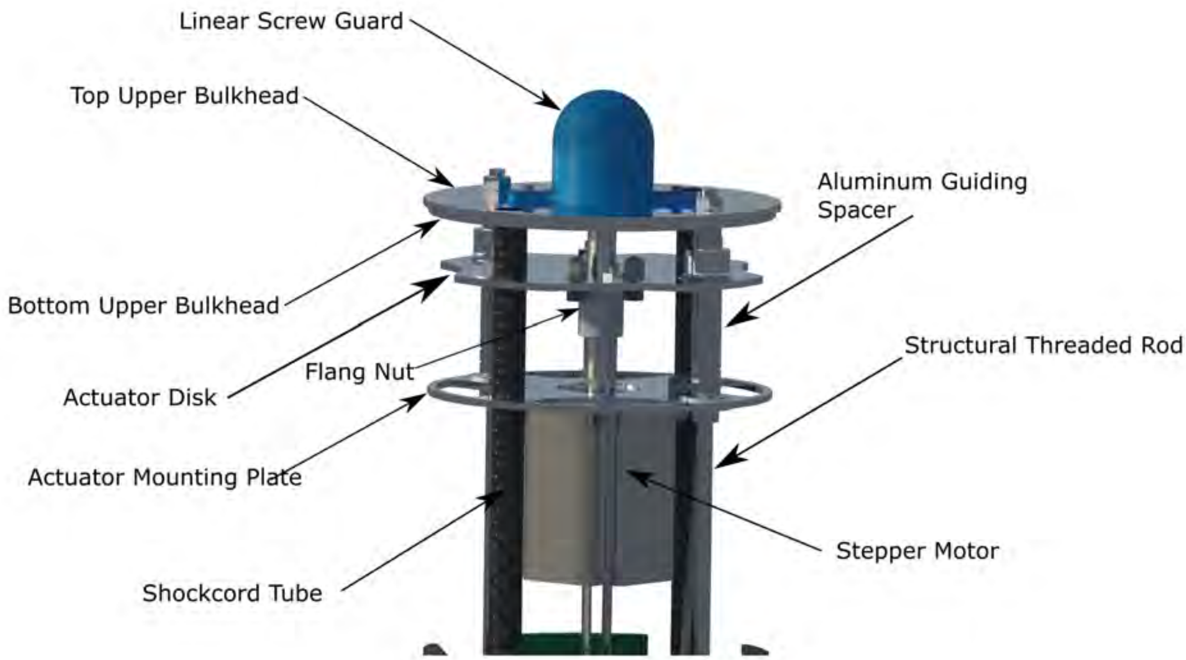

Fig. 49 Upper section of the air brake

Middle Section Below the upper section is housed the flap assembly and electronics as shown in Fig. 52. The flap assembly is composed of four parts; hinge, hinge mount, control horn, and flap. These four parts were fabricated separately in the 4" scale air brake but this caused the part to be weak since there was no good way to fasten them together. Various different materials were considered since there are restricting requirements. The thickness of the bottom of the flap can only be 0.17", the wall thickness of the Wildman 6" fiberglass airframe. The tolerances must be close enough so the hinge assembly can be printed together, the upper section must be able to hold the shear forces applied by the screws, and it must have a high heat deflection rating since it will be exposed to the sun on the launch pad in New Mexico. Onyx nylon was chosen as the filament using the Markforged Mark Two. To further strengthen the part, carbon fiber strands were placed in be between layers of filament. To reduce cost of the 3d print the carbon fiber strands were only placed concentric to the part as shown in fig. 53. This added the necessary strength to the thin parts of the flap assembly. To get the hinge to work properly many different tolerances were tested until one was found allowing the flap to rotate freely yet rigidly.

The actuator rods are 8-32 stainless steel threaded rod. They are fixed to actuator disk by nuts and washers and are epoxied into PETG 3d printed clevis rod ends. This rod end is then pinned to the control horn.

The electronics sled is also 3d printed with PETG and is used to mount all of the electronics. The top of the sled is the driver wire guide. Control wires are fed from the motor driver to the stepper motor and and sleeve was added to ensure the wires do not get caught in any of the moving parts. Towards the bottom of the sled is where the sensors and micro-controllers are secured. Above the sensors is the Turbulent Airflow Guard. This guard is used to isolate the barometer from the turbulent flow that enters the air brake module cavity when the flaps are deployed. The Rocket Motor Heat Guard serves a similar function, to protect the sensors from the heat of the motor casing.

Fig. 50 Actuator mounting plate CAD

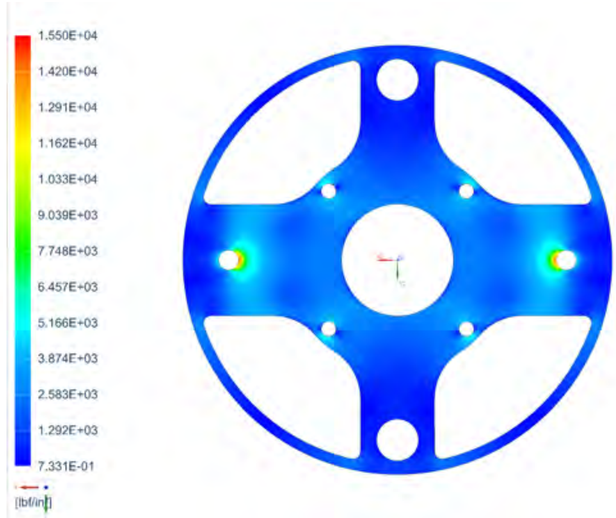

Fig. 51 Actuator mounting plate FEA

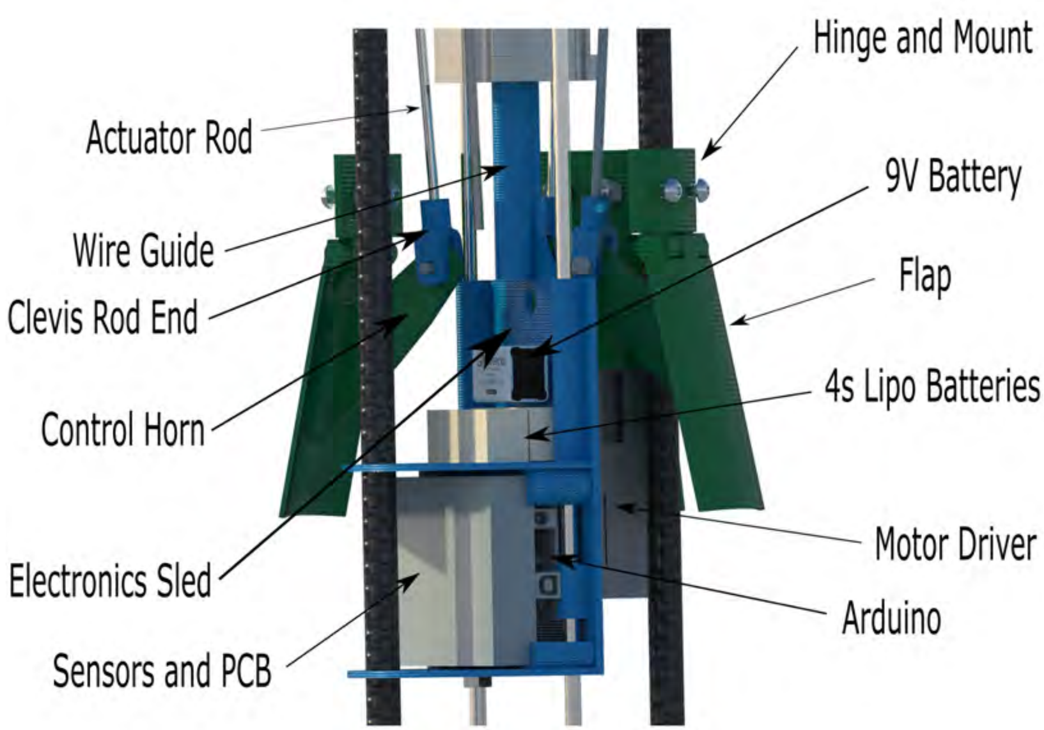

Fig. 52 Middle section of the air brake

Lower Section The bottom of the air brake module contains the two lower bulkheads. These bulkheads serves a similar function to the upper bulkheads, providing a place to mount the threaded rods and to center the bulkheads. These bulkheads have a space to in the middle to allow the motor casing to fit through. This design allows the air brake

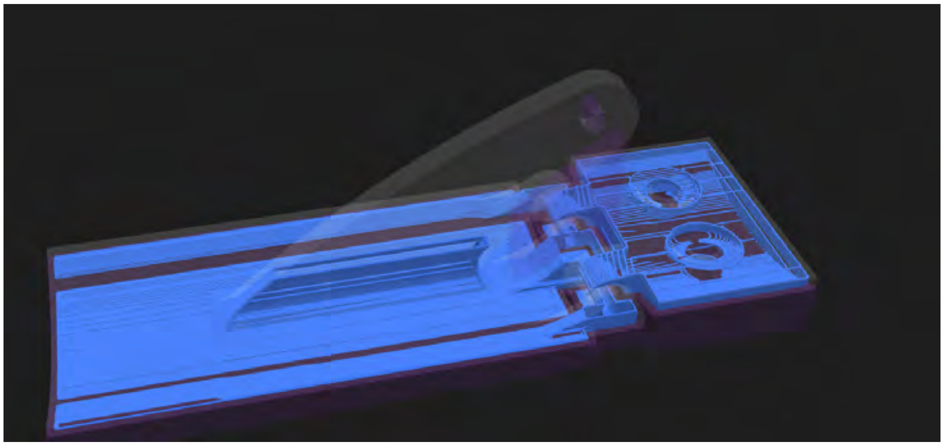

Fig. 53   Carbon fiber placement on the flap

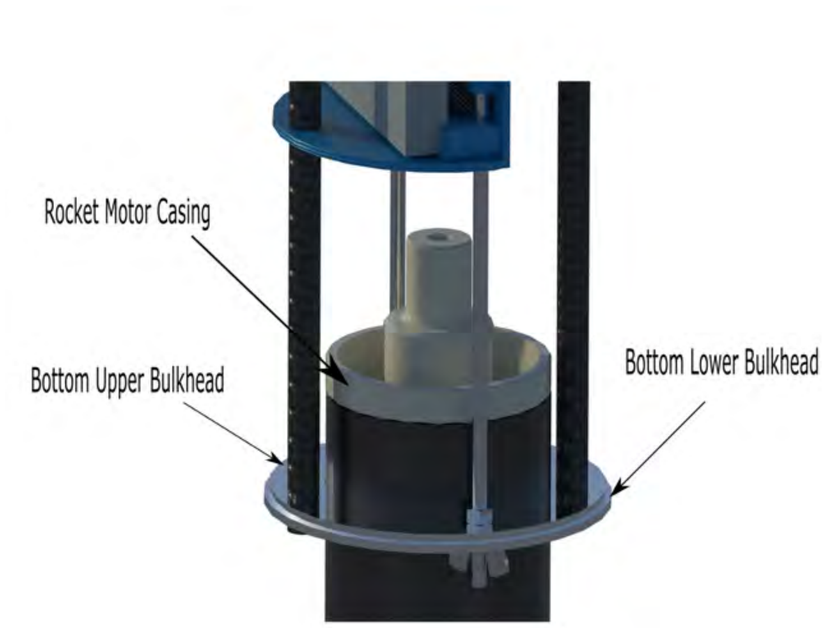

Fig. 54   Lower section of the air brake

module to move as far aft as possible.

6. Avionics

PCB Overview   The PCB of the air brake, shown in Figure 57, primarily an Arduino Zero and a Teensy 4.1. These micro controllers are supplied with flight data from a ICM20649 IMU, a BMP388 Barometric Pressure Sensor, and an Adafruit Ultimate GPS. There is also a buzzer installed onto the board for basic diagnostic feedback. The PCB was designed in Fritzing and underwent many changes between the first version and the latest revision.

Sensor Data Overview

- Data from the IMU provides acceleration and gyroscopic data, so we can determine our orientation and relative speed

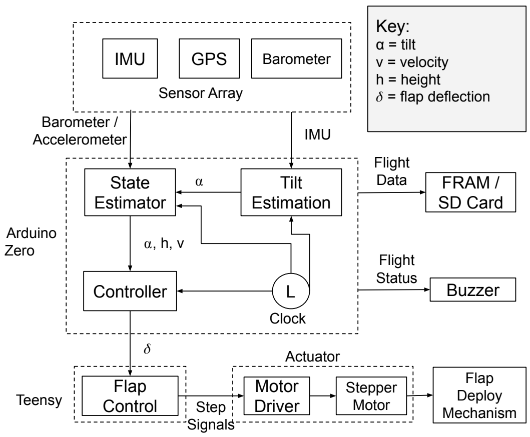

Fig. 55 Schematic of the avionics of the air brake

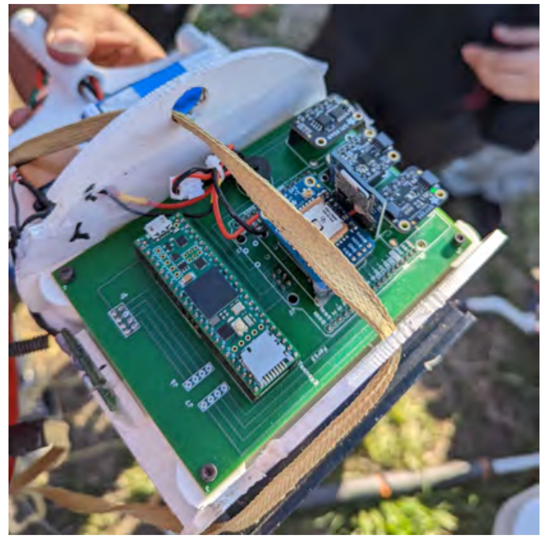

Fig. 56 Air brake sled and electronics

- Data from the Barometric Pressure Sensor allows us to estimate our altitude
- Data from the GPS allows us to plot the path of the rocket from a birds-eye view post-launch

Data Storage Overview To store data from our sensors along other diagnostic information, we utilize an SPI FRAM card for short term storage and an SD Card Adapter for long term storage. While testing, we noticed that the process of writing to an SD Card is quite slow, but writing to FRAM was significantly faster. To take advantage of this finding, we write the flight data to FRAM before copying the data to the SD Card after the Arduino Zero detects the recovery event. The data on the SD Card is in a CSV format for easy importing into MatLab and Microsoft Excel.

Offloading of Actuation Along with data collection, the Arduino Zero is tasked with using said data to determine how much actuation is required for the air brake flaps. While we could actuate from the Arduino Zero directly, the process of stepping the motor causes a critical slowdown in sensor collection, we therefore use a Teensy 4.1 to step the motor driver.

Main Computer Code Breakdown On the Arduino Zero, the code consists of a setup process that initializes and calibrates the sensors as well as a control loop that repeatedly polls data that feeds into a state machine. A block diagram of our system is on Figure 55.

Before launch, sensor data will be written directly to the SD Card until our pre-programmed launch conditions are met. Once the launch condition is met, sensor data will be written to our FRAM module instead, and we will calculate the desired actuation angle for transmission to the Teensy actuation controller. We will also watch for a pre-programmed condition to determine when the first recovery event has occurred. Once triggered, the contents in FRAM will be copied to the SD Card. Sensor data will continue being written to the SD Card until the power is turned off.

Actuation Controller Code Breakdown The Teensy actuation controller operates in a loop of polling for desired actuation angles from the Arduino Zero. When the Teensy actuation controller receives a degree of actuation, it will convert it to steps before comparing it to the current actuation and actuating accordingly. Not all steps are completed in one sequence, so the desired actuation can change mid-sequence and the controller will account for that. If the Arduino detects any off nominal behavior it will command the Teensy to fully retract the flaps and remained closed.

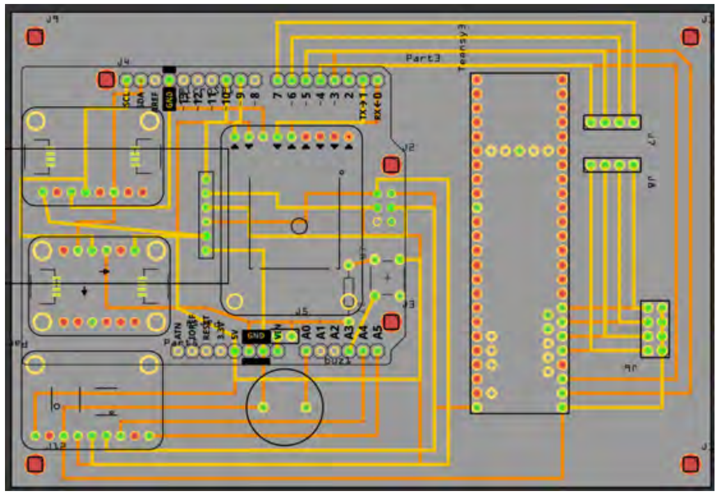

Fig. 57 ***Terpulence II* air brake PCB diagram**

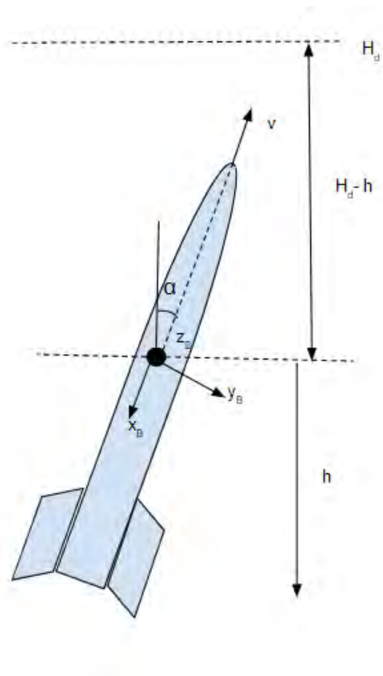

Fig. 58 The relevant states (h, v and tilt off the vertical-axis α) of the closed-loop altitude control system and body axis

7. Control Loop

A closed-loop feedback controller is designed to determine the flap deflection angle that ensures the rocket to reach the desired altitude. In order to synthesize the controller and as well as, simulate the rocket's behaviour, the dynamics of the rocket during its ascent is derived using Newton-Euler formulation.

$$m\dot{v} = T - D - mg - F_b(\delta) \tag{5}$$

where T is Thrust, D is aerodynamic drag and $F_b(\delta)$ is the braking force as a function of flap-deflection δ. m is the mass and v is the free-stream velocity of the rocket. The flaps are deployed after burnout, i.e. unpowered ascent and hence, $T = 0$. The aerodynamic drag is modelled as: $D = k_a v^2$.

k_a depends on air-density, cross-sectional area of the rocket, and co-efficient of drag, obtained from openRocket. The braking force is modelled as drag on a *flat-plate* in a free-stream. k_b is currently estimated but will be obtained from the flight test May 28th and confirmed using CFD analysis.

$$F_b(\delta) = k_b v^2 \sin\delta \tag{6}$$

An altitude-error term is defined in terms of desired altitude H_d, current altitude H, and the tilt of the rocket α.

$$e = \frac{(H_d - H)}{\cos\alpha} \implies \dot{e} = -v \implies \ddot{e} = -\dot{v} \tag{7}$$

A *feedback-linearization* based control law is derived in terms of the defined altitude-error term. Substituting $T = 0$, and Eqs.(6)−(7) in Eq. (5),

$$\ddot{e} = \frac{k_a v^2}{m} + g + \frac{k_b v^2 \sin\delta}{m} = w \tag{8}$$

w is the transformed input, and a P.I. controller is derived for this transformed input. The derivative term is unnecessary here because there won't be underdamped *oscillatory* behavior because the flaps provide only "braking" force. More so, the ambient aerodynamic drag acts as a natural damper.

$$w = -k_p e - k_i \int e dt \tag{9}$$

Plugging the above control-law into the error-dynamics (Eq. (7)), we infer that $\dot{e} \to 0$, $e \to 0$ and hence, $H \to H_d$. This validates that the NDI-based controller is able to reach the desired setpoint. Based on the difference in altitude and tilt of the rocket, w is calculated according to Eq. (9). The required flap deflection, δ is then calculated using Eq. (8).

The controller gains, k_p and k_i are tuned based on rocket characteristics, air brake-system limitations and desired performance. The added integral term ensures zero steady-state tracking-error and adds robustness to the closed-loop system. Additional controller design considerations are: Stability of closed-loop system, No undershoot, and settling time within time-to-apogee.

A **state machine** is designed to abstract the control logic into the air-brake computer. It ensures that we deploy the flaps only after a certain altitude and velocity, and retract fully on reaching apogee, $v = 0$. Additionally, it incorporates actuator-saturation that prevents the flaps from deflecting beyond a specified angle parameter.

8. State-Estimation

An important aspect of the closed-loop system is obtaining *state-feedback*, $\boldsymbol{x} = [h, v]^T$. To this effect we use an extended Kalman filter (EKF) as our state-estimator. EKF serves a dual purpose — estimating state-feedback and filtering sensor noise.

The Kalman filter comprises of 2 stages − predict and update. It uses the system's process model and prior state to predict, and sensor measurements to correct the prediction, hence obtaining a "filtered" estimate of the state. It's a linear, discrete-time, optimal estimator that assumes uni-modal Gaussian noise. In practice, with proper parameter-tuning, Kalman filters work really well for most systems with microelectro-mechanical sensors (MEMS).

Data measured from the accelerometer in the IMU, a_m is used to drive the process model, and height h_m measured from the barometer and GPS helps update the prediction. We explicitly account for the changing bias in the accelerometer by including it as a state, b. The tilt of the rocket, α is directly estimated from the on-board IMU. The state equations in discrete-time are, *Process model:*

$$\begin{bmatrix} h \\ v \\ b \end{bmatrix}_{k+1} = \begin{bmatrix} 1 & T_s \cos\alpha_k & -\frac{T_s^2}{2}(\cos\alpha_k + \sin\alpha_k) \\ 0 & 1 & -Ts \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} h \\ v \\ b \end{bmatrix}_k + \begin{bmatrix} \frac{T_s^2}{2}(a_{m_x}\cos\alpha_k + a_{m_y}\sin\alpha_k - g) \\ T_s(a_{m_x} - g\cos\alpha_k) \\ 0 \end{bmatrix} + \boldsymbol{\omega}_k \tag{10}$$
$$\boldsymbol{x}_{k+1} = \boldsymbol{F}_k\boldsymbol{x}_k + \boldsymbol{u}_k + \boldsymbol{\omega}_k$$

Measurement model:

$$\begin{bmatrix} h \end{bmatrix}_k = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} h \\ v \\ b \end{bmatrix}_k + \boldsymbol{\nu}_k \tag{11}$$
$$z_k = \boldsymbol{H}_k\boldsymbol{x}_k + \boldsymbol{\nu}_k$$

where, T_s is the sampling-time, a_{m_x} is x-component of acceleration measured from the accelerometer, a_{m_y} the y-component, g is acceleration due to gravity, and k indicates the time-instance. ω and ν are normal-distributed Gaussian noise with covariance matrices Q and R respectively. Using the process and measurement models Eqs. (10)–(11) in Kalman equations [10], we estimate the altitude and velocity of the rocket to be used by the NDI controller. The process and sensor co-variance matrices, Q and R were tuned based on data logged on a commercial flight computer, an Altus Metrum Telemega.

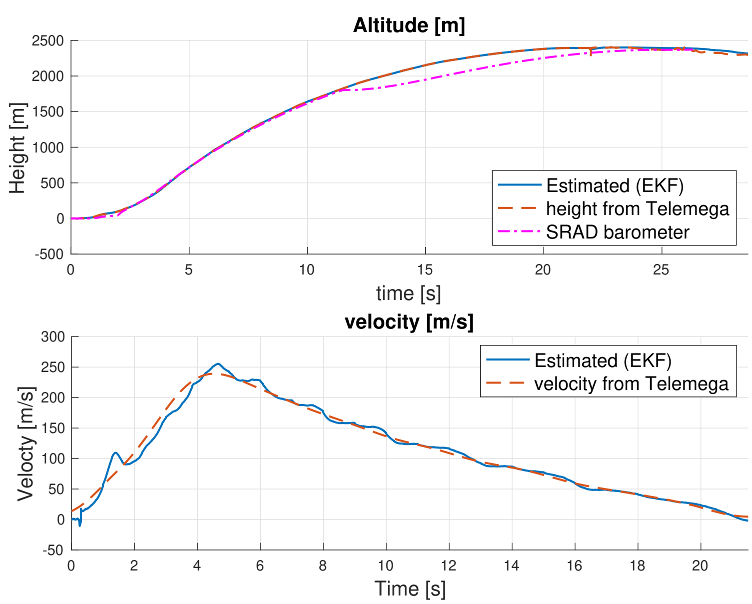

Fig. 59 Comparison of altitude and velocity estimates from our SRAD equipped with an EKF-based state estimator and a commercial flight computer – Telemega

9. Simulation

The control law as discussed above assumes incompressible flow. This assumption loses accuracy the closer to mach the flaps operate. A Matlab simulation was setup to determine if the flaps can stay dormant as Terpulence II travels in the transonic regime. A 1D model was used, the scalar equivalent to Eq. 5. The thrust curve of the N3800 was used to generate the thrust in the model. The induced drag of the flaps was assumed to be $1/2C_d A\rho v^2 \sin\delta$ where A is the area of the flaps, δ is the deployment angle, and $C_d = 1.5$. The test assumes an instantaneous deployment of the

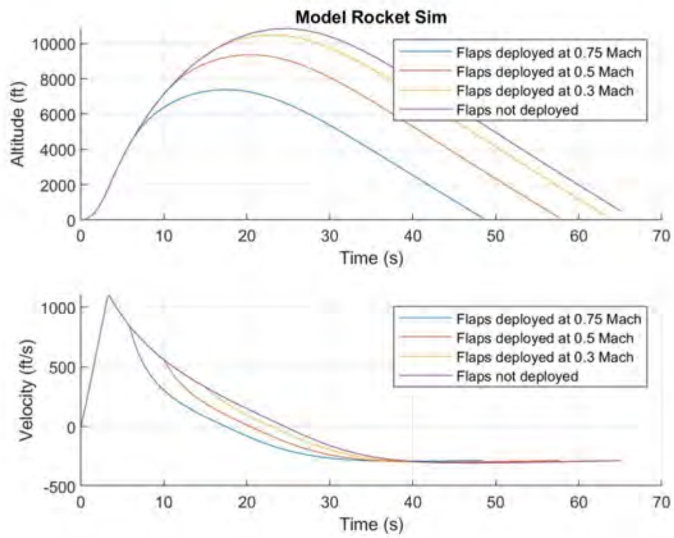

Fig. 60 Simulation of air brake flaps only active in certain flow regime. $\delta = 80°$ **with no control loop**

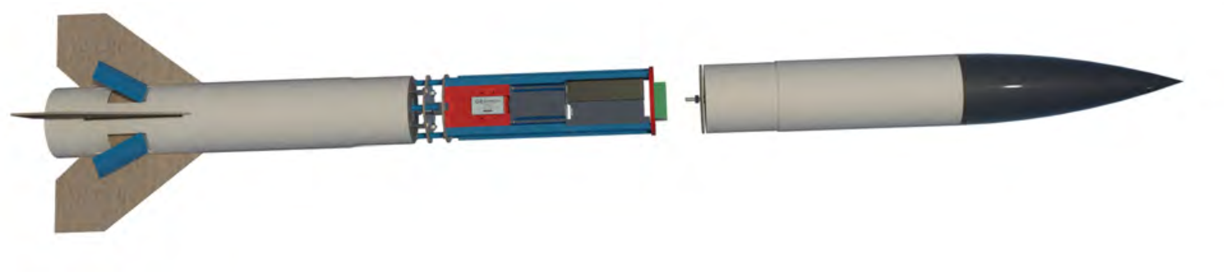

Fig. 61 CAD of 4in air brake test rocket

flaps to 80° without any control law. Fig. 60 shows the results of this simulation. Only 500 ft of altitude was able to be shaved off when the flaps stay closed until 0.3 Mach. Since Terpulence II has a predicted apogee over 11,000 ft this will not be sufficient. The flaps will need to start their control loop earlier in the flight. Even though the performance of the air brake will be lower at higher speeds, if it performs well in the low speed range it should be able to fine-tune the apogee to the desired 10,000 ft.

10. Testing

There were many new skills and techniques the team needed to learn during the development of the air brakes. There were also many new systems that the team either designed themselves or had little experience with. It was for this reason that many incremental steps were taken to build the confidence of the air brake team to build a working air brake module for Terpulence II. Most of these skills were learned during the construction of a 4" test rocket to house a scale version of air brakes. This project extended through most of the school year and had the desired affect of demonstrating the validity of the design and the competence of the team.

First, a full CAD was designed for a test rocket. This highlighted some of the initial issued with the design, mainly interference between parts. This full CAD is shown in Fig. 61. Next, the 4in test rocket was built, along the way part of the design was changed due to various issues including manufacturing complexities. Once the rocket was finally built there was plenty of bench testing to work with all the new sensors and micro-controllers. After the team was able to assemble a working flight computer with a breadboard, it was time to work out the intricacies of creating a flight computer that would fit into the rocket and satisfy the various requirements that come with a flight ready computer.

Fig. 63   4in air brake test rocket on the pad

Fig. 64   Successfully deployment of flaps

These requirements included prolonged battery power, surviving launch loads, an external power switch, and feedback to ensure a working system. This requirement satisfaction posed a greater than expected challenge.

Finally, in March the team achieved a flight ready air brake test rocket. The primary purpose of this test flight was to combine all of the systems. The flight computer needed to acquire data from the sensors and actuate the flaps based on these measurements. On launch day we first flew the flight computer on a less complex rocket to verify that all systems on the flight computer were working. This was a complete success. The flight computer logged all the necessary data and sent commands to the motor driver at the appropriate time. The altitude and acceleration estimated by the flight computer was compared to data from an EasyMini onboard and agreed quite well. Armed with this confidence we flew the full 4in test rocket. The primary goal was to prove that we could deploy and retract the flaps in flight based on sensor measurements. Fig 71 shows a still from the on-board video showing the successful deployment of the flaps, this test proved that the air brake design was feasible.

Fig. 62   4in air brake test rocket

With this major success the team was focused on building an air brake for Terpulence II. The main lesson learnt from the fabrication of the 4in air brake test rocket was to make the air brake as modular as possible. If a part breaks it should be easily replaceable instead of scrapping the entire system. This along with the experience using the sensors and electronics propelled the team to design and build the air brake module that will be installed for the 10k flight in New Mexico.

H. Payload

The payload will be testing a specific geometry's ability to use capillary action under micro-gravity conditions to "pump" a liquid (water in this case) in a certain direction. The application of such a system would be to control the movement of fuel in a rocket tank. Given the low-g environment of space, it can be difficult to move fuel from a tank to the engine if the tank is not completely full. Using this geometry would naturally guide the remaining fuel in a useful direction without the use of systems like ullage motors. The geometry we are using is a SLA resin 3d printed part that

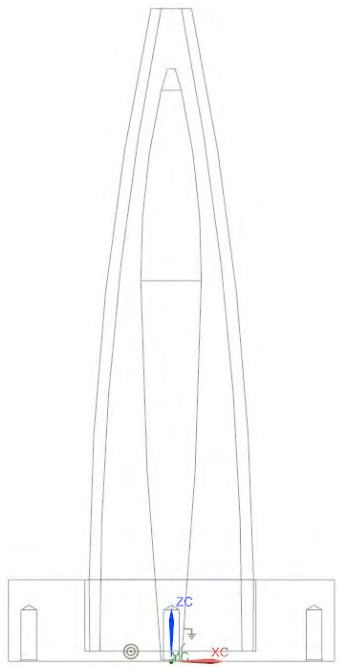

Fig. 65   Pump geometry

Fig. 66   Capillary action pump

has the surface area increase in the direction that we want the water to flow.

To test if the geometry works, we have connected a thin tube that the water will flow through and into a tank with a sponge in it. We will measure the weight sponge before and after the flight to see if it absorbed any water (hence water was pumped out of the geometry). Furthermore, the water will be dyed with food dye. This will provide a visual indication on the sponge as to whether water was transferred.

In order to make sure the sponge in the final tank is only collecting water when the payload is in micro-gravity (so capillary action is the primary driver) a normal-closed solenoid valve is placed between the thin tube and the final tank. This solenoid is only opened when the total acceleration of the payload is less than $1m/s^2$ and when the payload is above 8000 ft (this is to ensure no false positives as micro-gravity conditions should come near the apogee of the flight). Two 9v batteries connected in series power the solenoid during operations. This circuit is activated with a TIP120 transistor. An Arduino Uno will send a signal to the transistor when micro-gravity is detected to open the solenoid. In order to measure the acceleration, we are using an ADXL335. We are using a BMP barometer also wired to the Uno to measure the altitude.

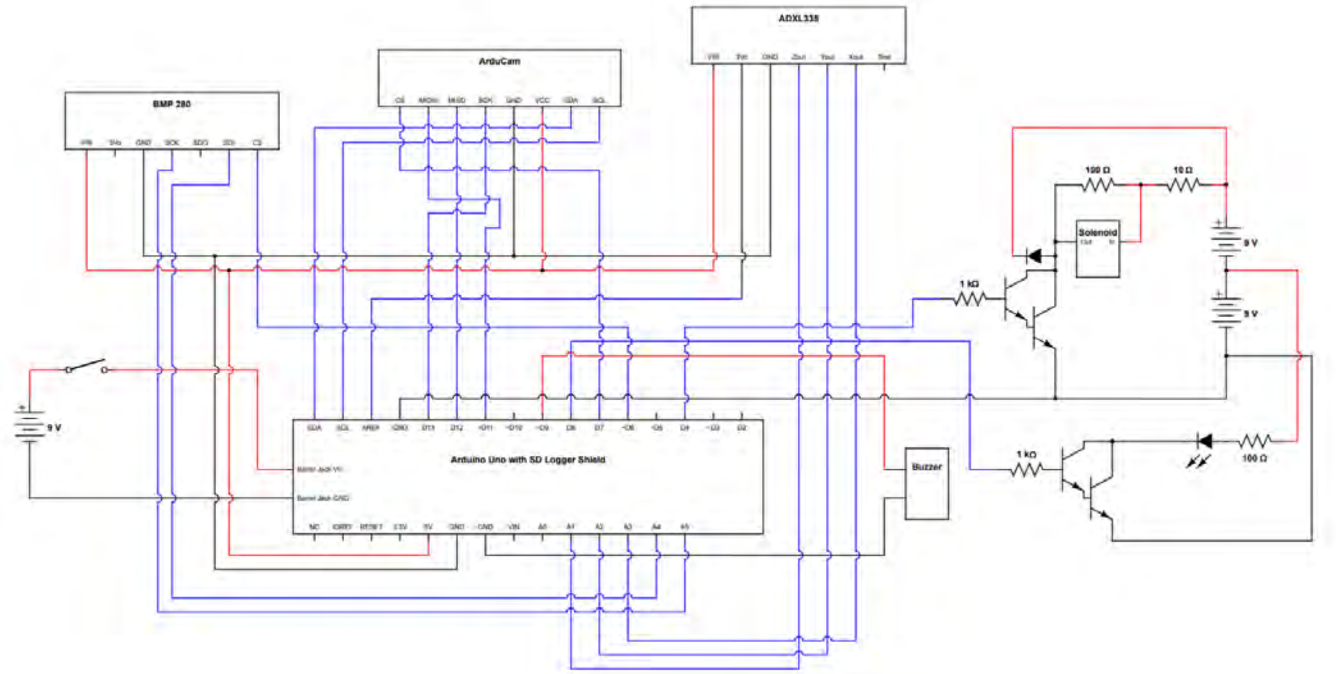

Fig. 68 Payload circuit diagram

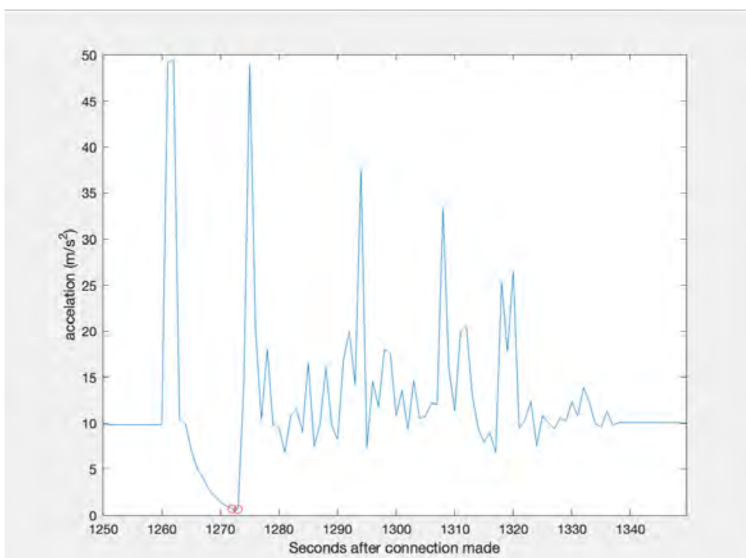

Fig. 67 Payload test flight acceleration data

To determine if capillary action was the primary driving force in moving the water from the pump to the final tank, the pump was 3D printed in a clear resin. This allows us to take pictures of the pump (with an Arducam) while capillary action should be occurring. This can guarantee capillary action is the primary driver as you can see the water clinging to the sides of the pump and an air bubble in the pump where parts of its volume are furthest from a wall of the pump. The dye added will also help contrast the water and tank or air. To ensure the water is visible inside the payload, a high-power LED is wired in parallel with one of the 9v batteries used to power the solenoid. This circuit is also controlled by a TIP120 transistor, allowing the Uno to save power while the payload is sitting on the pad or awaiting recovery.

Pictures of the pump are logged to an SD card along with time, barometer, and acceleration data, as well as the state of the solenoid (open or closed). This information can then be reviewed after the launch to determine what micro-gravity conditions the payload experienced, how long the solenoid was open, and whether the camera identified signs of capillary action within the pump. An SD card shield was chosen to avoid I2C conflicts between the Arducam and a standard SD card module. This shield also provided a real-time clock. A screw switch was used to activate the payload. For easy access, this is separated from the payload and connected directly to the nose cone. The switch is connected to the payload electronics while in the nose cone using two 9v battery connectors, one wired to the switch and payload respectively. These provide a very tight connection and ensure the switch will not be separated during launch. In addition to the previously mentioned electronics, a buzzer was added to provide audio feedback when the payload is activated. These components were assembled on a PCB for organization and a secure connection.

To determine when the solenoid would open, we used the accelerometer data in conjunction with barometer data. While the solenoid would ideally open when the accelerometer reads 0 with little tolerance, the camera took roughly a second to take and store a photo on the SD card, which determined the rate at which data from sensors could be checked. As a result, the tolerance also had to take into account that the Uno would only receive an updated acceleration value every second or so. We decided that the solenoid would be opened at a range of $-1m/s^2$ to $1m/s^2$. This range was qualified by the fact that the payload should not be below 500ft in elevation. Given the varying conditions in atmospheric pressure from one launch to another, the payload records the initial pressure conditions when it is first activated and sets that as ground level. For the Arducam, we used code we found on the ArduCam website and used it to make a function ‘pictures’ which took time as an input so that we could have the filename of each photo be the time at which the photo was taken. This naming convention would make paring a picture with when the solenoid is open much easier. Using a function also allowed us to easily change when we were taking the pictures by changing where we call the function rather than moving hundreds of lines of code around. The high-power LED was constantly turned on while the payload would be taking pictures (regardless of whether it was taking a picture at that moment) to ensure there were no issues with the light turning on or off mid-picture.

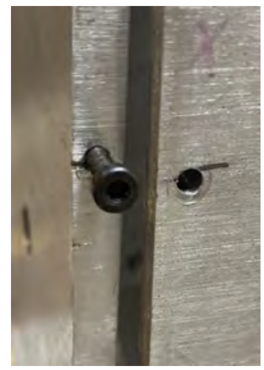

Fig. 69 Method for frame assembly

The payload frame was constructed from 1/4" thick aluminum plates. This allowed M3 screws to thread into the thickness of the plates, which reduced the number of parts needed for the frame. The use of 1/4" plates also provided the strength required for direct mounting into the nose cone, as detailed in the payload bay section. To meet the 8.8lb weight requirement, a 2.2 lb aluminum block is connected to the top plate of the frame. This ballast also serves as a connection point for the threaded rod that holds the payload in the nose cone. The bulkhead connects to the bottom of the payload frame with 4 3/8" inch bolts. These bolts thread into 2 1/4" inch plates to increase the number of engaged threads. Two internal shelves were added, one for the Uno and one for the solenoid. Components were connected to the frame through 3D-printed mounts. These mounts were printed in PETG for higher temperature resistance. For reduced complexity, the battery and solenoid mounts use very tight friction fits.

Fig. 72 Mounting system. Left: Nose cone shell. Right: Payload frame and bulkhead on support blocks

1. Payload Bay

The payload is mounted within the nosecone. One end is bolted to the nosecone bulkhead and the other is connected to a threaded rod that runs to the nosecone tip. This rod is threaded into the payload ballast, as seen in Fig 72. All connections are secured with Loctite Threadlocker to prevent unscrewing in flight.

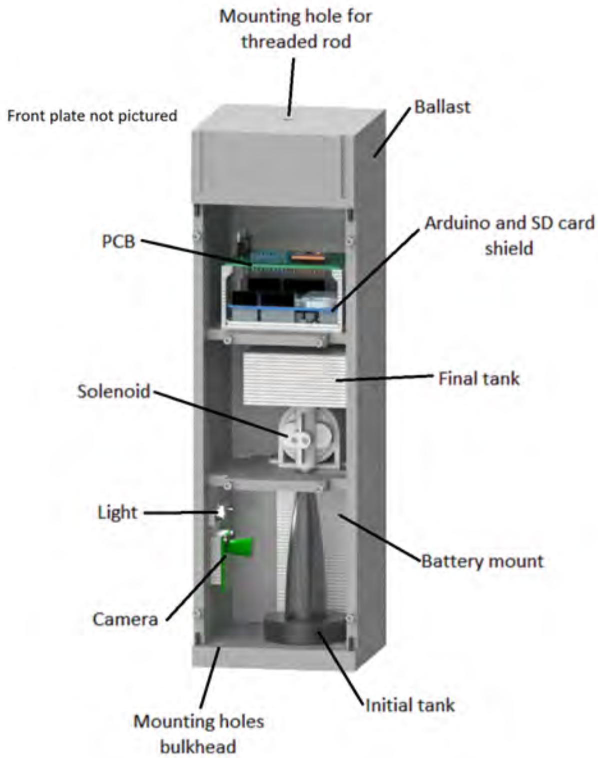

Fig. 70 Payload CAD

Fig. 71 Final assembled payload

The payload was placed within the nosecone to move the CG as far forward as possible for increased stability. The payload was designed to withstand a significant amount of force, allowing for direct integration into the connection between the nosecone bulkhead and the nosecone itself. Using this method allows for easy integration of the payload into the rocket, as it can easily be accessed by removing the nosecone tip. In addition, this method reduces the complexity of the nosecone assembly. Alternative methods would have required a large shoulder on the bulkhead to allow for a direct connection to the nosecone. Fabricating a bulkhead with such geometry would be more difficult than desired. Using the payload as an adapter removes this requirement, and allows the bulkheads to be cut on a water jet.

2. Payload Sizing and Mass

The payload follows the 3U size constraints independent of the ballast and is 3.3U when the ballast is connected. The final weight comes to 8.9 pounds.

I. Test Rocket

At the beginning of the school year, a 4" fiberglass rocket was built to practice construction, launch, and recovery. This rocket flew twice, first on a J295 to 3000ft and then on a K735 to 6000ft 73. Both times, it flew with the same altimeters that would be used in the competition rocket. The first purpose of this rocket was to practice the construction techniques on our competition rocket. The fin can was constructed using the same epoxies and in a similar manner so that we could become familiar with the handling characteristics and curing times of each. The second goal was to run through the entire launch procedure of making the charges, wiring up the electronics bay, and preparing it for flight. This helped us work out any kinks in the process as well as create a checklist of all materials we may need at a launch. Third, this rocket was used to test the electronics in flight and track the rocket after it had landed. The radio beacon and GPS on the TeleMega were used to practice locating the rocket after launch.

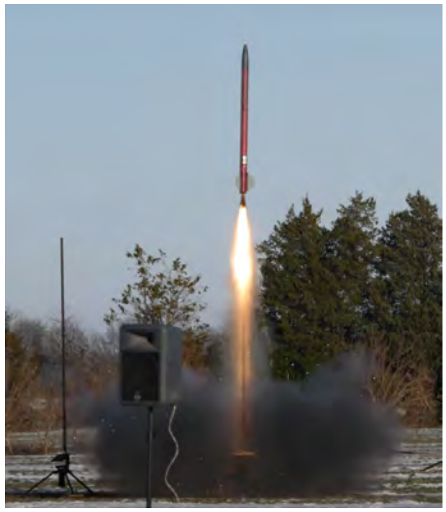

Fig. 73 The 4" test rocket flying on a K735 to 6000 ft.

J. Full-Scale Test Flights

Fig. 74 Top half of our rocket after the main parachute failed to deploy

Our competition rocket has had a total of 3 test flights so far and will have a final test flight at the end of May. Our goal this year was to complete our competition rocket early so that we could launch during the winter, which is the time the larger field at MDRA is open. The first flight of the competition rocket was on a Cesaroni M1830 to 6000ft 75. This configuration did not include the air brake and was significantly lighter than the current rocket. After a good boost and drogue deploy, the main came out as expected, however it did not deploy as planned. After tangling for a few seconds, it finally inflated right before hitting the ground. We think that this is due to the comparatively heavy nose cone on this rocket. When the nose cone came off, it continued travelling straight down, taking the shock cord with it. When the parachute tried to open, it wrapped around the cord. This issue was fixed by switching the positions of the nose cone and main parachute. The kevlar cord has three loops, 2 for connections to the airframe one for the parachute. Previously, the nose cone was on the end and the main parachute on the middle loop. By switching these, the nose cone no longer pulls the cord down and the parachute can deploy into clean air.

Our second test flight was on a Loki M3000 to 8500ft. This flight also excluded the air brake module. After a successful boost and drogue deploy, the main charges fired, however the nose cone did not come off. Two of the fins broke on landing and the threaded rod holding the payload had slight plastic deformation. While the same sized charges were used as the first test flight, 4g and 4.5g, the nose cone did not come off. We think this could be for a variety of reasons. First, it was very cold weather that day which may impact the performance of the black powder. Second, the charges were made at the launch site, and may not have been properly prepared. Third, the parachute may have been packed more loose than usual, making it harder to push out of the rocket. To amend this issue, the charge sizes were increased to 5g and 6g to make sure both sets of parachutes would be ejected.

After this flight, the fins and fin can damage were inspected and it was decided that it was repairable. First, the corners of the fin slots were cut out with a dremel to allow the fins to be removed. Once they were removed, it was confirmed that the only damage was to the fillets, both the fin and airframe were in good condition. The excess epoxy was sanded off of each of the fins so that they could fit back into the fin slot. What was left in the airframe was cleaned with a vacuum and q tips to prepare the surfaces for bonding. The fins were first reattached with a generous amount of Rocketpoxy. Then, using the areas cut from the fin slots, laminating epoxy with chopped carbon tow was once

Fig. 75 The first flight of Terpulence II on an M1830

Fig. 76 Damage to two of the fins after Impact

Fig. 77 Airframe with expanded fin slots cut out

Fig. 78 Fins after sanding down remaining epoxy

Fig. 79 Reapplied external fillets curing

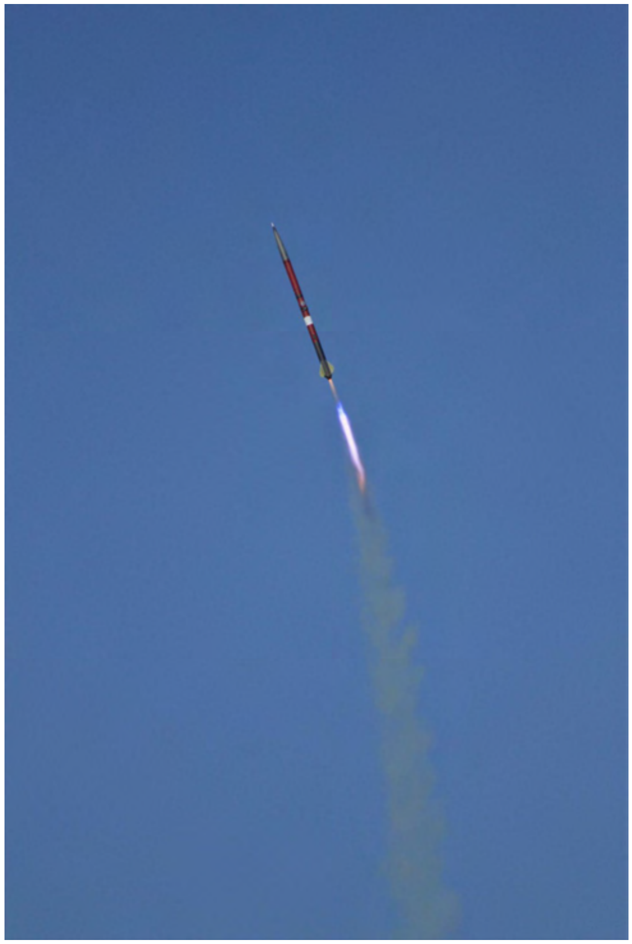

Fig. 80 The third flight Of Terpulence II. Photo credit Carvac on Flickr [5]

again injected into the airframe and spread along the root of the fin. Once cured, external fillets were reapplied with Rocketpoxy to cover any remaining holes or gaps.

Our third flight was on an Aerotech M2500 to 8000 ft. This was the first flight of the rocket with the airbrake module so the M2500 which was originally supposed to fly the rocket to 10,000ft only took it to 8000. This flight had a nominal boost, drogue deployment, and main deployment. The only issue with this flight was some telemetry issues. Another college team had launched from the same rack as us and had been using an Altus Metrum product with telemetry. While we received telemetry during flight, some of the values were incorrect and the reported GPS values were wrong. Luckily, we had a radio beacon as a backup which helped us find the rocket. This issue will be fixed in the future by coordinating with others at launches to make sure everyone is on their own frequencies. Our fourth and final test flight will be at the end of May during NYPower in Geneseo New york. We will be flying on our competition motor, the Loki N3800 to just above 10,000 ft. This flight will also include our full air brake and payload for one final test. The larger motor and air brake system increased our weight substantially so we had to upgrade from our Cert3XL parachute to a Cert3XXL.

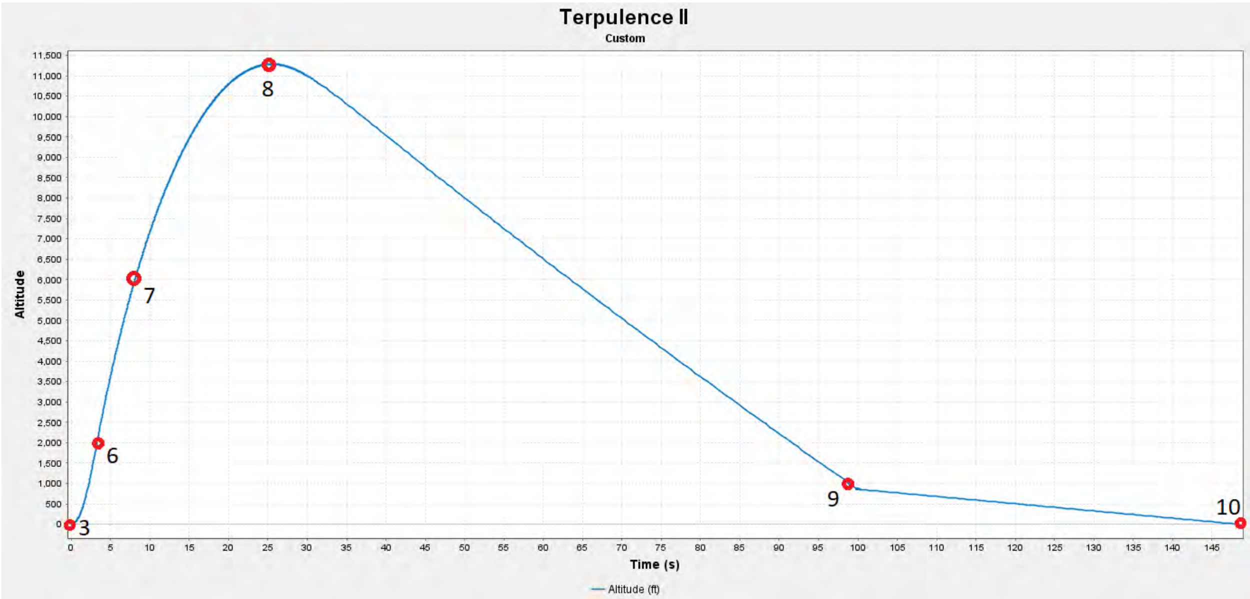

Fig. 81 ***Terpulence II*** **Concept of operations**

III. Mission Concept of Operations Overview

Terpulence II's mission profile will be that of a standard two break dual deploy high power rocket. The use of a smaller drogue and a larger main minimizes drift from the launch site and makes recovery easier. The concept of operations for Terpulence II can be found below 81 along with the phases on a simulation plot.

1) Phase 1: Launch Pad Integration
   The rocket is slid onto the rail and payload electronics are turned on. The rail is raised vertical and locked.
2) Phase 2: Arming
   Flight computers are powered on. Continuity on all E-matches is confirmed via auditory cues from computers. Telemetry is checked for continuity and GPS lock. Air brake computer is powered on. Unnecessary personnel are cleared from the area and the motor igniter is installed.
3) Phase 3: Ignition (t = 0.00 s)
   Current is sent through the igniter and the motor is lit. Smoke is seen coming out the aft end of the motor.
4) Phase 4: Lift-off (t = 0.01 s)
   The motor begins to produce thrust and vertical motion is visible. The rocket clears the rail in .3 seconds with a velocity of 116 ft/s
5) Phase 5: Powered Ascent (t = 0.3 s)
   The rocket accelerates upward under motor power. This phase lasts approximately 3.25 seconds, at which point the rocket is 2000ft above the ground.
6) Phase 6: Unpowered Ascent (t = 3.25 s)
   The rocket continues to coast until it detects an altitude of 6000ft. This occurs at approximately 7 seconds into flight.
7) Phase 7: Active Air Braking (t = 15 s)
   The air brakes detect the state of the rocket and deploy as needed to get as close as possible to the 10,000 ft goal. Air Brakes begin deploying once the rocket reaches 6000 ft and can continue until apogee if necessary. The payload will also begin attempting to pump fluid during this phase.
8) Phase 8: Apogee, Drogue Deployment, and Descent (t=26 s)
   At apogee, the TeleMega fires its drogue charge followed by the EasyMini on a two second delay. The booster separates from the electronics bay and the two shear pins break. The two halves of the rocket separate and the drogue parachute inflates and the rocket falls at a rate of 90 ft/s.

9) Phase 9: Main Deployment and Descent (t=100 s)
   When the TeleMega detects an altitude of 1000ft, its main charge fires. This is followed by the EasyMini which is set to deploy its charge at 800ft. The nose cone is separated from the rocket and the main parachute inflates, slowing it to a safe descent velocity.
10) Phase 10: Ground Recovery
   The rocket has hit the ground and the flight has ended. A recovery team will be sent to locate the rocket using GPS data received from the TeleMega and pings from the onboard radio Beacon. Once found, electronics are powered off and the rocket is taken back to the judges for post-flight evaluation. Flight, Payload, and Airbrake data is then downloaded and analyzed.

IV. Conclusions and Lessons Learned

Like many other teams competing this year, this will be our first time attending the competition since 2018. At the 2018 event, our rocket launched, but was never recovered. One of the primary goals this year was to successfully deploy parachutes, track, and recover the rocket. To accomplish this we planned to launch as often as we could at our local club, the Maryland Delaware Rocketry Association (MDRA). This would let us become very familiar with launch operations as well as iron out any issues our rockets had. We started as early as possible in September and began flying dual deploy flights on an existing 4" fiberglass rocket. We then built another 4" fiberglass rocket with a 75mm mount in order to have test flights to 10,000 ft. Building both of these rockets also let us perfect construction methods which were new to the team. Many of the lessons learned building these rockets such as how to do internal fillets, electronics sled design, recovery attachment, and many more were implemented in our competition rocket.

As we were already traveling to launches, we heavily emphasized certifications this year. Our team now has one L3, one L2, and over a dozen L1s, with many more in the process of building their rockets. One of the issues that our team suffered from in past years was overcomplicating many aspects of the rocket. This led to issues in manufacturing, recovery, and general launch operations. Our competition rocket this year is built using techniques standard to high power rocketry and many of the skills are similar to those used on certification rockets. This led to us being ahead of schedule this year, launching our competition rocket in february and every month following that. This is a major improvement compared to last year when our rocket was only getting built at the end of the semester. This accelerated schedule allowed us to implement many features that we were not originally planning on including such as the air brake system. Following our successes this year, we are planning more ambitious projects. We will soon be starting an experimental solids project with the help of our mentors at MDRA. We hope to compete in the SRAD solids category in the future and use this knowledge for large scale projects. We've also begun two high performance projects with a minimum diameter rocket and a two stage rocket. These will allow the team to reach altitudes and speeds it never could before.

As this was the first L3 class rocket built by the club, there were many lessons learned that informed our future builds. At the beginning of the year, we set out to manufacture all of our airframes in house. The team made many carbon fiber airframes last year and we were confident in our ability to make a flight worthy airframe. For our mandrel, we purchased a full length of 6" Blue Tube coupler. Blue Tube is more resilient than cardboard while still relatively cheap. One of the first issues was that this coupler was a little smaller than the coupler tubing from Wildman that we would be using in the rocket. This meant that we had to increase the outer diameter of the mandrel by wrapping extra layers of Mylar. Not only was this wasteful, but it also made it more difficult to make the Mylar tight over the tube. The first carbon fiber tube we manufactured seemed to work great. Our Wildman coupler fit into the tube right off the mandrel and that tube was later used as the fin can tube. We made two more tubes out of fiberglass that were destined to be our upper fin can tube and recovery tube. The first fiberglass tube required hours of sanding the inner diameter in order to get the coupler to barely fit. For the coupler to freely slide without binding took another few hours. Eventually we got to this tube to a usable state and it flew twice on our first and second test flights. The second fiberglass tube was abandoned after we decided to use a commercial fiberglass tube instead. With the addition of our air brake, it was deemed not worth the effort to make and sand another tube and it was replaced with another section of commercial tubing. Many of these issues came from the fact that Blue Tube is very susceptible to changes in environment, especially humidity. As we are in Maryland, humidity changes significantly between seasons, so even though we were using the same process we were getting very different tubes. In order to remedy this for future years, we instead purchased a full length of Wildman coupler. Fiberglass tubing wont change nearly as much as Blue Tube and it will already be perfectly sized for the couplers we use.

Something else that became apparent throughout the year was having checklists for launches. We forgot to bring certain objects to launches multiple times over the year whether it was a motor adapter or dowels to hold our igniters in. Having a well made checklist and adhering to it saves time for everyone, especially under the stress of a launch weekend. Our launches also showed us how important redundancy is for these rockets, especially in regards to recovery. On one of our small scale test flights, we had issues with one of our flight computers and its charges failed to fire. Luckily we had our backup computer onboard that worked perfectly and saved the rocket. On our third test flight, we were launching on the same rack as another Spaceport team. Both of our rockets contained Altus Metrum flight computers broadcasting telemetry data. When we went out to recover our rocket, the GPS location we were receiving was that of the other rocket instead of ours. Luckily, we had a radio beacon as a backup which led us directly to the rocket.

Acknowledgments

This year would not have been possible without the support of our mentors, advisors and donors. We have accomplished so much this year because of their generous support. First we would like to thank our Tripoli Mentor Dennis Kingsley as well as the Maryland Delaware Rocketry Association (MDRA). Dennis has been working with us as our mentor for two years and has shared a great amount of experience with us. MDRA has been our primary launch site and our test flights would not have been possible without such a great organization and members close by. We'd also like to thank our faculty advisor Dr. Christopher Cadou as well as Dr. David Akin, Henry Mulkey, and David Nazemi for their helpful reviews of our project.

Additionally, we would like to thank our generous donors and sponsors this year. The A. James Clark School of Engineering, The University of Maryland Student Government Association, ABL Space Systems, The Maryland Robotics Center, Boeing, Aerojet Rocketdyne, and Siemens have all been critical in our successes this year. Lastly, we'd like to thank Terrapin Works who have been instrumental in assisting the team with prototyping and manufacturing many of our components.

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V. Appendix A - System Weights, Measures, and Performance Data

A. Rocket Information

Table 4 Overall Rocket Parameters

Airframe Length (in)	145
Airframe Diameter (in)	6.17
Fin-Span (in)	5
Vehicle Weight (lb)	46.2
Propellant Weight (lb)	25.6
Payload Weight (lb)	8.8
Liftoff Weight (lb)	80.6
Number of Stages	1
Strap-on Booster Cluster	No
Propulsion Type	Solid
Propulsion Manufacturer	Loki Research

Table 5 Propulsion System

Propulsion Type	Solid
COTS, SRAD, or Combo	COTS
Propulsion manufacturer	Loki Research
Motor	Loki N3800-LW
Motor Classification	N
Average Thrust (N)	3,851
Total Impulse (N-s)	12,500
Motor Burn Time (s)	3.3

B. Predicted Flight Data and Analysis

Table 6 Flight Predictions

Launch Rail	ESRA Provided Rail
Rail Length (ft)	17
Liftoff Thrust-Weight Ratio	10.85
Launch Rail Departure Velocity (ft/s)	116
Minimum Static Margin During Boost	2.51
Maximum Acceleration (G)	13.6
Maximum Velocity (ft/s)	1,040
Target Apogee (ft AGL)	10,000
Predicted Apogee (ft AGL)	11,664

C. Recovery Information

Table 7 Recovery Information

COTS Altimeter	AltusMetrum TeleMega
Redundant Altimeter	AltusMetrum EasyMini
Drogue Primary & Backup Deployment Charges (g)	6 & 8 of black powder
Drogue Deployment Altitude	Apogee
Drogue Decent Rate (ft/s)	90
Main Primary & Backup Deployment Charges	5 & 6 of black powder
Main Deployment Altitude (ft)	1,000
Main Descent Rate (ft/s)	18
Shock Cord Length (ft)	8 (Y harness), 70 (drogue), 35 (main)

VI. Appendix B - Project Test Reports

Table 8 Outline of Tests

Date	Type	Description	Status	Comments
12/21	Ground	TelaMega Range Testing	Successful	Tested flight computer telemetry and GPS functionality
12/21	Ground	Test Rocket Ejection Test	Successful	Ground testing of black powder charges for subscale test rocket
12/21	In-Flight	Test Rocket Flight 1	Partial Failure	Flight test to 3000 ft on subscale test rocket. TeleMega failed to go into pad mode.
01/22	In-Flight	Test Rocket Flight 2	Successful	Flight test to 6000 ft on subscale test rocket
02/22	Ground	Full Scale Rocket Ejection Test	Successful	Ground testing of black powder charges for full scale competition rocket
02/22	In-Flight	Full Scale Rocket Flight 1	Successful	Flight test of competition rocket to 6000 ft. Slightly delayed main deployment due to tangling
03/22	In-Flight	Full Scale Rocket Flight 2	Partial Failure	Flight test of competition rocket to 9000 ft. No main deployment
03/22	In-Flight	Payload Flight Test 1	Failure	Flight test of payload in nose cone during flight. Switch disconnected at launch due to G forces. Switched to using a screw switch.
03/22	In-Flight	Airbrake Flight Computer Test	Successful	Flight test of airbrake computer to 2000 ft to verify functionality
03/22	In-Flight	Airbrake Test Rocket Flight	Successful	Flight test of airbrake test rocket. Deployed flaps in flight based on onboard sensors
04/22	In-Flight	Full Scale Rocket Flight 3	Successful	Flight test of competition rocket to 8000 ft with payload and airbrakes installed. Nominal deployment of both parachutes.
04/22	In-Flight	Payload Test Flight 2	Successful	Flight test of payload hardware in nose cone. Completed data logging throughout flight and ran through experiment.
05/22	In-Flight	Full Scale Rocket Flight 4	Pending	Flight test of competition rocket to 10,000 ft with payload and airbrakes installed.

Test 1 - TeleMega Range Test

Test 1	TeleMega Range Test	
This test was performed to verify the functionality of the TeleMega as well as test the range of the telemetry and GPS signal from within the electronics bay. The electronics bay contains steel threaded rods, aluminum bulkheads, and a U-bolt which are all potential points for antenna interference. The TeleMega was secured to the electronics bay and then telemetry was verified at various locations. The Altus Metrum software provides an age for the last received signal so this was used to determine if we were still receiving telemetry. The signal was tested at a variety of distances away at different angles relative to the electronics bay. At the furthest distance tested, there was no longer line of sight to the electronics bay which helped simulate getting signal from the rocket after landing.		
Event and Success Criteria		
Event 1 - TeleMega enters "Pad" mode	PASS	12/4/2021
Event 2 - GPS lock acquired	PASS	12/4/2021
Event 3 - Telemetry at 100 ft	PASS	12/4/2021
Event 4 - Telemetry at 500 ft	PASS	12/4/2021
Event 5 - Telemetry at 1000 ft	PASS	12/4/2021
System Analysis	**Success**	12/4/2021

Test 2 - Test Rocket First Flight

The test rocket prior to its first flight

The test rocket after recovery

<table>
<tr><th>Test 2</th><th colspan="3">Test Rocket First Flight</th></tr>
<tr><td colspan="4">The first flight of our 4" fiberglass test rocket was used to flight test both of our flight computers. The TeleMega and EasyMini were flown in the same configuration as our competition rocket with the same batteries and switches. Both the main and drogue parachute were packed in the same way as well to verify that they would be protected and ejected successfully. This flight flew on a Cesaroni J295 3 grain 54mm motor to approximately 3000 ft. While the rocket was successfully recovered, the TeleMega failed to enter pad mode and recovery events were entirely controlled by the EasyMini. While it did not enter pad mode, the TeleMega still broadcast its GPS coordinates. More ground testing was done with the TeleMega to better understand the conditions to enter pad mode.</td></tr>
<tr><th colspan="4">Event and Success Criteria</th></tr>
<tr><td colspan="2">Event 1 - Ignition and liftoff</td><td>PASS</td><td>12/19/2021</td></tr>
<tr><td colspan="2">Event 2 - Drogue deployment charges activate, parachute deployment</td><td>PARTIAL FAILURE</td><td>12/19/2021</td></tr>
<tr><td colspan="2">Event 3 - Main deployment charges activate, parachute deployment</td><td>PARTIAL FAILURE</td><td>12/19/2021</td></tr>
<tr><td colspan="2">Event 4 - Maintain telemetry with TeleMega</td><td>PARTIAL FAILURE</td><td>12/19/2021</td></tr>
<tr><td colspan="2">Event 5 - Recover all airframe sections</td><td>PASS</td><td>12/19/2021</td></tr>
<tr><td colspan="2">System Analysis</td><td>Partial Success</td><td>12/19/2021</td></tr>
</table>

Test 3 - Test Rocket Second Flight

Test 3	Test Rocket Second Flight	
The second flight of our fiberglass test rocket was done to fix the issues of the first flight and practice recovery from higher altitudes. This flight also let us practice assembling motors as we had previously only used Cesaroni 38mm and 54mm reloads which do not require an involved assembly. This was largely the same configuration as the first flight except the TeleMega had a setting changed. On the first flight, the TeleMega was mounted right side up but would only go into pad mode if it was upside down. This flight flew on a Cesaroni K735 2 grain 75mm motor. The test rocket flew to approximately 6000 ft and maintained telemetry throughout the entire flight.		
Event and Success Criteria		
Event 1 - Ignition and liftoff	PASS	1/8/2022
Event 2 - Drogue deployment charges activate, parachute deployment	PASS	1/8/2022
Event 3 - Main deployment charges activate, parachute deployment	PASS	1/8/2022
Event 4 - Maintain telemetry with TeleMega	PASS	1/8/2022
Event 5 - Recover all airframe sections	PASS	1/8/2022
System Analysis	**Success**	1/8/2022

Test 4 - Competition Rocket Ejection Test

Competition rocket set up for ejection tests

Drogue ejection charge on Terpulence II

Test 4	Competition Rocket Ejection Test	
Ejection charge sizes for both the drogue and main charges were based on values obtained from an online calculator. These values were calculated as 3.8 g for the Main and 7.5 g for the main. These values were rounded up to 4 g and 8 g respectively. Both charges were packed and routed out of the switch band. The entire rocket was then assembled and the proper shear pins were inserted. Terpulence II was set up in front of the A rack at MDRA and both charges were connected to the launch system.		
Event and Success Criteria		
Event 1 - Main charge activation	PASS	2/12/2022
Event 2 - Nosecone separation	PASS	2/12/2022
Event 3 - Main parachute ejection from airframe	PASS	2/12/2022
Event 4 - Drogue charge activation	PASS	2/12/2022
Event 5 - Booster separation	PASS	2/12/2022
Event 6 - Drogue parachute ejection from airframe	PASS	2/12/2022
System Analysis	**Success**	2/12/2022

Test 5 - Competition Rocket Flight 1

Terpulence II's main parachute wrapped around the kevlar harness

The main parachute inflated after untangling

Inspecting Terpulence II following its first flight

Test 5	Competition Rocket Flight 1	
Terpulence II's first flight was in the original configuration without the airbrake module. It also contained a non functioning boilerplate payload to simulate the competition flight and help with stability. A Cesaroni M1830 4 grain 75mm motor was used which pushed the rocket to approximately 6000 ft. The drogue and main deployment charges worked nominally, however the main parachute got tangled in the main shock cord. Luckily, it became untangled and the parachute inflated before impacting the ground. This issue was mitigated by switching the connection point of the nosecone and main parachute along the main recovery harness.		
Event and Success Criteria		
Event 1 - Ignition and liftoff	PASS	2/12/2022
Event 2 - Drogue deployment charges activate, parachute deployment	PASS	2/12/2022
Event 4 - Main deployment charges activate, parachute deployment	PARTIAL SUCCESS	2/12/2022
Event 5 - Maintain telemetry with TeleMega	PASS	2/12/2022
Event 6 - Recover all airframe sections	PASS	2/12/2022
System Analysis	**Partial Success**	2/12/2022

Test 6 - Competition Rocket Flight 2

Terpulence II Prior To Flight

Terpulence II after no main deployment

Test 6	Competition Rocket Flight 2	
Terpulence II's second flight also used the original configuration without the airbrake module. In addition to the boilerplate payload, a payload electronics testbed was included in the nosecone which was turned on before raising the rocket. This flight went to around 8500 ft using a Loki M3000 in the 76/8000 casing. While drogue deployment worked normally, when both the primary and backup main charges fired, the nosecone failed to seperate. This led to Terpulence II impacting the ground at 90 ft/s, breaking two of the fins cleanly off the airframe along their fillets. This issue was attributed to possible poor packing of the charges as well as cold weather. To remedy this, the drogue charges were increased to 5 g and 6 g.		
Event and Success Criteria		
Event 1 - Ignition and liftoff	PASS	3/13/2022
Event 2 - Drogue deployment charges activate, parachute deployment	PASS	3/13/2022
Event 3- Payload data collection and apogee detection	FAILURE	3/13/2022
Event 4 - Main deployment charges activate, parachute deployment	FAILURE	3/13/2022
Event 5 - Maintain telemetry with TeleMega	PASS	3/13/2022
Event 6 - Recover all airframe sections	PASS	3/13/2022
System Analysis	**Failure**	3/13/2022

Test 7 - Payload Flight Test 1

Powering The payload before raising the rocket

Test 7	**Payload Flight Test 1**		
The first payload test flight was simply an electronics test, the frame itself was not launched (a boilerplate was used instead). The goal was to test the accelerometer, camera, and SD card shield. The Arduino would also process acceleration data to determine when to open the solenoid and store that information on the SD card. To turn on the payload inside the nose cone, we made a rudimentary switch by twisting two wires together. Connecting these wires would close the circuit, and power the electronics. While the payload collected data up until the launch, the force of this launch disconnected the wires, and we did not get any meaningful data after that. Because of this, we could not determine if the Arduino would open the solenoid at microgravity.			
Event and Success Criteria			
Event 1 - Collect acceleration data		FAILURE	3/13/2022
Event 2 - Log data to SD card		PASS	3/13/2022
Event 3 - Log photos to SD card		PASS	3/13/2022
Event 4 - Determine solenoid state		FAILURE	3/13/2022
System Analysis		**Failure**	3/13/2022

Test 8 - Air Brake Flight Computer Test

Flight computer assembly

Test 8	Airbrake Flight Computer Test	
The air brake flight computer test was to confirm that the flight computer was able to log data during flight and send commands to the motor driver based on the sensor input. The air brake flight computer was removed from the 4in air brake test rocket and installed in a smaller less complex rocket. This test also was in place to confirm all sensors' data agreed with the commercial flight computer on board. This test was a success, all data was logged and the computer sent commands at the appropriate time. The altitude and acceleration sensors agreed quite well with EasyMini that was collecting data at the same time. No electronics were dislodged during flight.		
Event and Success Criteria		
Event 1 - Configure flight computer for launch	PASS	3/13/2022
Event 2 - Collect data from Barometer and IMU	PASS	3/13/2022
Event 3 - Log data to SD card	PASS	3/13/2022
Event 4 - Send command to motor driver based on altitude measurements	PASS	3/13/2022
Event 5 - Survive all rocket loads	PASS	3/13/2022
System Analysis	**Success**	3/13/2022

Test 9 - Air Brake Test Rocket Flight

4in air brake test rocket assembly

4in air brake test rocket on the pad

Deployment of flaps in flight

Test 9	Air Brake Test Rocket Flight	
The 4" air brake rocket test was manufactured to test the flap configuration, deployment mechanism, flight computer, and lithium polymer batteries in flight. This test taught the team many lessons in the design of the air brake that were implemented for the air brake in Terpulence II. This test culminated in March when the 4in air brake test rocket was launched with to confirm that the test rocket was able to collect data from sensors and based on these sensor measurements deploy the flaps. There was a camera onboard that collected video of the air brakes deploying. Unfortunately the recovery system failed and the rocket was destroyed.		
Event and Success Criteria		
Event 1 - Build 4 in air brake test rocket	PASS	3/13/2022
Event 2 - Prepare test rocket for launch	PASS	3/13/2022
Event 3 - Collect Sensor data	PASS	3/13/2022
Event 4 - Write logs and sensor data to SD card	UNKNOWN	3/13/2022
Event 5 - Deploy flaps in flight	PASS	3/13/2022
Event 5 - Recover Rocket	FAILURE	3/13/2022
System Analysis	**Success**	3/13/2022

Test 10 - Competition Rocket Flight 3

Terpulence II shortly after liftoff

Test 10	Competition Rocket Flight 3	
Terpulence II's third flight was the first in the configuration with the airbrake as well as payload airframe. Since the airbrake added a significant amount of mass, this flight flew much lower than the originally planned 10,000 ft since we could not change the motor. Drogue and Main deployment occurred nominally and Terpulence II was safely recovered. While telemetry with the rocket was maintained during flight, interference with another team's flight computer led to receiving the wrong GPS coordinates while attempting to recover the rocket. Luckily, the rocket was found using the radio beacon. This issue will be fixed in the future by coordinating frequencies with other fliers.		
Event and Success Criteria		
Event 1 - Ignition and liftoff	PASS	4/2/2022
Event 2 - Drogue deployment charges activate, parachute deployment	PASS	4/2/2022
Event 3- Payload data collection and apogee detection	PASS	4/2/2022
Event 4 - Main deployment charges activate, parachute deployment	PASS	4/2/2022
Event 5 - Maintain telemetry with TeleMega	PARTIAL SUCCESS	4/2/2022
Event 6 - Recover all airframe sections	PASS	4/2/2022
System Analysis	**Success**	4/2/2022

Test 11 - Payload Flight Test 2

Test 11	Payload Flight Test 2	
The second payload test was mostly a rerun of the first test, this time using a screw switch. In addition to the previous electronics, we added a barometer to determine altitude. However, due to the lack of vent holes in the nose cone, this sensor did not provide accurate data. We also launched the final payload frame in place of the boilerplate payload.		
Event and Success Criteria		
Event 1 - Collect acceleration data	PASS	4/2/2022
Event 2 - Collect barometer data	FAILURE	4/2/2022
Event 3 - Log data to SD card	PASS	4/2/2022
Event 4 - Log photos to SD card	PASS	4/2/2022
Event 5 - Determine solenoid state	PASS	4/2/2022
Event 6 - Frame integrity	PASS	4/2/2022
System Analysis	**Success**	4/2/2022

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VII. Appendix C - Hazard Analysis

(As found on the following page)

Table 9 Hazard Analysis

Hazardous Material	Storage	Handling	Transportation	Risk of Mishap	Mitigation (Process/Design)	Risk of Injury after Mitigation
Black Powder	Stored in a dry cabinet away from any flammable substances.	When used, avoid any heat and ignition sources. Use Black Powder vials to measure and load. Do not touch directly. Wear safety glasses of face shield.	Kept in original packaging until used.	Low	Restricted access to individuals who are experienced and familiar with the material and handling procedures.	Very Low
Fuel Grains	Ensure fuel grains remain in original packaging. Keep stored in a flame locker.	Keep fuel grains in original packaging until ready to be loaded into casing. Loading should only be done by certified individuals. Once in the casing, the motor is handled carefully to prevent fracturing the grains or nozzle.	Keep in original packaging out of the sun and somewhere cool and dry.	Low	Only individuals whom hold certifications for given rocket motor (or are in the process of obtaining) are authorized to handle fuel grains.	Very Low
Lipo Batteries	Keep in cool dry places. Ensure in a flame retardant battery case. Stored at "storage voltage".	LiPo batteries should be stored in safe places until ready for use. Avoid sharp objects and high temperature areas.	Batteries should only be transported in the authorized LiPo battery transportation bags per safety instructions.	Low	Ensure battery charging is done correctly with multi cell battery charger. Charging only prior to launch/test events. Inspect batteries before/after use for punctures or any other signs of damage.	Very Low
E-Matches Igniters	Stored in a dry flame locker. Keep away from any ignition sources or energetics.	Careful when handling to ensure circuitry doesn't prematurely detonate. Leads are twisted or shunted when not connected to flight computer	Transport in a separate container from energetics and ignition sources	Low	Circuit switches will be switched off and flight computers will only be powered on once vehicle is on the pad ready for flight to prevent premature ignition.	Very Low

VIII. Appendix D - Risk Assessment

(As found on the following page)

Risk Assessment					
Hazard	**Possible Causes**	**Risk of Mishap and Rationale**	**Mitigation Approach**	**Risk of Injury After Mitigation**	**Overseeing Division**
Explosion of solid-propellant rocket motor during launch with blast or flying debris causing injury	Cracks in propellant grains, incorrect assembly of reload	Low, commercial motors are reliable	Grains will be inspected after purchase and the motor will be assembled only by those certified and to manufacturer standards.	Low	Propulsion
Rocket deviates from nominal flight path, comes in contact with personnel at high speed	Rocket has low rail exit velocity, is unstable, or fins have broken off	Low	Simulate rocket in Open Rocket to calculate stability caliber, calculate fin flutter for expected speeds	Low	Aerostructures
Recovery system fails to deploy, rocket or payload comes in contact with personnel	Flight computers fail to fire charges, charges are undersized	Low	Redundant independant flight computers, batteries, and charges. Ground and flight testing of ejection and separation.	Low	Recovery
Recovery system partially deploys, rocket or payload comes in contact with personnel	Parachutes become tangled, main does not deploy	Medium	Parachutes carefully packed to ensure clean exit from body tube and easy inflation. Test flights to check for correct packing of recovery system and charge sizing.	Low	Recovery
Recovery system deploys during assembly or prelaunch, causing injury	Flight computers are turned on while loading and packing the rocket. E-matches are accidentally shorted	Low	Flight computers are powered off while connected to igniters and charges. Computers are only powered on once on the pad and ready for launch. Igniters are twisted or shunted until connected to flight computers. Personell handling energetics are minimized and wearing proper safety equipment	Low	Recovery
Main parachute deploys at or near apogee, rocket or payload drifts to highway(s)	Incorrect wiring to flight computers, heavy nosecone seperates due to drogue ejection forces	Medium	Flight computer connections are checked by multiple team members to verify correctness. Long drogue lines and extra shear pins in nosecone are in place to prevent early separation	Low	Recovery
Rocket does not ignite when command is given (“hang fire”), but does ignite when team approaches to troubleshoot	Igniter incorrectly inserted, not following manufacturer specifications	Low	Make sure igniter is inserted all the way into the motor. Tape dowel to launch tower to prevent it from falling out.	Low	Propulsion
Rocket falls from launch rail during prelaunch preparations, causing injury	Rail buttons fall off	Low, Rail buttons tighly secured	Rail buttons are tightened into nuts in airframe. Rocket is raised by the rail buttons to make sure they are on properly.	Low	Aerostructures
Power loss	Batteries not charged, wired disconnected during flight, flight causes a switch to flip	Low	Batteries are charged/replaced prior to flight. Only switches used are those that will not turn off during flight	Low	Recovery
Fail to detonate at decoupling event altitude	Power loss due to severed wires or flipped switch. Insufficient ejection force to break shear pins. Bad e-match.	Medium	Redundant independant flight computers, batteries, and switches. Ground testing of ejection and seperation. Switches used cannot be turned off by flight forces. E-matches are checked with multimeter to check continuity before connecting to computers.	Low	Recovery

IX. Appendix E - Assembly, Preflight, and Launch Checklists

(As found on the following page)

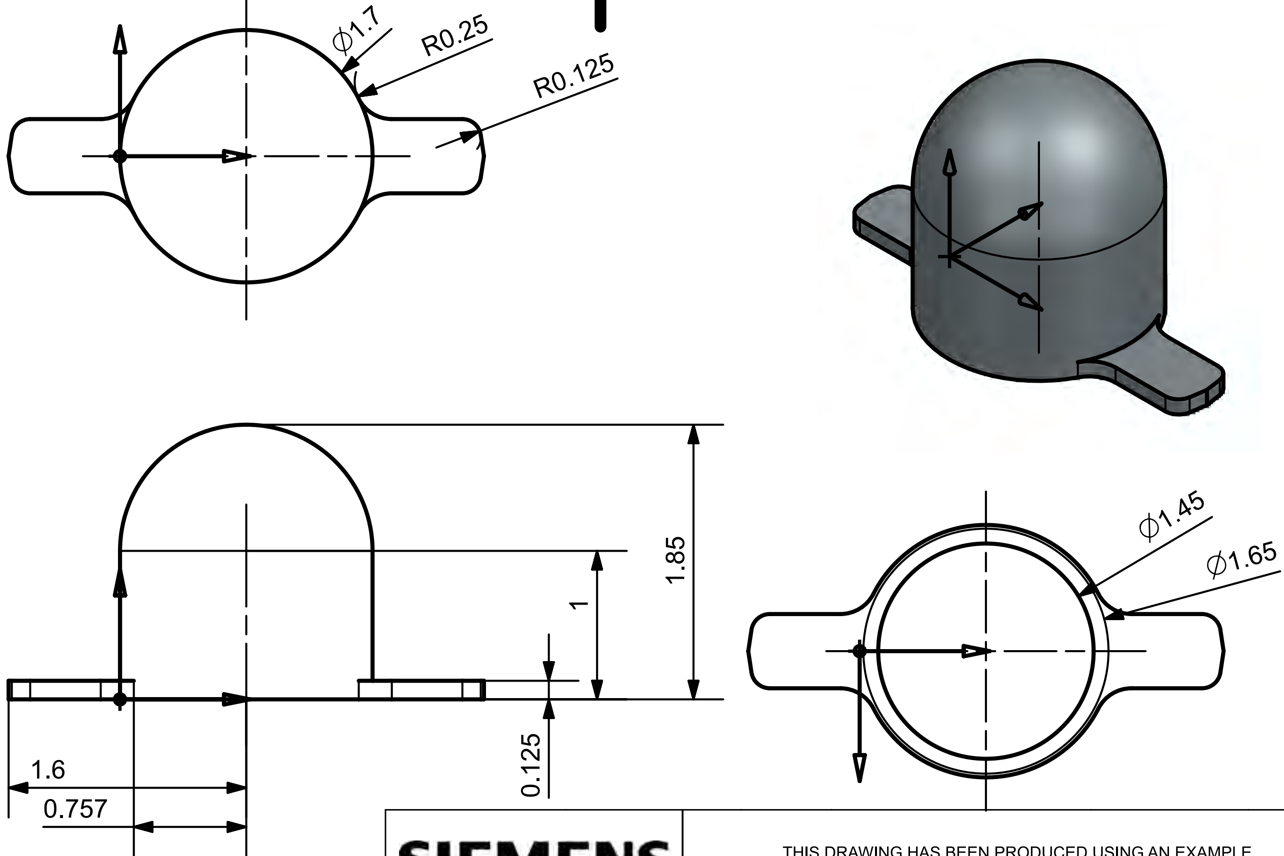
Assembly, Preflight, and Launch Checklists

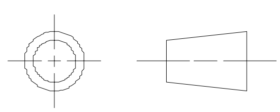
Project Terpulence II			June 2022
Step	**Division**	**Task**	**Complete**
		ASSEMBLE MAIN RECOVERY SECTION	☐
1.0	Recovery	Fold main tightly and burrito wrap in nomex blanket	☐
1.1	Recovery	Verify nosecone is connected to second loop from the top and the main parachute to the top loop	☐
1.2	Recovery	Verify all quick links are connected to shock cords and tightened	☐
1.3	Recovery	Insert packed main parachute into recovery airframe	☐
1.4	Recovery	Carefully fold shock cord and insert behind main parachute	☐
1.5	Recovery	Slide nosecone into recovery airframe and align marks for shear pins	☐
1.6	Recovery	Stand section vertically and insert 6 4-40 shear pins	☐
		ASSEMBLE PAYLOAD SECTION	☐
2	Payload	Secure the ballast and threaded rod to the payload frame	☐
2.1	Structure	Connect the payload to the bulkhead	☐
2.2	Payload	Connect the arming switch to the payload	☐
2.3	Structure	Secure the payload in the nose cone by threading on the tip	☐
		ASSEMBLE DROGUE RECOVERY SECTION	☐
3	Recovery	Fold drogue tightly and burrito wrap in nomex blanket	☐
3.1	Recovery	Verify all knots and quick links are tightened	☐
3.2	Recovery	Assemble air brake module (see section 6)	☐
3.3	Recovery	Feed Y harness lines through airbrake module	☐
3.4	Recovery	Secure airbrake module using 2 1/4"-20 screws on foward and aft ends	☐
3.5	Recovery	Insert battery into radio tracker and verify transmission with receiver	☐
3.6	Recovery	use electrical tape to secure radio tracker to drogue shock cord	☐
3.7	Recovery	Carefully fold shock cord lines and place into airframe with drogue	☐
		ASSEMBLE AVIONICS BAY	☐
4.0	Recovery	Make sure main power switches are turned off and batteries are disconnected	☐
4.1	Recovery	Locate four 3ft ematches and twist leads. Verify continuity with	☐
4.2	Recovery	Pack charges using 4F black powder to the following amounts: main	☐
4.3	Recovery	feed charges through bulkheads and secure into proper terminals	☐
4.4	Recovery	lightly tug each wire to make sure it is secure in the screw terminal	☐
4.5	Recovery	use electrical tape to seal wire holes on both bulkheads	☐
4.6	Recovery	plug in batteries	☐
4.7	Recovery	slide aft bulkhead onto threaded rods and align sled with screw switch holes	☐
4.8	Recovery	on each threaded rod add a washer and two 3/8" nuts. Tighten each with	☐
4.9	Recovery	Verify quick links have been connected to U-bolts and tightened	☐
4.1	Recovery	Align electronics bay with marks on recovery airframe. Secure with two 1/4" 20 screws	☐
4.11	Recovery	Align electronics bay on booster section, stand rocket vertically	☐
4.1	Recovery	insert 2 4-40 shear pins into booster - electronics bay connection	☐

		ASSEMBLE MOTOR SECTION	
5.0	Propulsion	Glue grains to liner at least 24 hrs before launch	☐
5.1	Propulsion	Grease liner and assemble motor following manufacturer instructions	☐
5.2	Propulsion	Insert motor into motor tube and secure with aeropack retainer	☐
5.3	Propulsion	Tape igniter to thin dowel rod. Tape multiple dowels together if	☐
5.4	Propulsion	do not insert igniter until on pad and electronics have been turned on	☐
		Assemble Air Brake Module	
6.0	Air Brake	Charge all three 4s Lipo Batteries	☐
6.1	Air Brake	Insert fresh 9V Battery	☐
6.2	Air Brake	Plug in Lipo Batteries	☐
6.3	Air Brake	Install air brake electronics bay into module	☐
6.4	Air Brake	Flash ardiuno test code and test configuration	☐
6.5	Air Brake	Turn off arduino	☐
6.6	Air Brake	Turn linear screw until flaps are fully retracted	☐
6.7	Air Brake	Install linear screw guard	☐
		PREFLIGHT CHECKLIST	
		Nominal Procedure	☐
7.0	N/A	Carry rocket out to launch pad	☐
7.1	N/A	Install rocket on rail	☐
7.2	Avionics	Power on payload electronics	☐
7.3	N/A	Lift launch rail vertically	☐
7.4	Avionics	Turn on EasyMini switch and verify continuity on both charges	☐
7.5	Avionics	Turn on TeleMega and verify continuity on both charges	☐
7.6	Avionics	Verify TeleMega is in Pad mode and has GPS lock	☐
7.7	Avionics	Verify Radio beacon is still transmitting	☐
7.8	Air Brake	Turn on Airbrake module	☐
7.9	N/A	Clear area of personnel and insert motor igniter. Tape to Launch rail.	☐
		Off-nominal Procedure	☐
7.0A	Safety Officer	Remove engine igniter	☐
7.1A	Safety Officer	Turn off switches for TeleMega and EasyMini	☐
7.2A	Safety Officer	Lower rail and turn off payload and airbrake	☐
	N/A	Remove rocket from rail	☐
		LAUNCH CHECKLIST	
		Nominal Procedure	☐
8.0	Propulsion	Ignite motor	☐
8.1	All	Track rocket through telemetry, radio beacon, and visually	☐
		Off-nominal Procedure	☐
8.0A	All	Take cover until given all clear to approach rocket or rocket wreckage	☐
8.1A	Safety Officer	Turn off flight computers if necessary	☐
8.0A	Safety Officer	Disconnect charges from flight computers	☐
8.1A	Safety Officer	Remove any LiPo batteries that may be damaged	☐
		RECOVERY CHECKLIST	
9.0	Avionics	Turn off flight computers, payload, and airbrake	☐
9.1	Avionics	remove battery from radio beacon	☐
9.2	All	Verify all sections of the rocket have been accounted for	☐

X. Appendix F - Engineering Drawings

(As found on the following page)



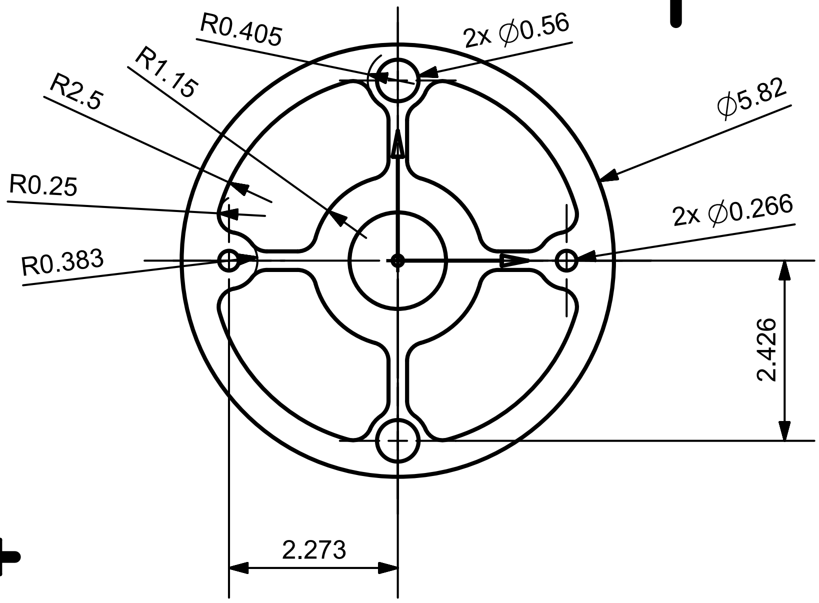


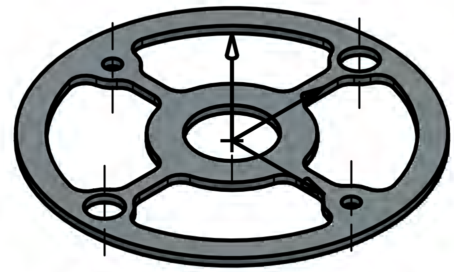
ALL DIMENSIONS IN INCHES

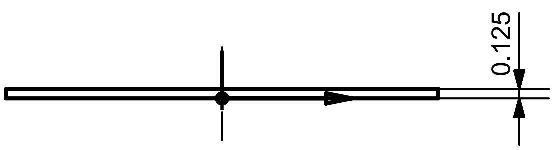
SIEMENS

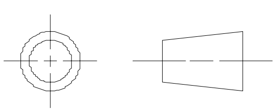
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE

FIRST ISSUED	05/13/2022	TITLE: Linear Screw Guard
DRAWN BY	Hailu Daniel	
CHECKED BY	N/A	
APPROVED BY	N/A	SIZE: A — DRG NO.: Terrapin Rocket Team LSG — SHEET REV: A
		SCALE 1:1 — SHEET 1 OF 2









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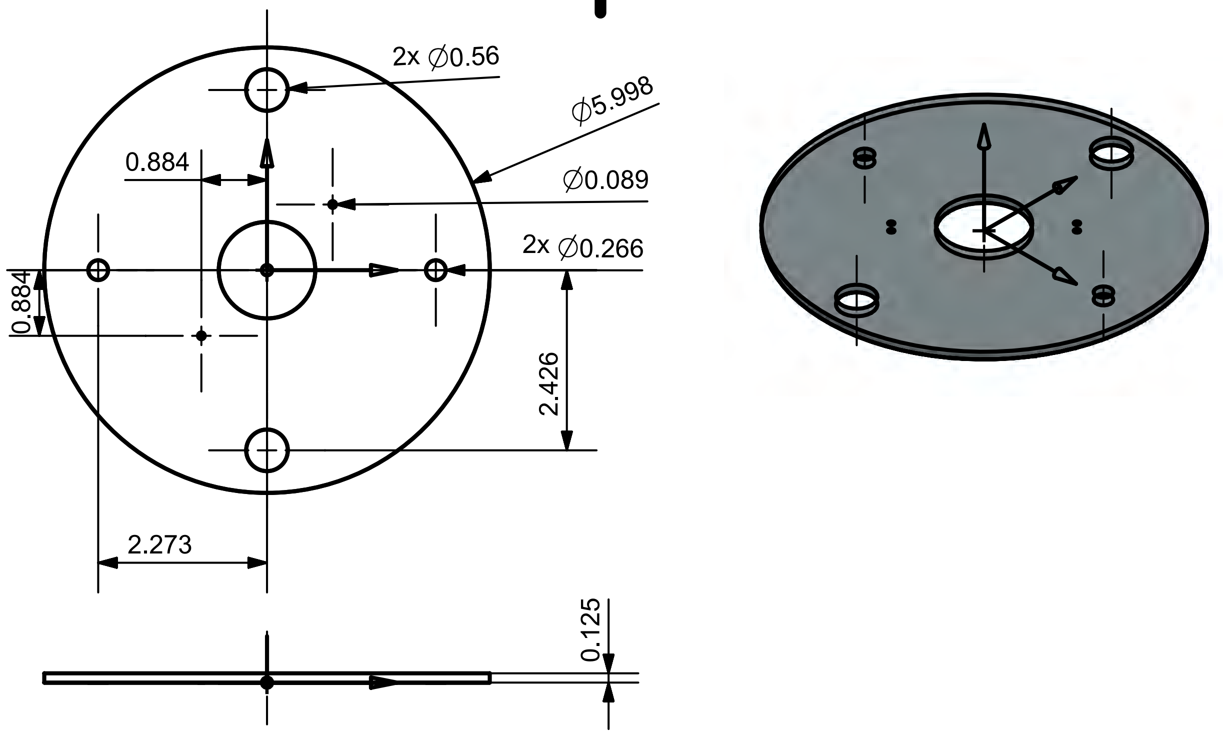
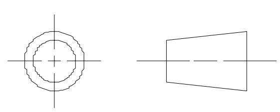
SIEMENS		THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE		
FIRST ISSUED	05/13/2022	TITLE Upper Bulkhead Bottom		
DRAWN BY	Hailu Daniel			
CHECKED BY	N/A			
APPROVED BY	N/A	SIZE	DRG NO.	SHEET REV
		A	Terrapin Rocket Team U.B.B	A
		SCALE 1:1		SHEET 1 OF 1





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FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

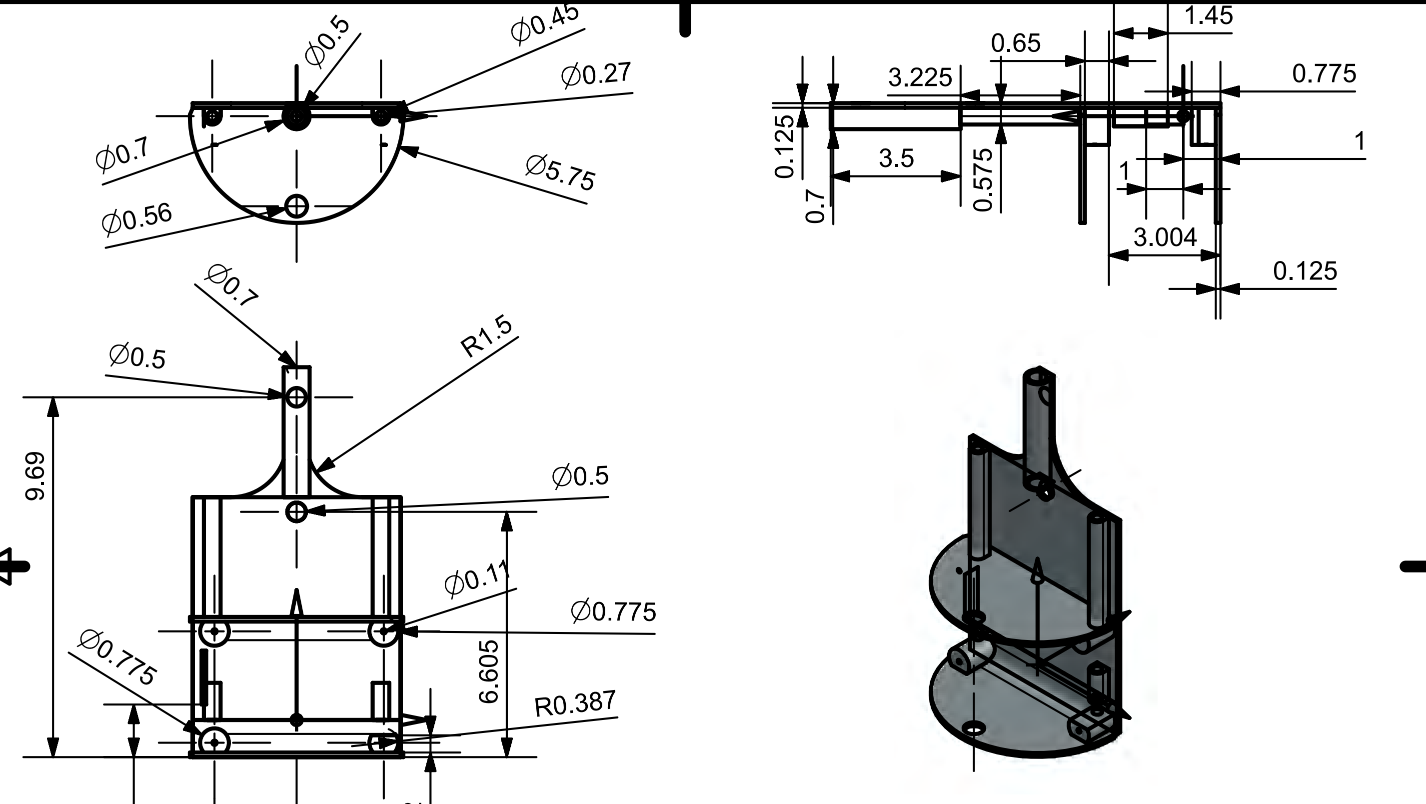
TITLE

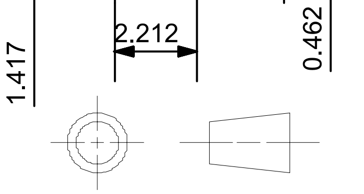
Upper Bulkhead Top

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team U.B.T	A

SCALE 1:1

SHEET 1 OF 1





ALL DIMENSIONS IN INCHES

SIEMENS

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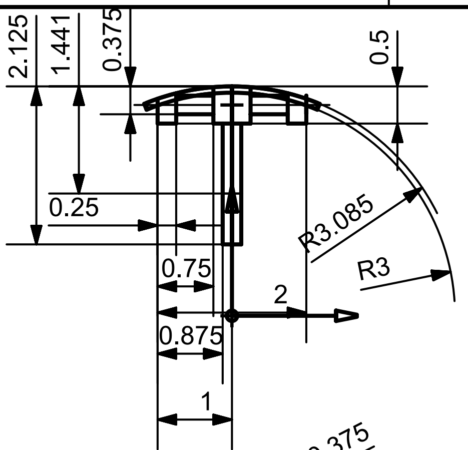
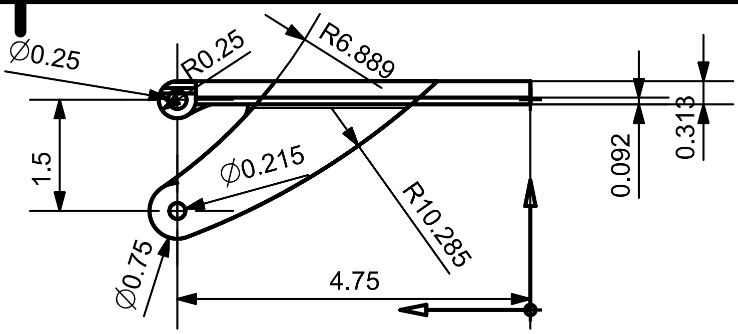
FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

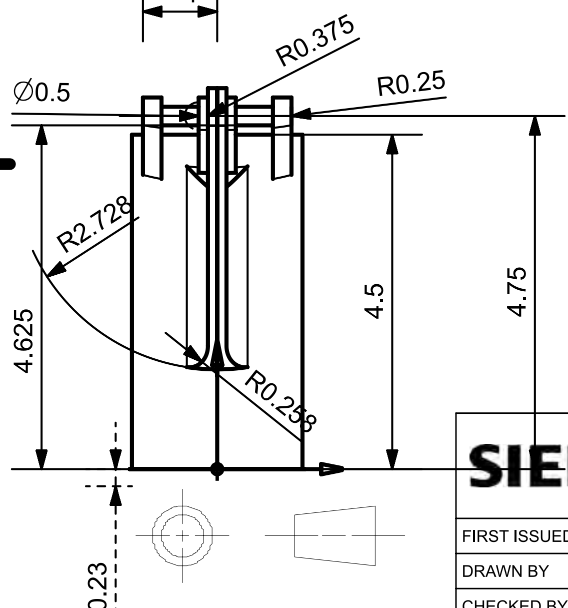
TITLE

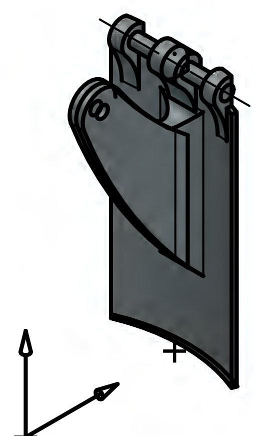
Ebay Sled

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team E.S	A
SCALE 1:1		SHEET 1 OF 1









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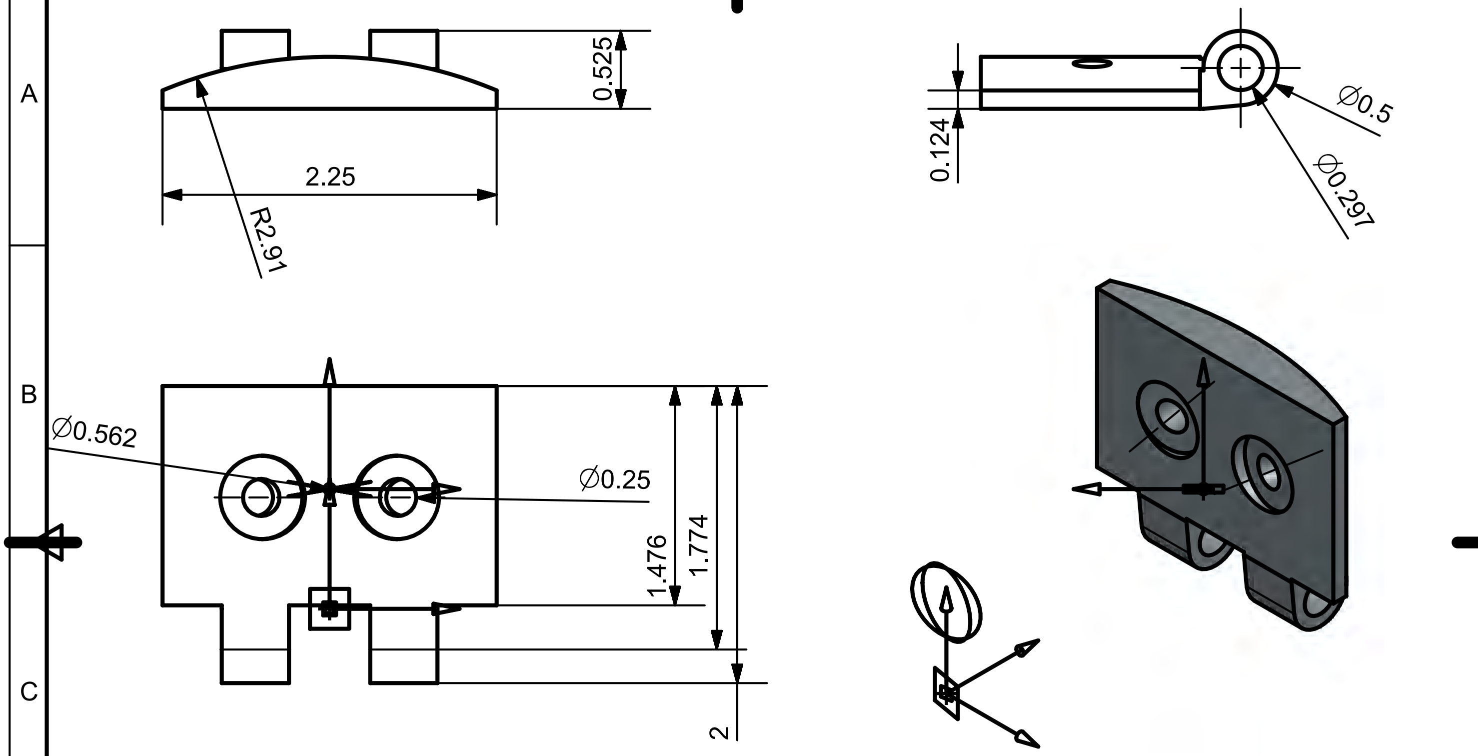
FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

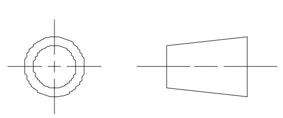
TITLE

Flap Bottom

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team Flap Bottom	A

SCALE 1:1 | SHEET 1 OF 1





ALL DIMENSIONS IN INCHES

SIEMENS

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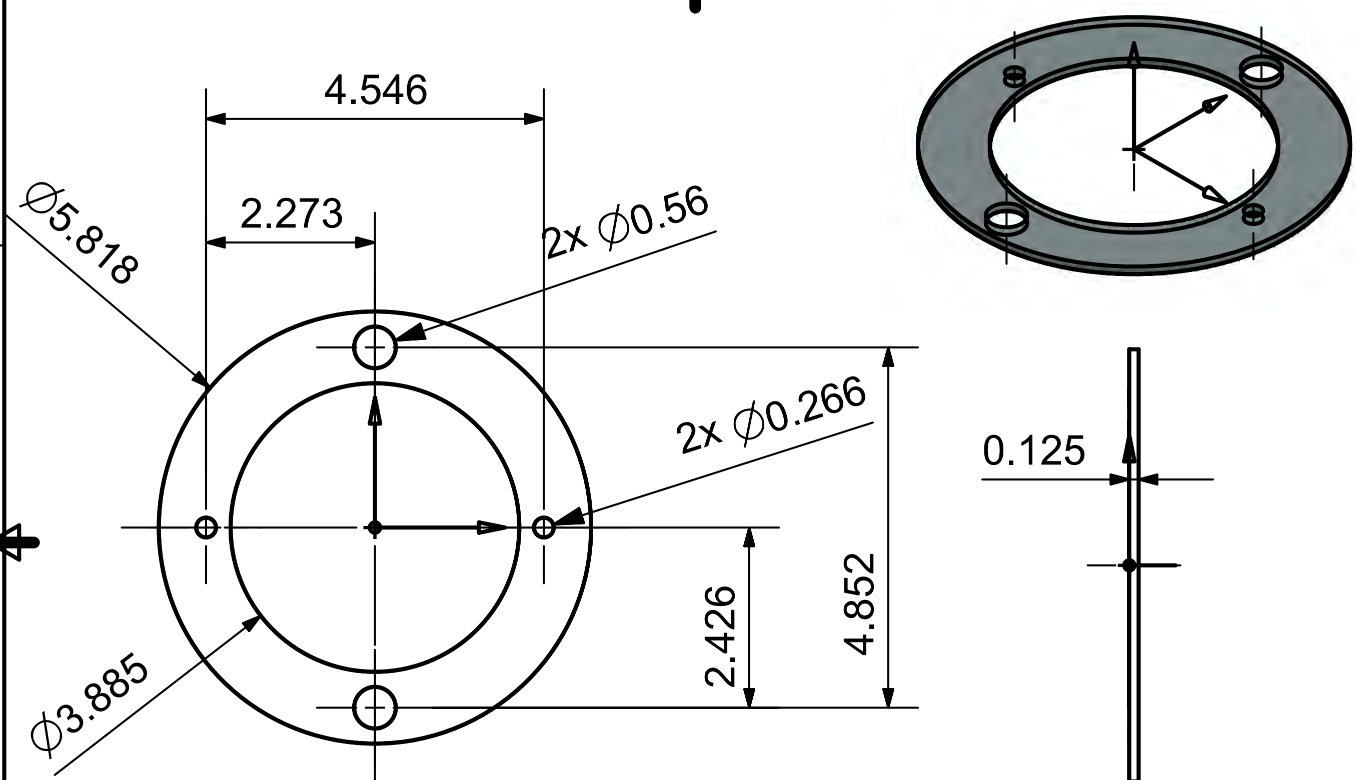
FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

TITLE: Flap Top

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team Flap Top	A
SCALE 1:1		SHEET 1 OF 1



ALL DIMENSIONS IN INCHES

SIEMENS

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FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

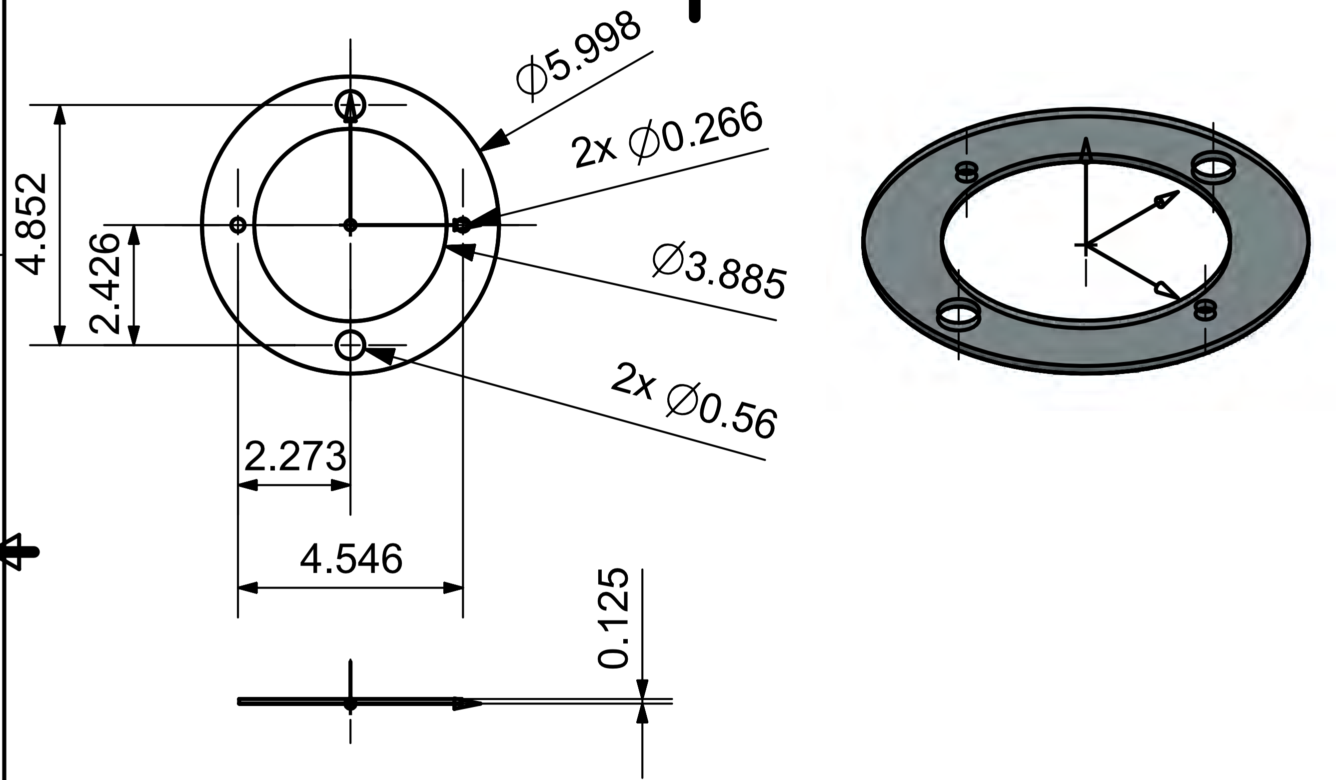
TITLE

Lower Bulkhead Top

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team L.B.T	A

SCALE 1:1

SHEET 1 OF 1



ALL DIMENSIONS IN INCHES

SIEMENS

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FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

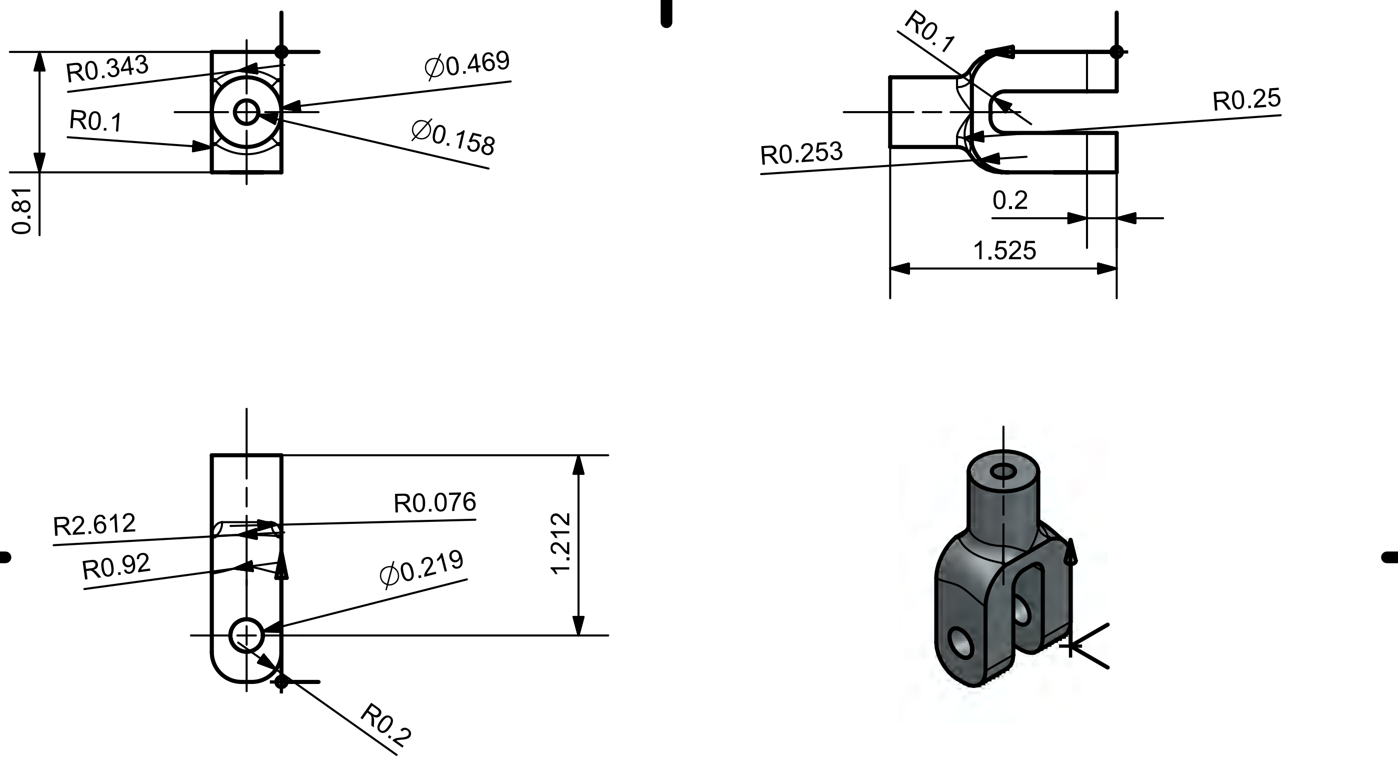
TITLE

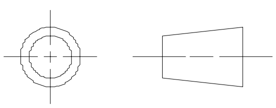
Lower Bulkhead Bottom

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team L.B.B	A

SCALE 1:1

SHEET 1 OF 1





ALL DIMENSIONS IN INCHES

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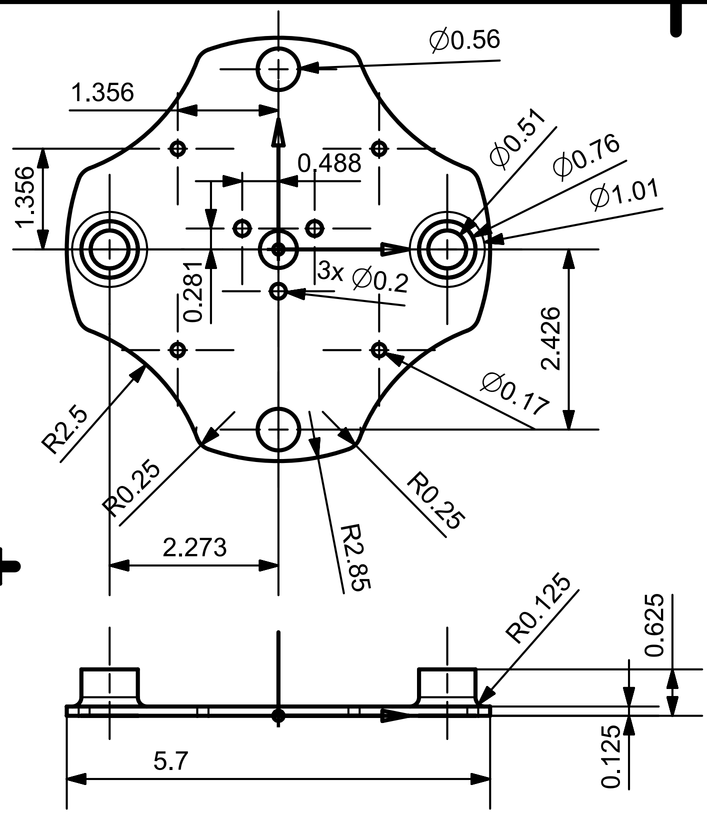
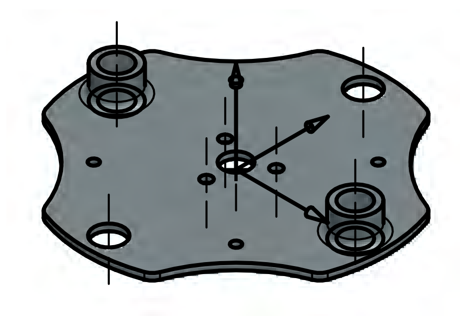
FIRST ISSUED	05/13/2022	TITLE Clevis Rod End		
DRAWN BY	Hailu Daniel			
CHECKED BY	N/A			
APPROVED BY	N/A	SIZE A	DRG NO. Terrapin Rocket Team C.R.E	SHEET REV A
		SCALE 1:1		SHEET 1 OF 1





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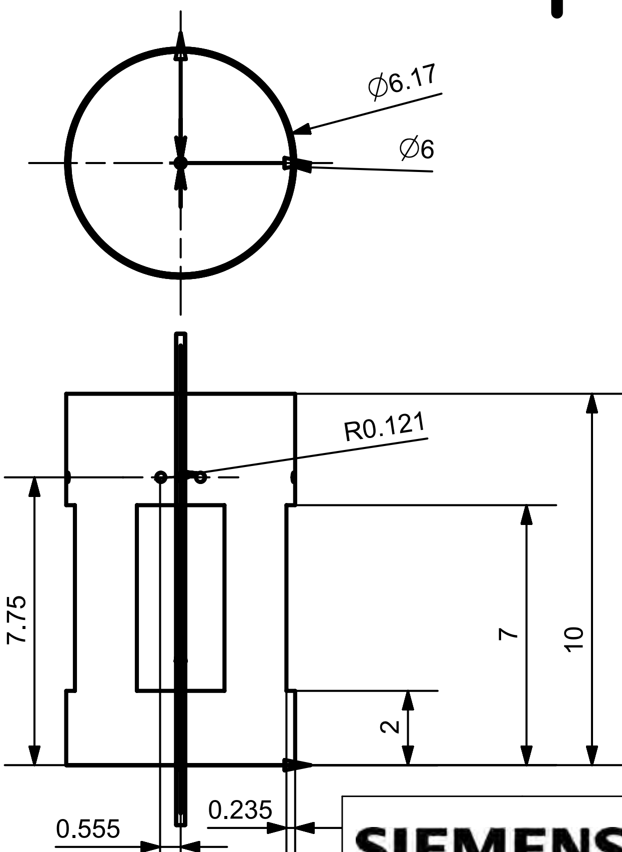
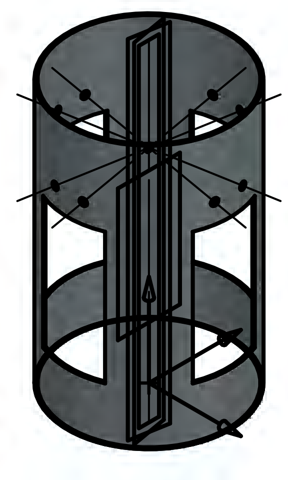
FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

TITLE
Actuator Disk

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team A.D	A

SCALE 1:1 | SHEET 1 OF 1





ALL DIMENSIONS IN INCHES

SIEMENS

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FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

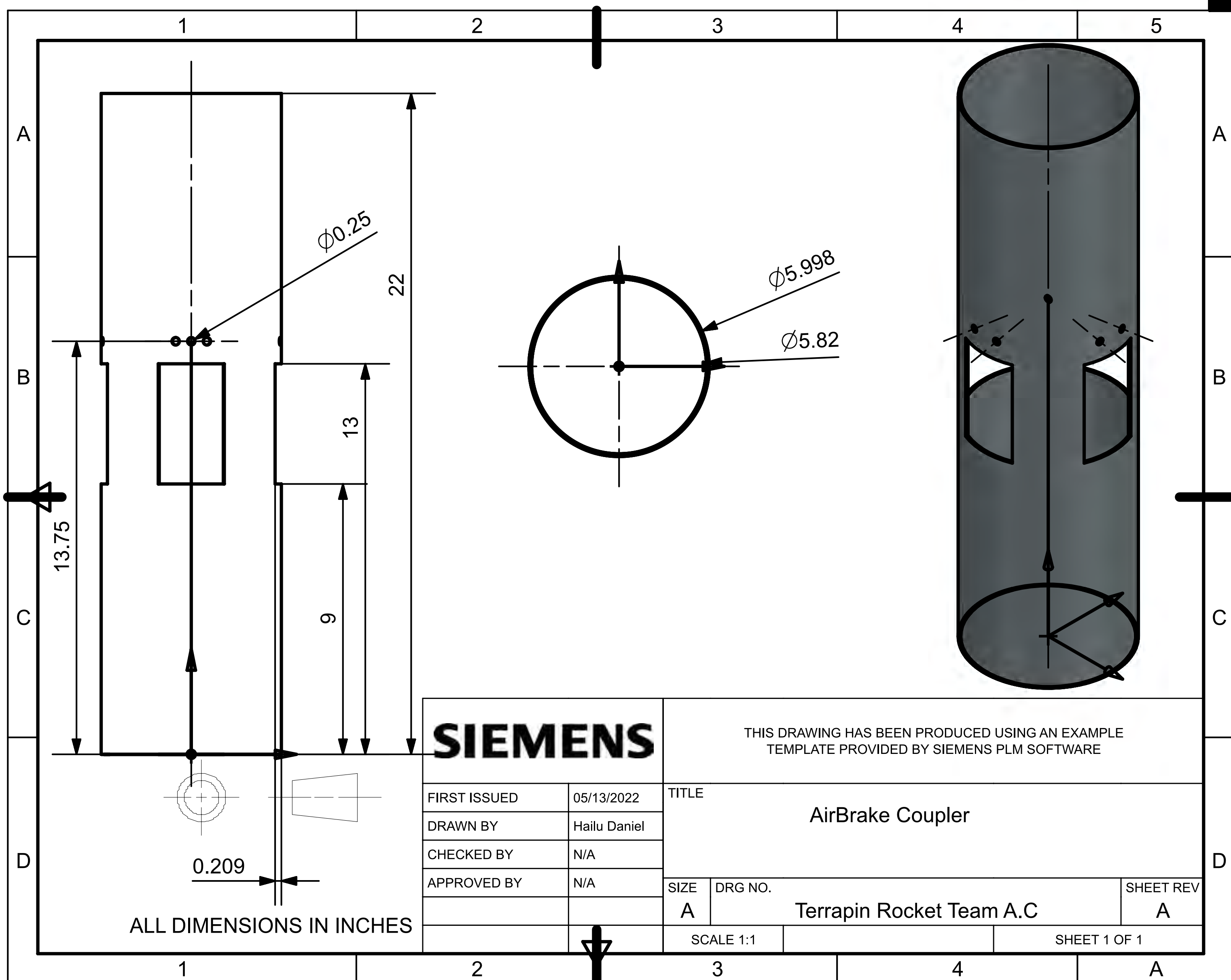
TITLE

Switchband

SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team Switchband	A

SCALE 1:1

SHEET 1 OF 1



SIEMENS

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FIRST ISSUED	05/13/2022
DRAWN BY	Hailu Daniel
CHECKED BY	N/A
APPROVED BY	N/A

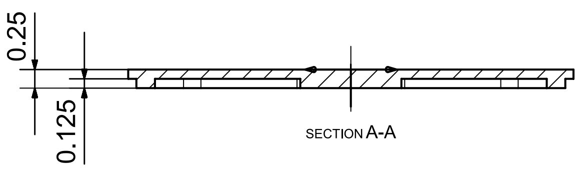
TITLE

AirBrake Coupler

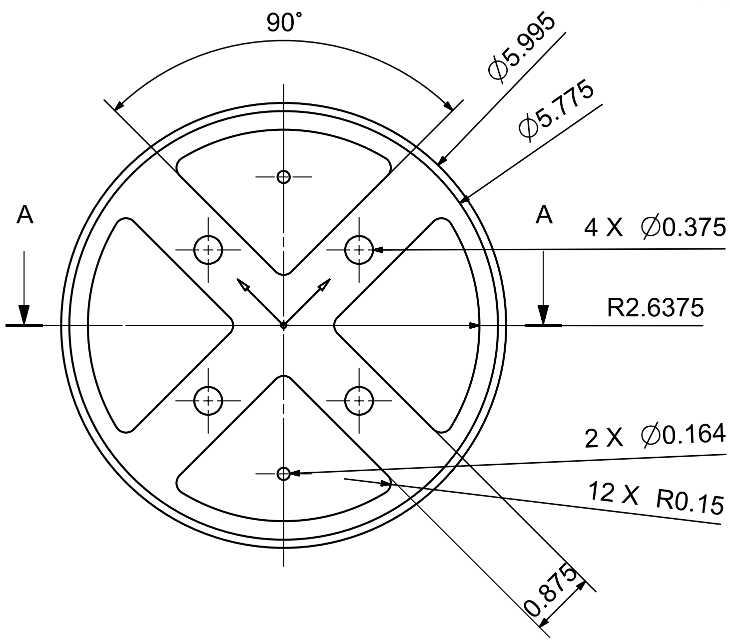
SIZE	DRG NO.	SHEET REV
A	Terrapin Rocket Team A.C	A

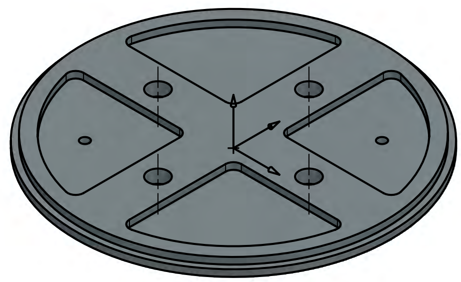
SCALE 1:1

SHEET 1 OF 1



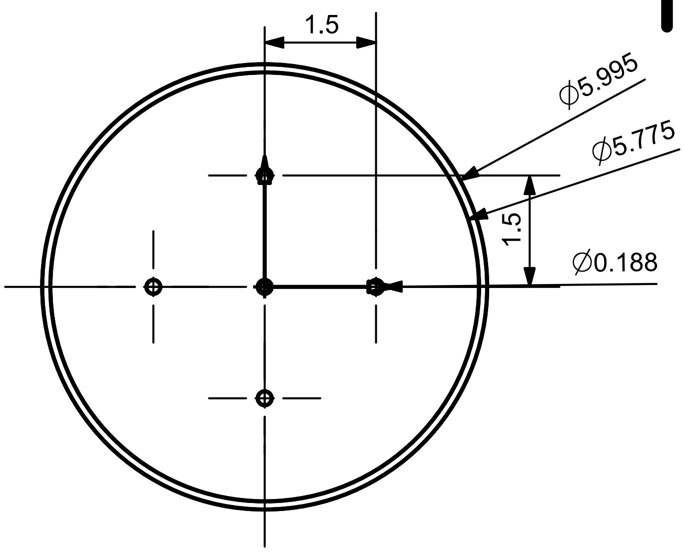
SECTION A-A

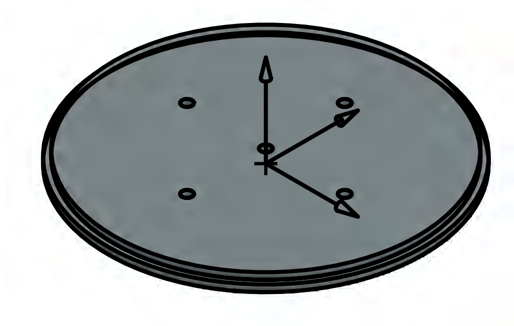


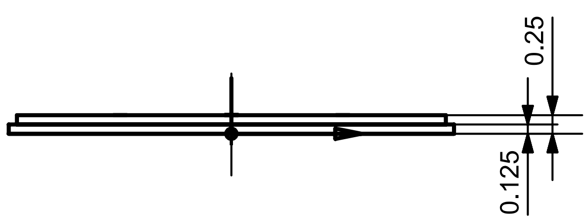


ALL DIMENSIONS IN INCHES

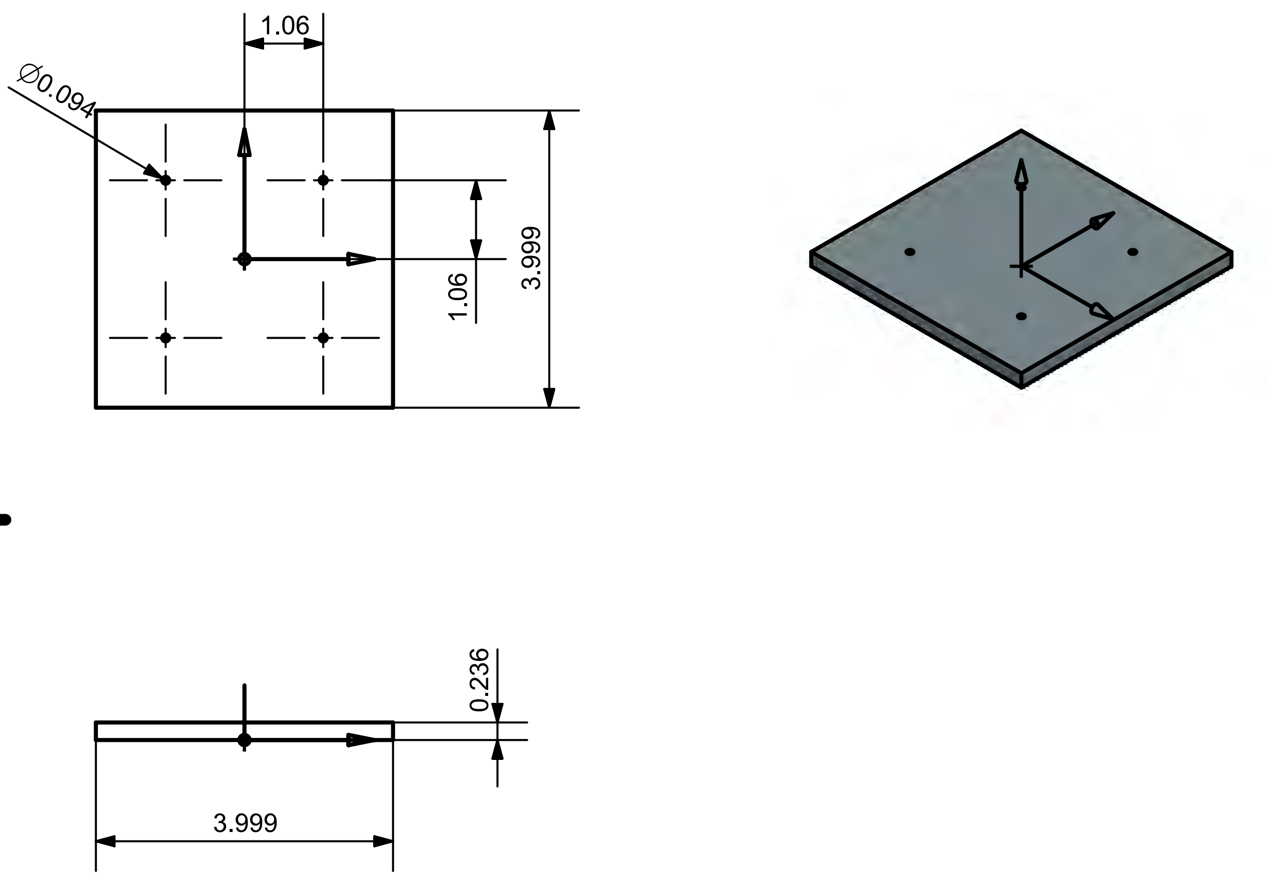
SIEMENS	THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE		
FIRST ISSUED	TITLE		
DRAWN BY			
CHECKED BY			
APPROVED BY	SIZE C	DRG NO. Ebay_Bulkhead	SHEET REV A
	SCALE 1:1		SHEET 1 OF 1





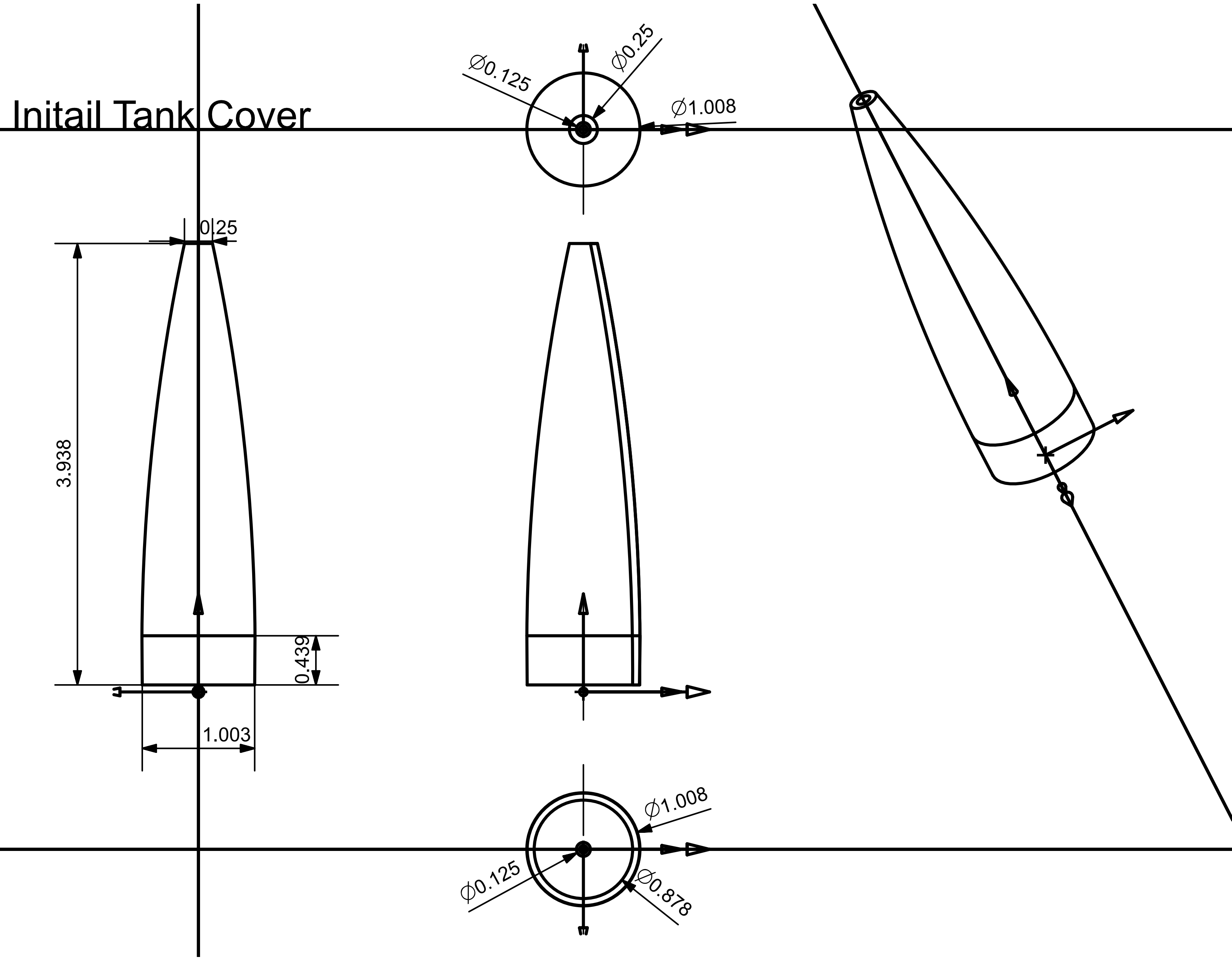


Date of Issue	05/13/2022
Drawn By	Hailu Daniel
Title	Nosecone Bulkhead
DRG. NO.	Terrapin Rocket Team

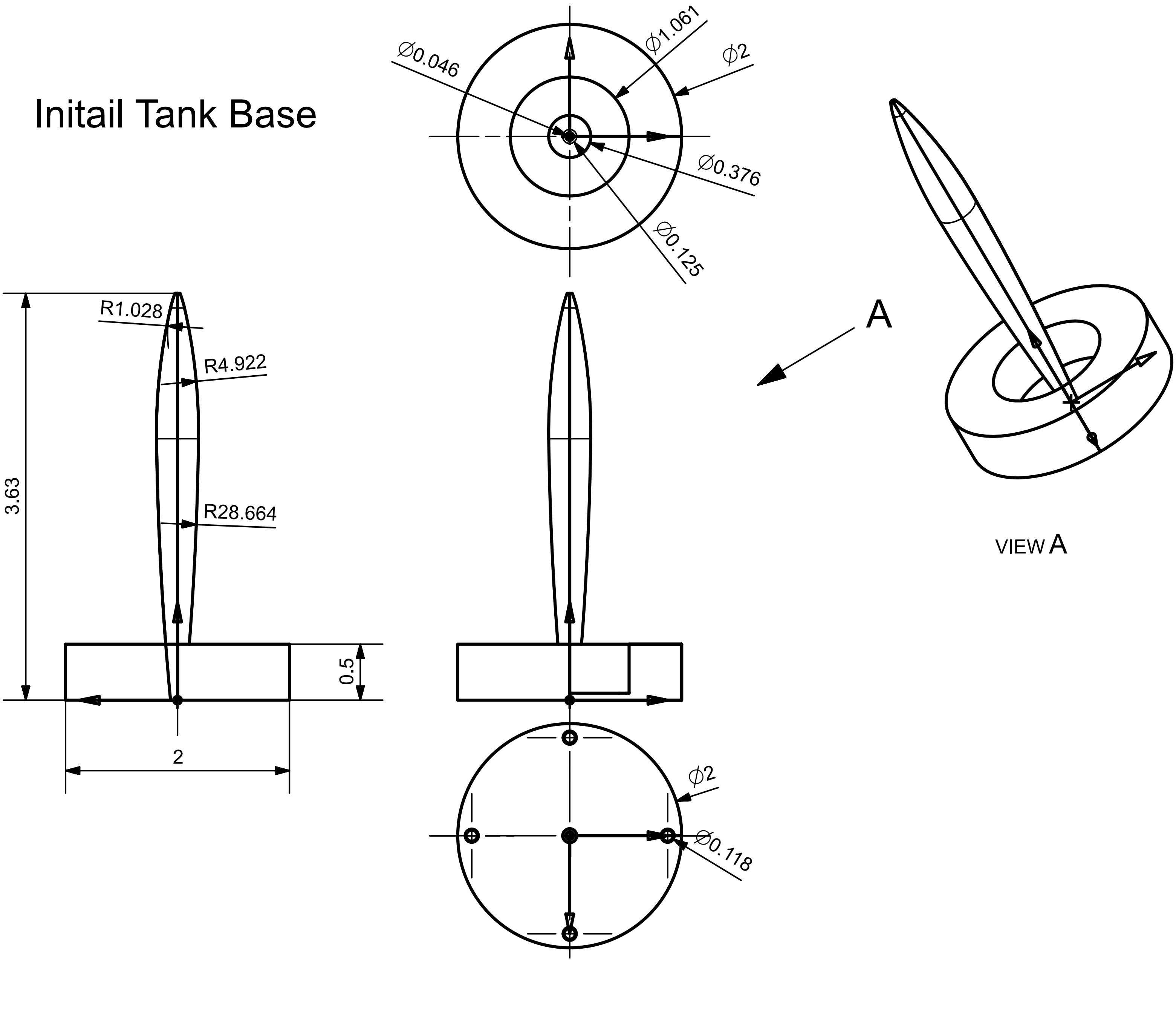


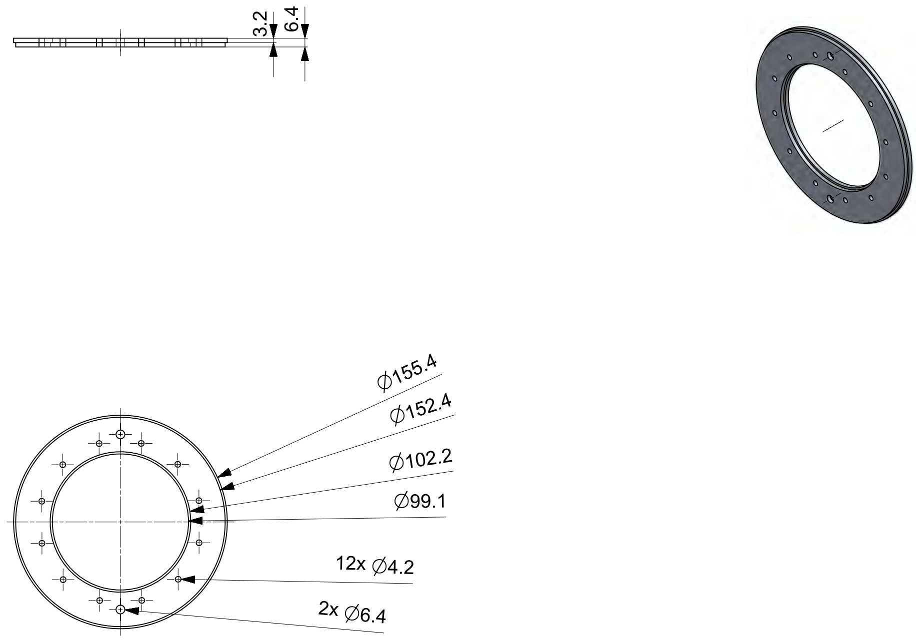
Date of Issue	05/13/2022
Drawn By	Hailu Daniel
Title	Payload Bulkhead
DRG. NO.	Terrapin Rocket Team

Initail Tank Cover



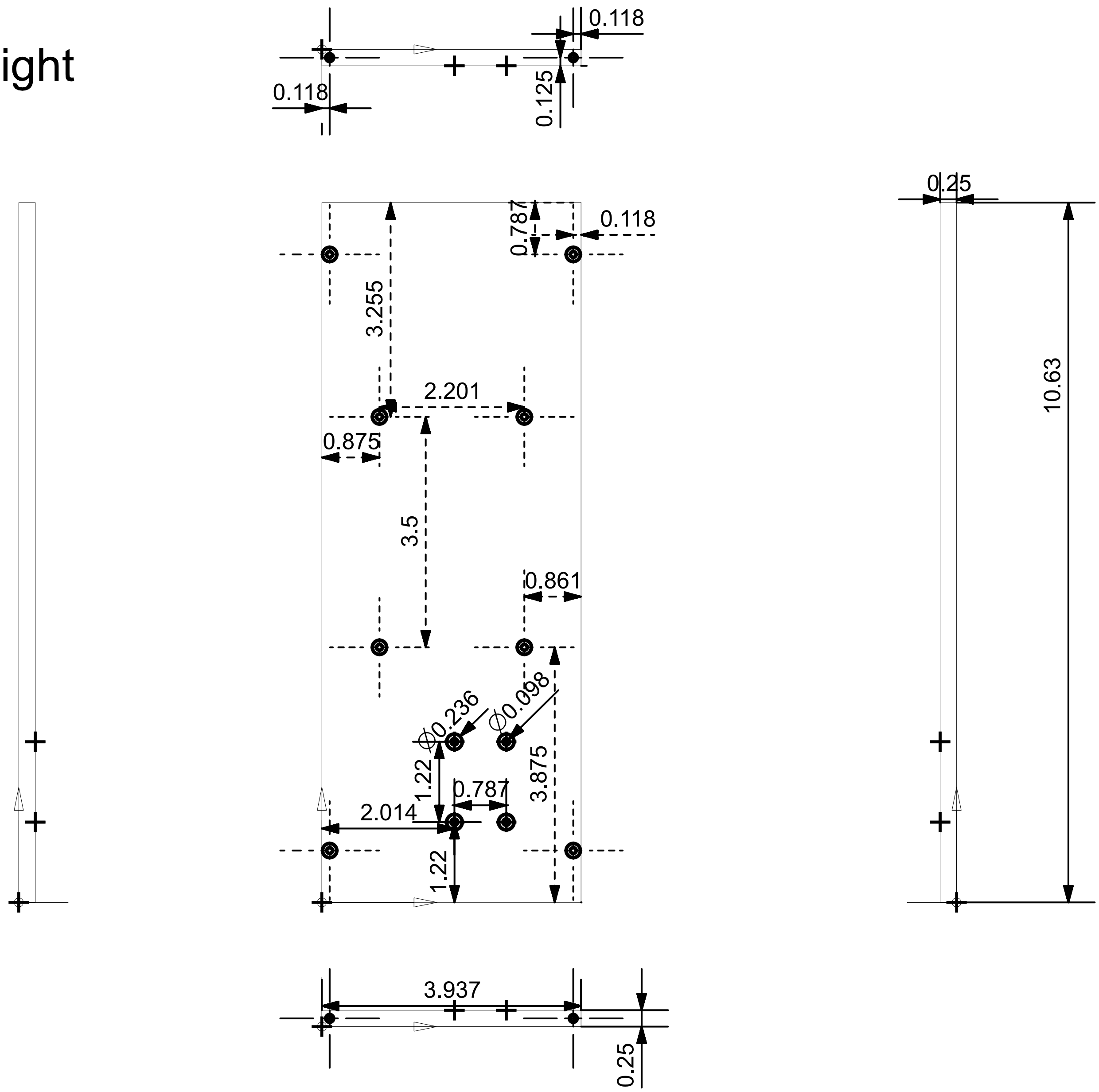
Initail Tank Base





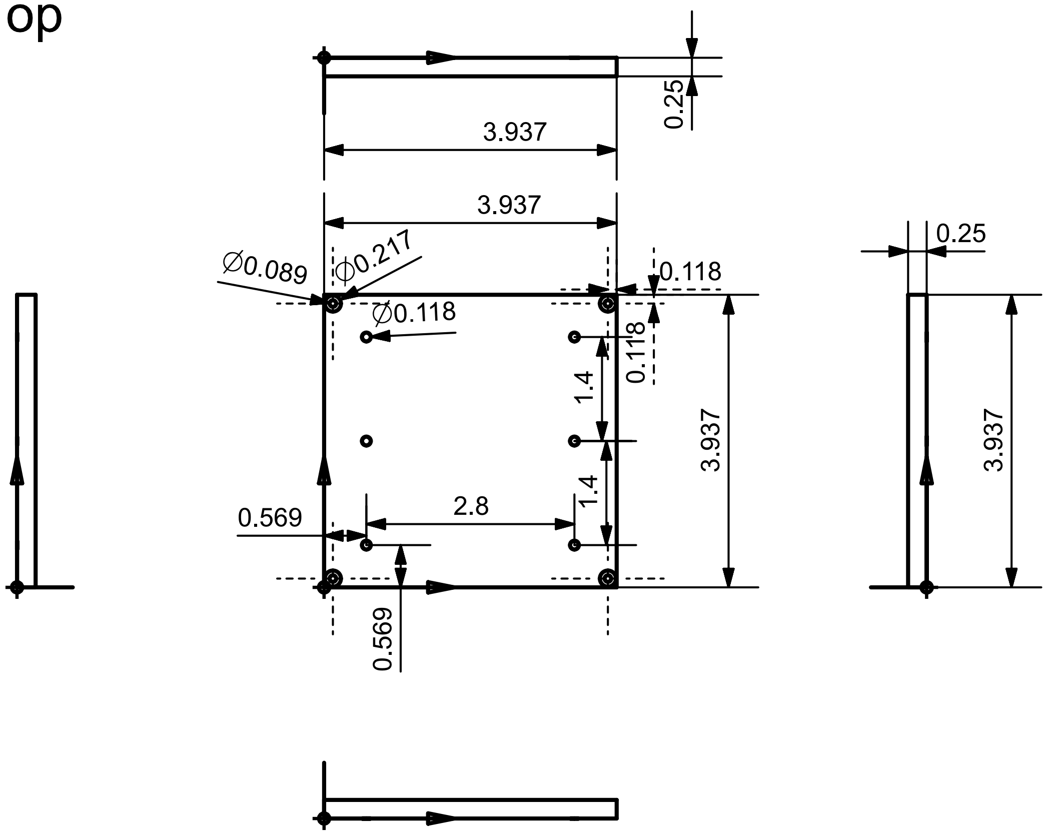
Date of Issue	05/13/2022
Drawn By	Hailu Daniel
Title	Thrust Plate
DRG. NO.	Terrapin Rocket Team

Frame Right



0.118
0.118
0.125
0.787
0.118
3.255
2.201
0.875
3.5
0.861
∅0.236
∅0.098
1.22
0.787
2.014
3.875
1.22
0.25
10.63
3.937
0.25

Frame Top



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3.937
∅0.089
∅0.217
∅0.118
0.118
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1.4
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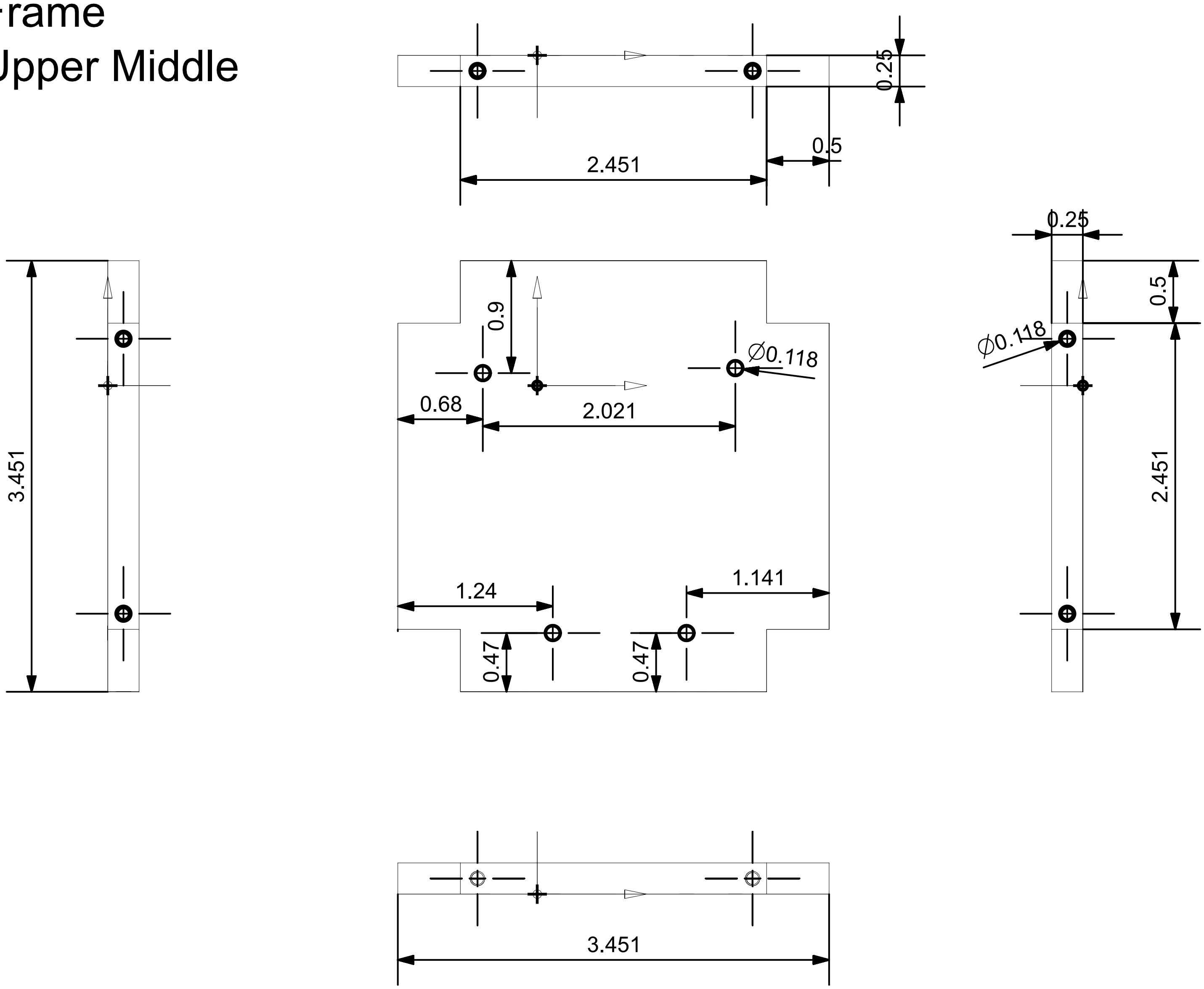
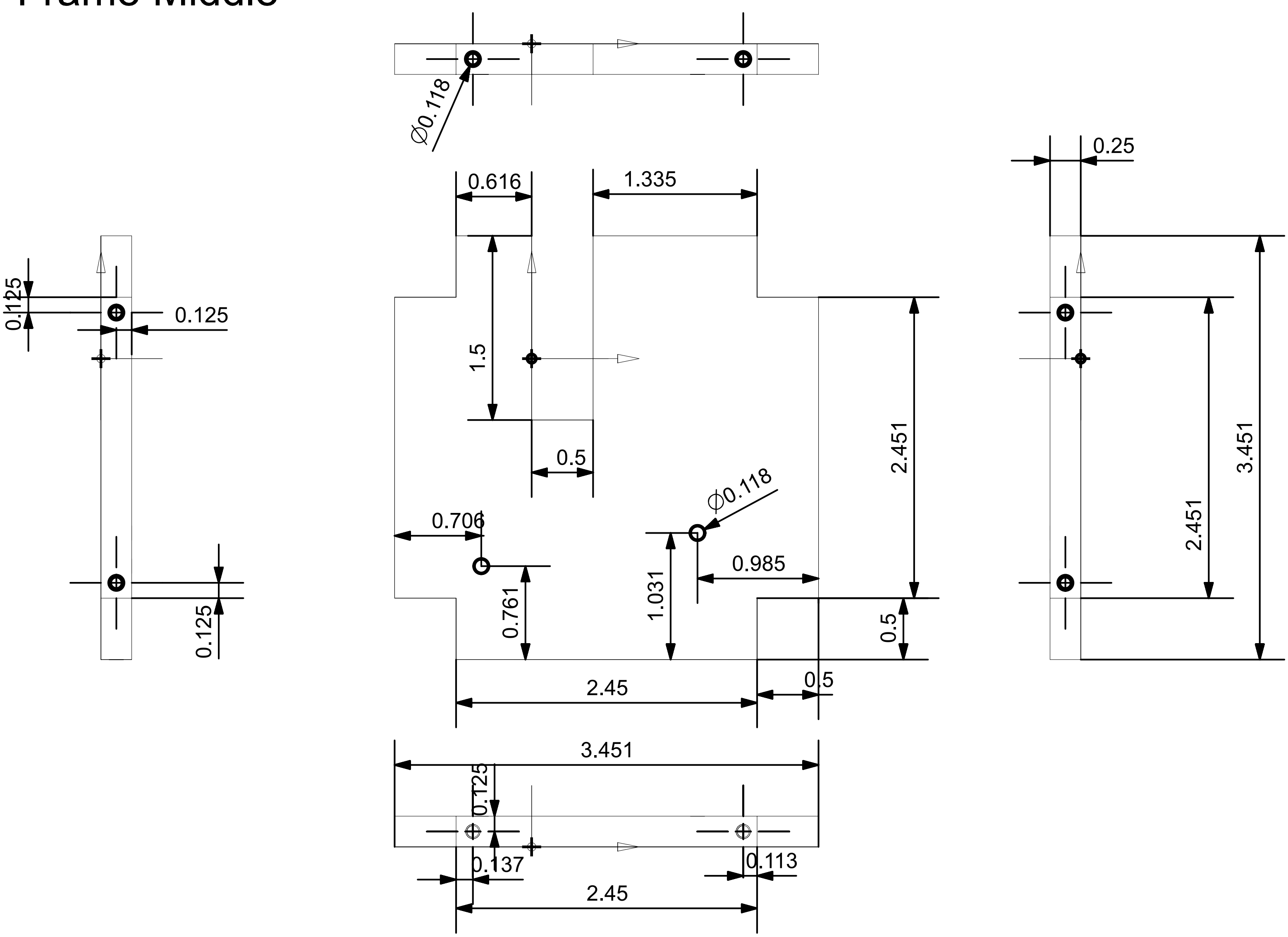
0.25
3.937

Frame
Upper Middle



Frame Middle



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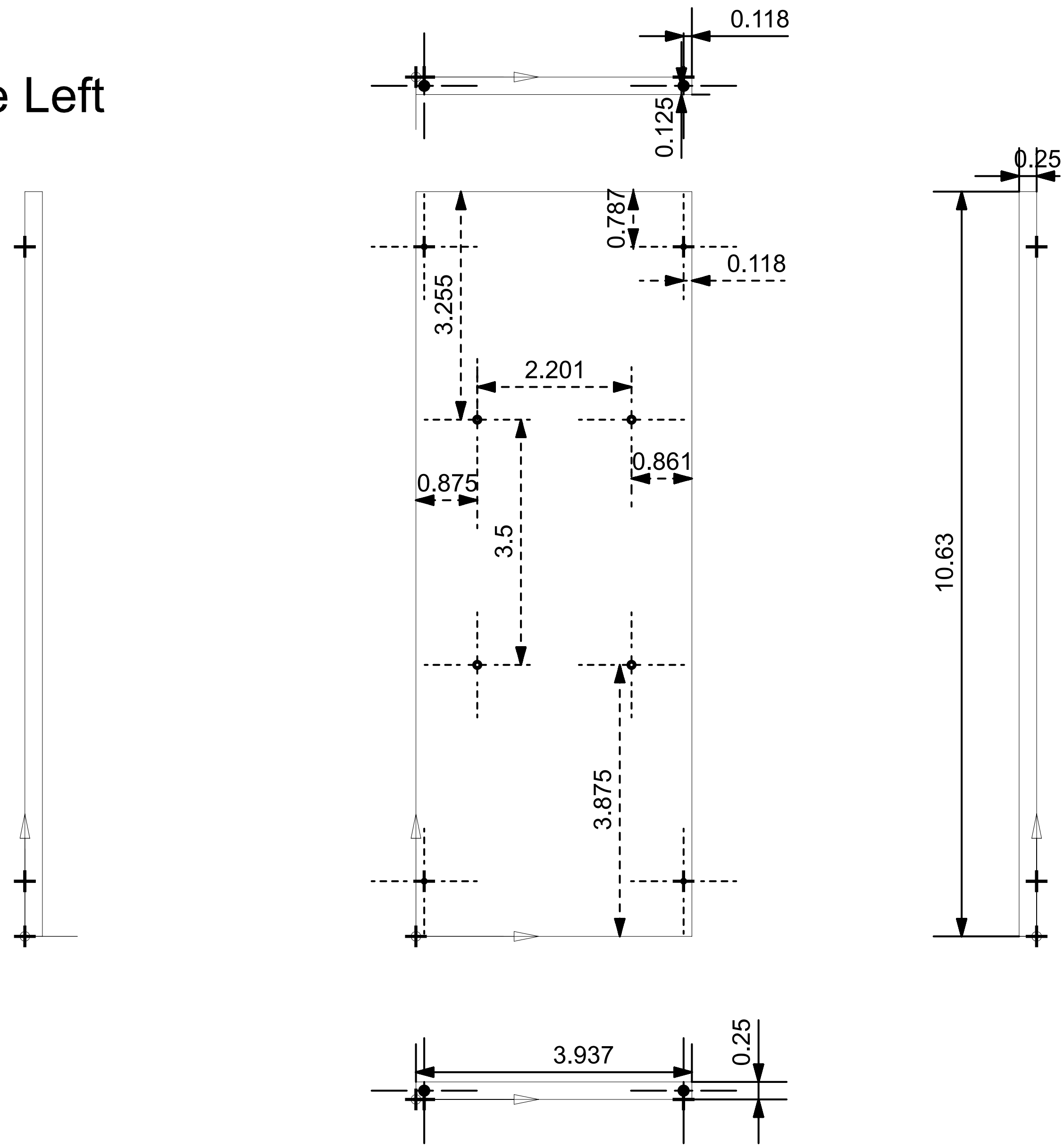

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0.25
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0.875
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10.63
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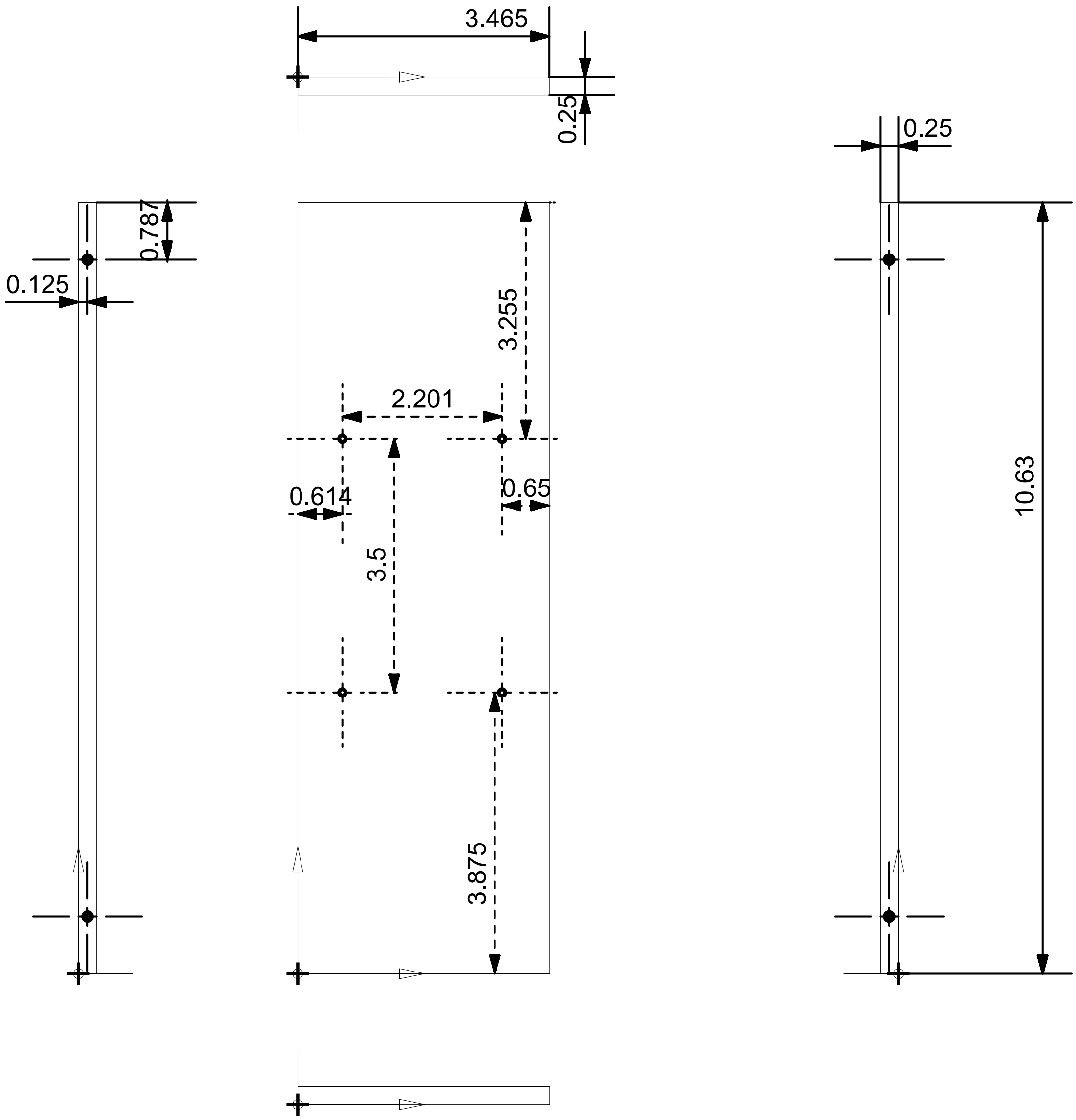
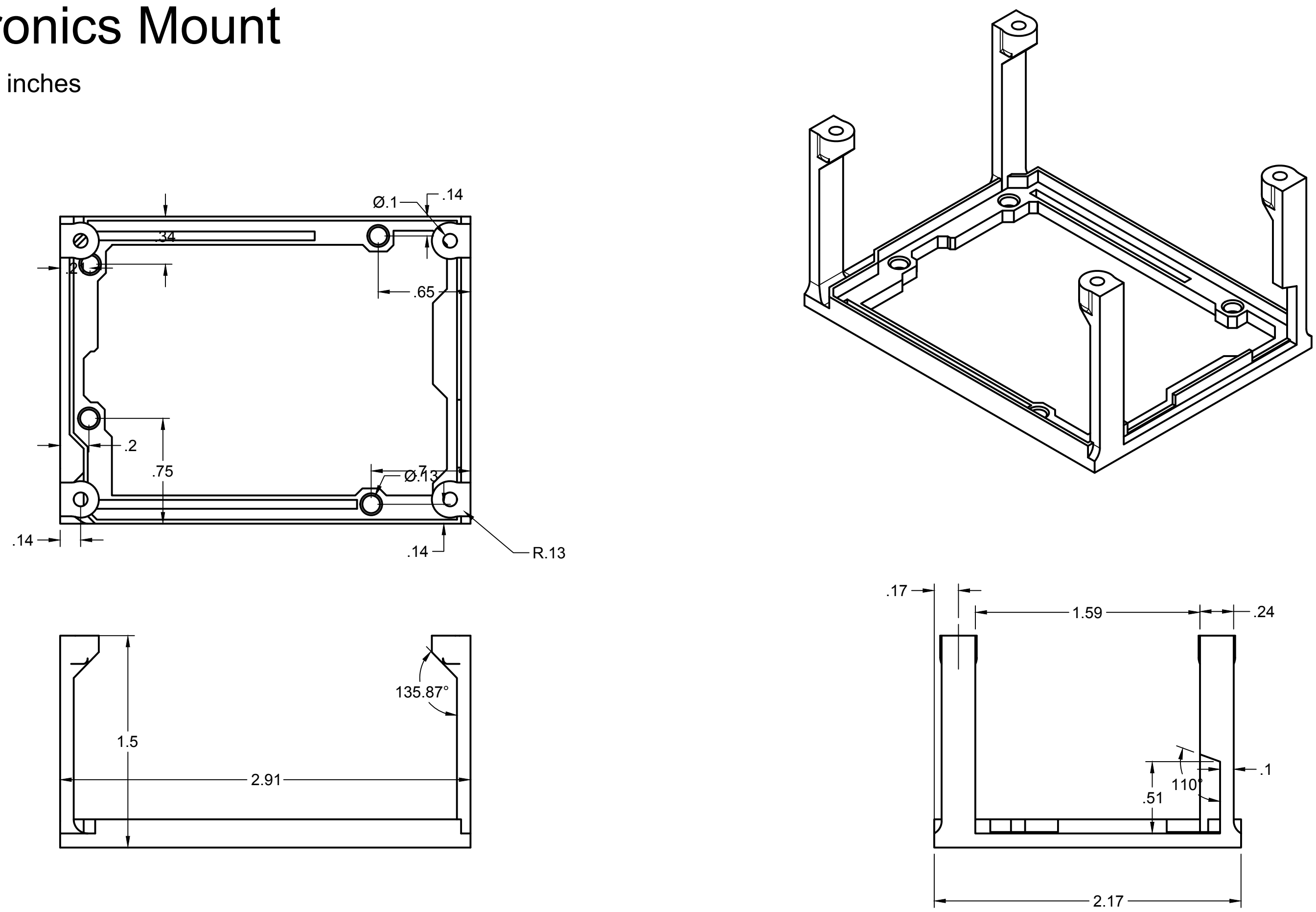
3.937
0.25

Frame Front



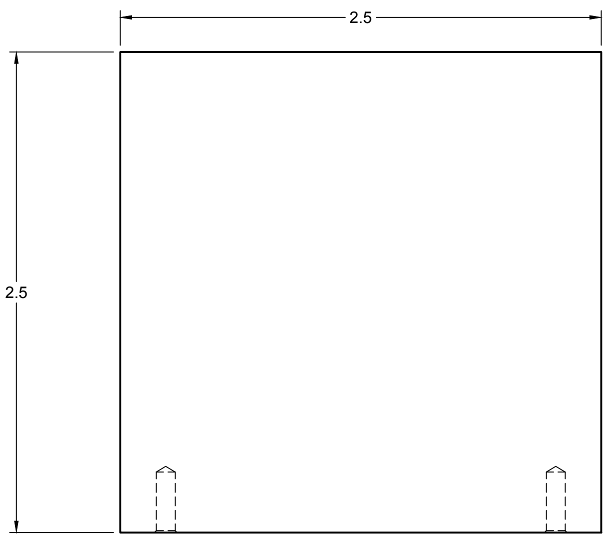
Electronics Mount

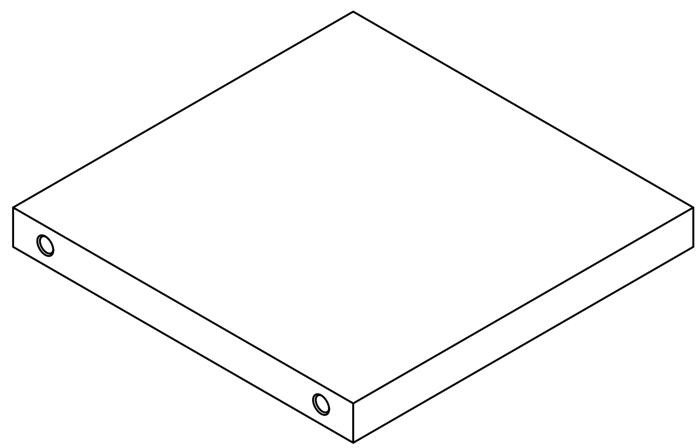
All units in inches

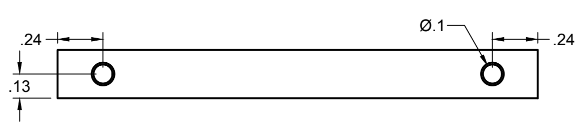


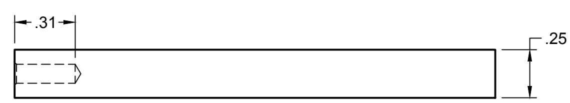
Final Tank Lid

All units in inches

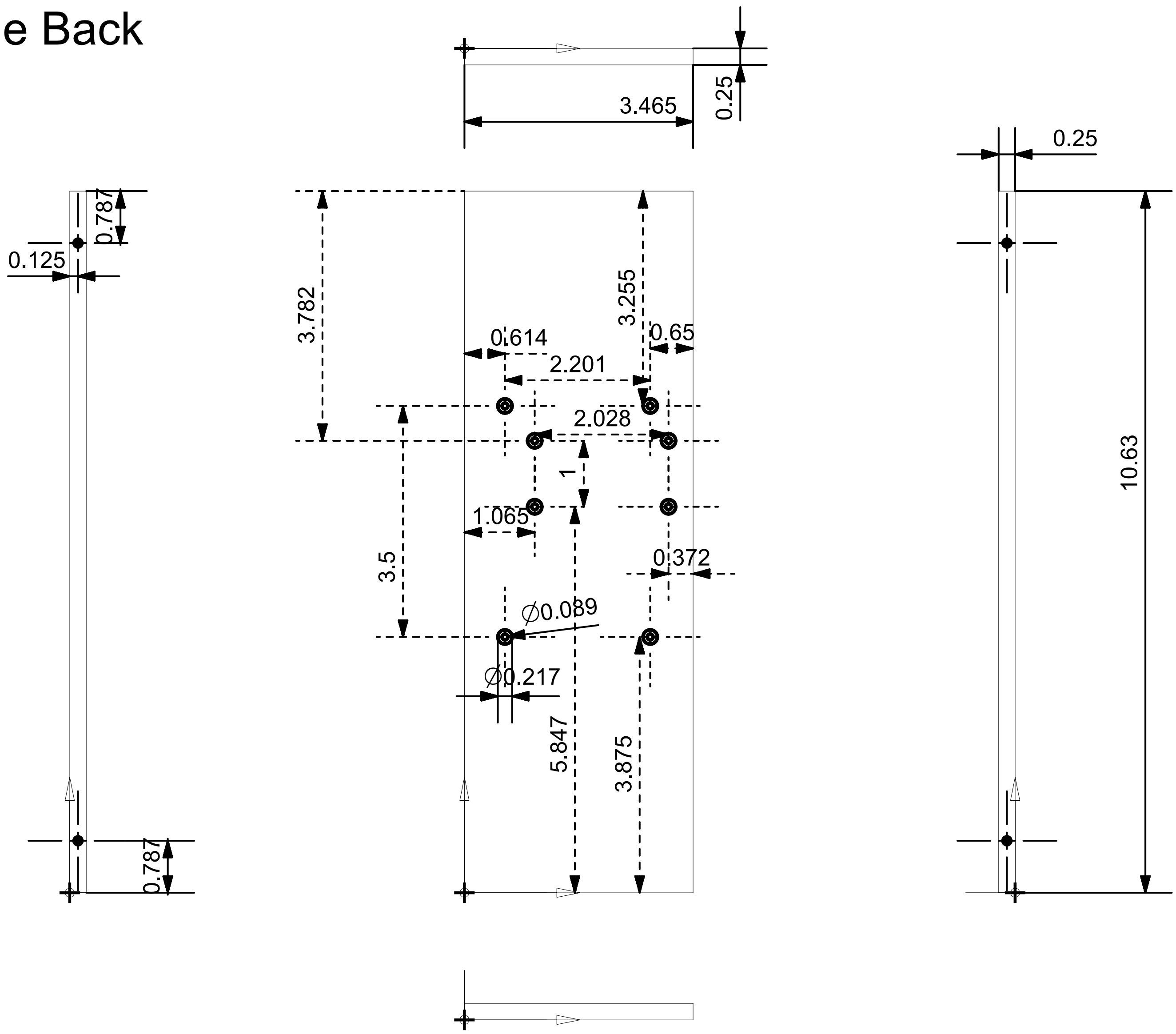








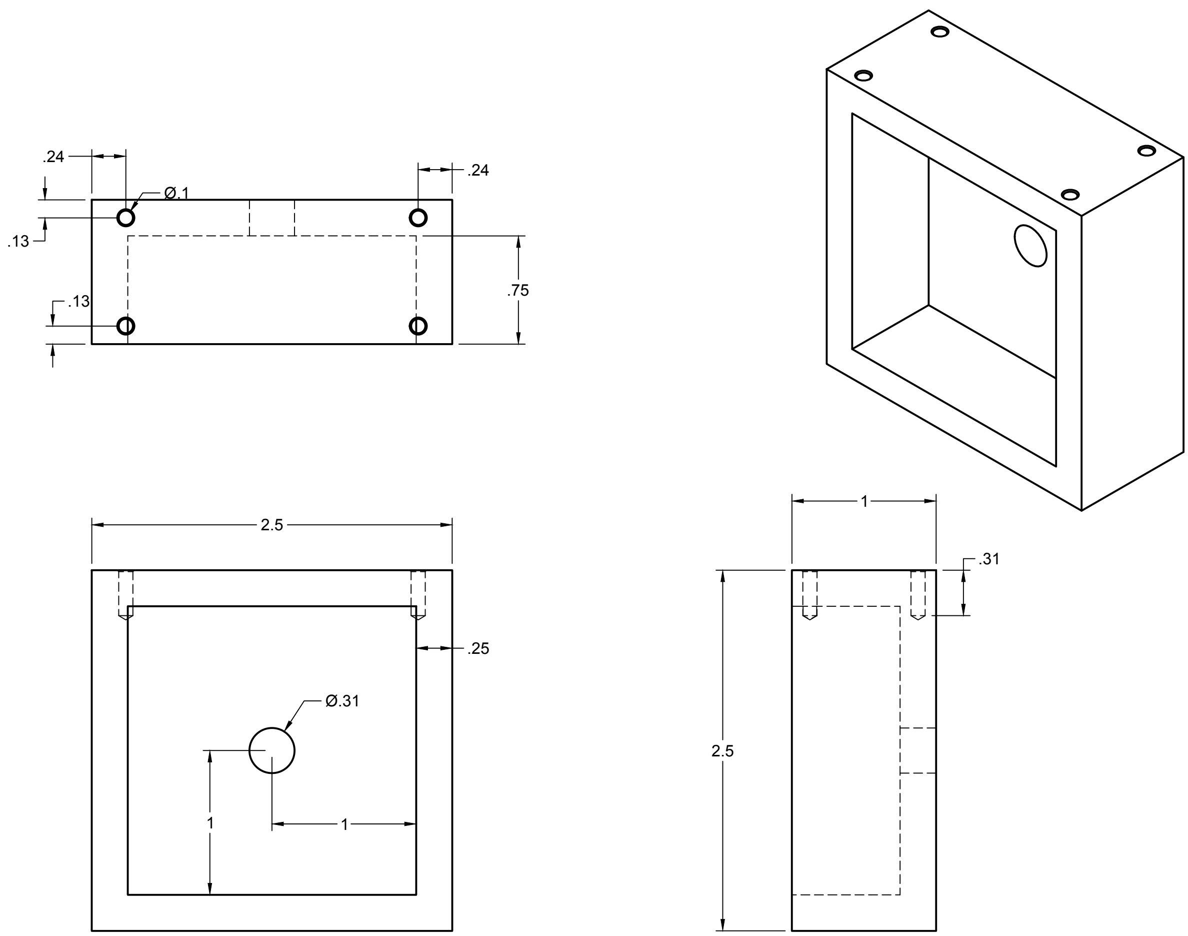
Frame Back



3.465
0.25
0.25
0.787
0.125
3.782
3.255
0.614
0.65
2.201
2.028
1
1.065
0.372
3.5
∅0.089
∅0.217
5.847
3.875
10.63
0.787

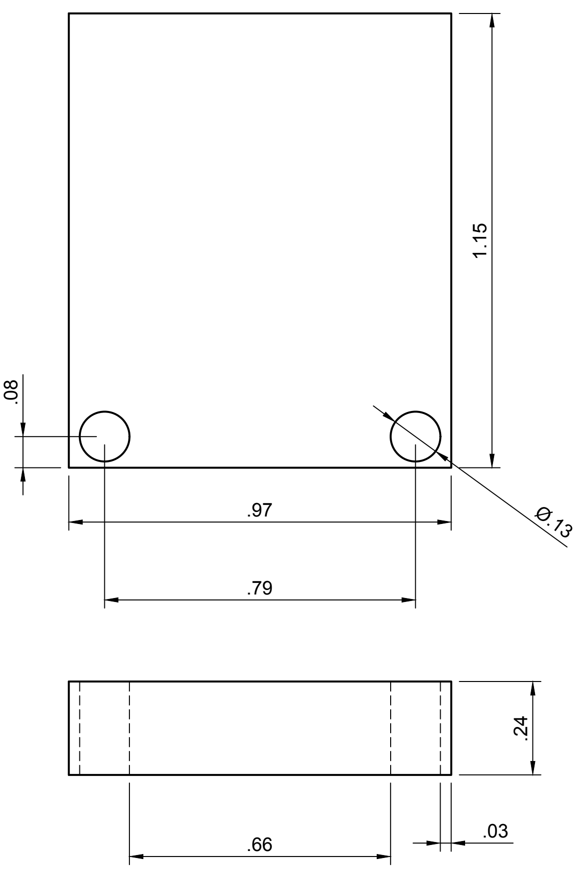
Final Tank

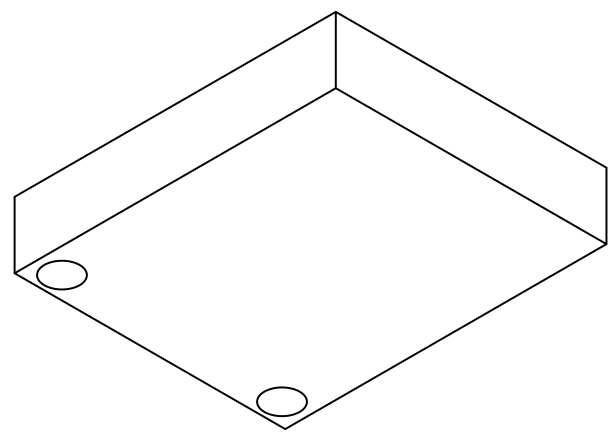
All units in inches



Camera Spacer

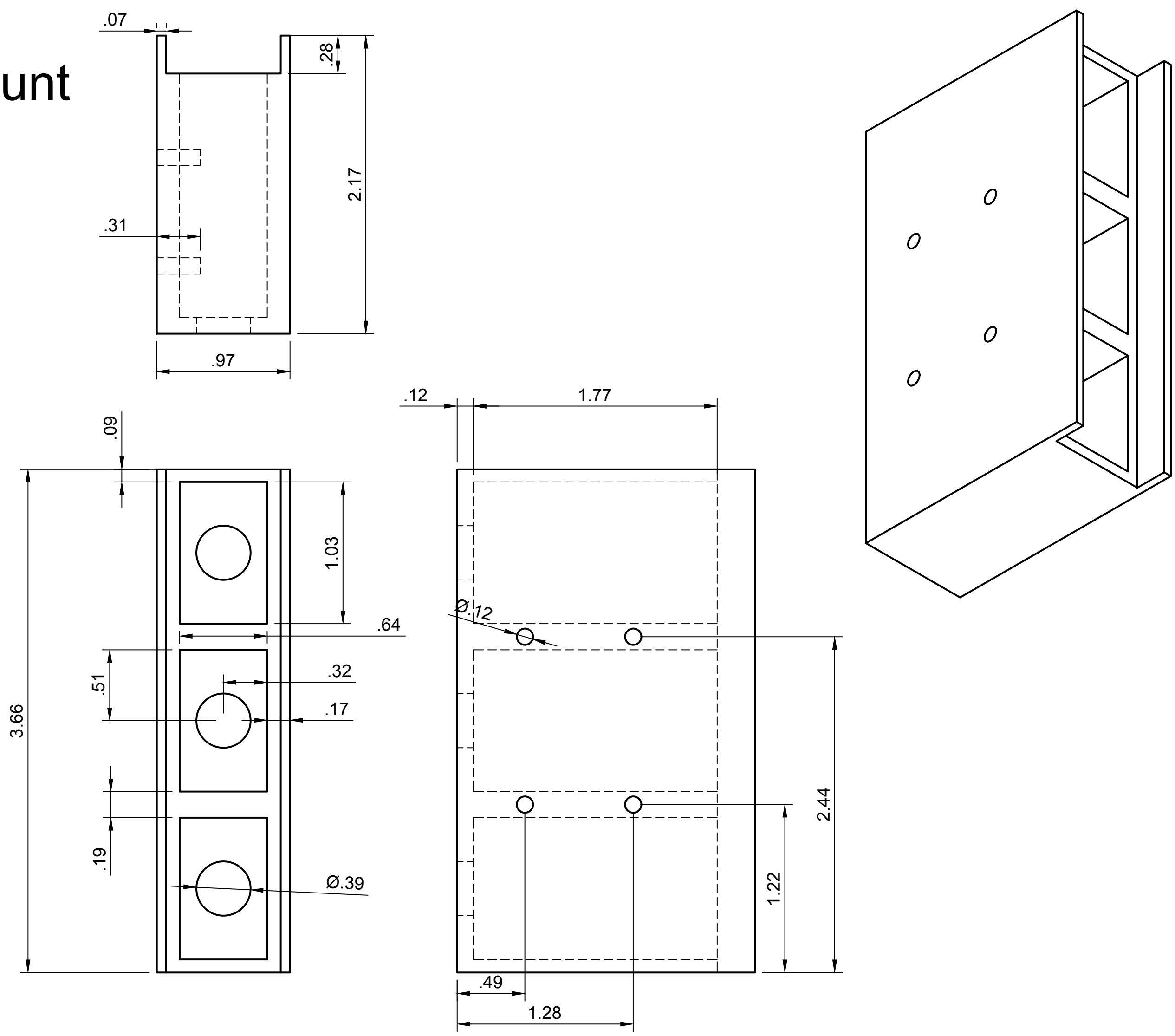
All units in inches



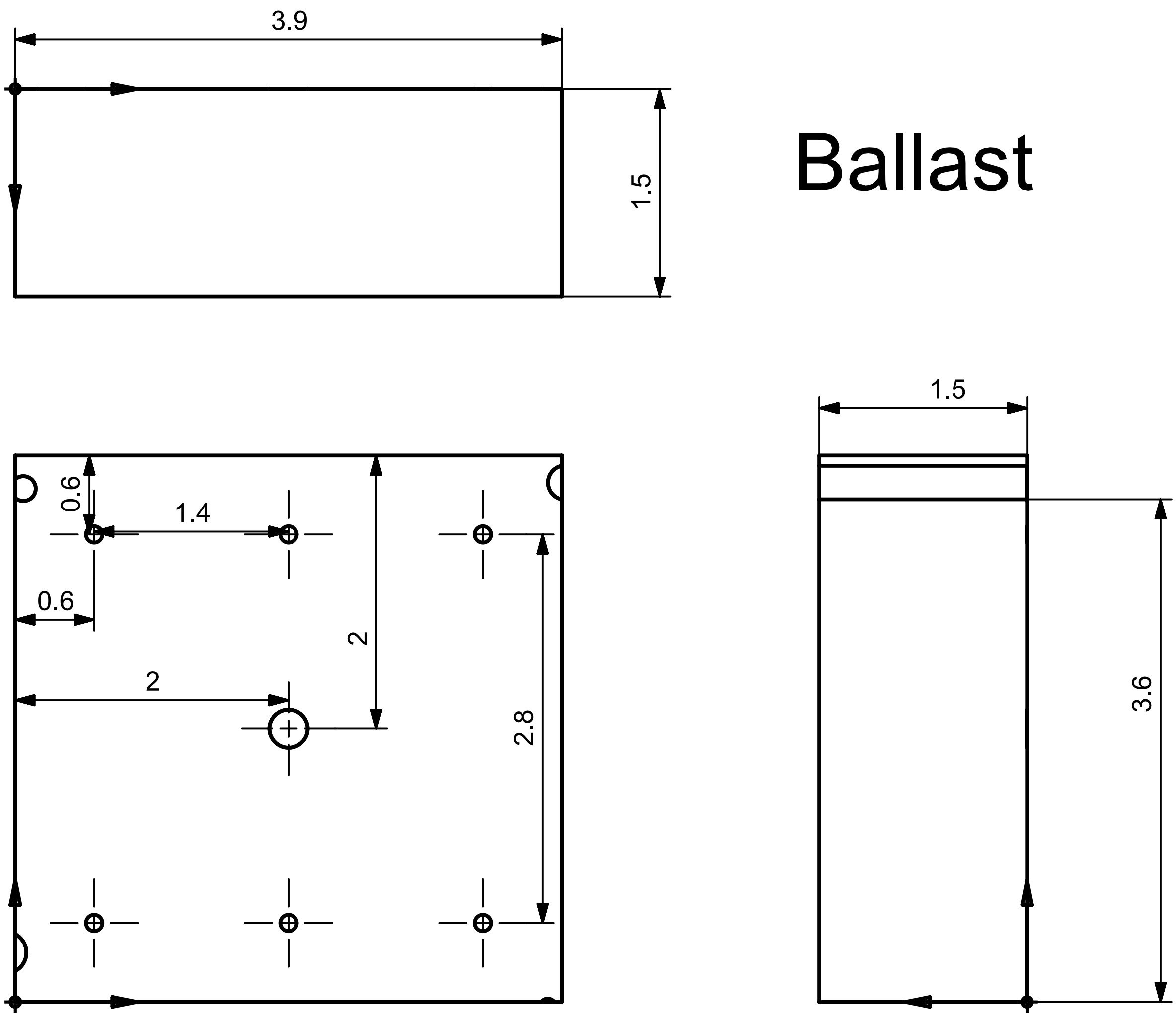


Battery Mount

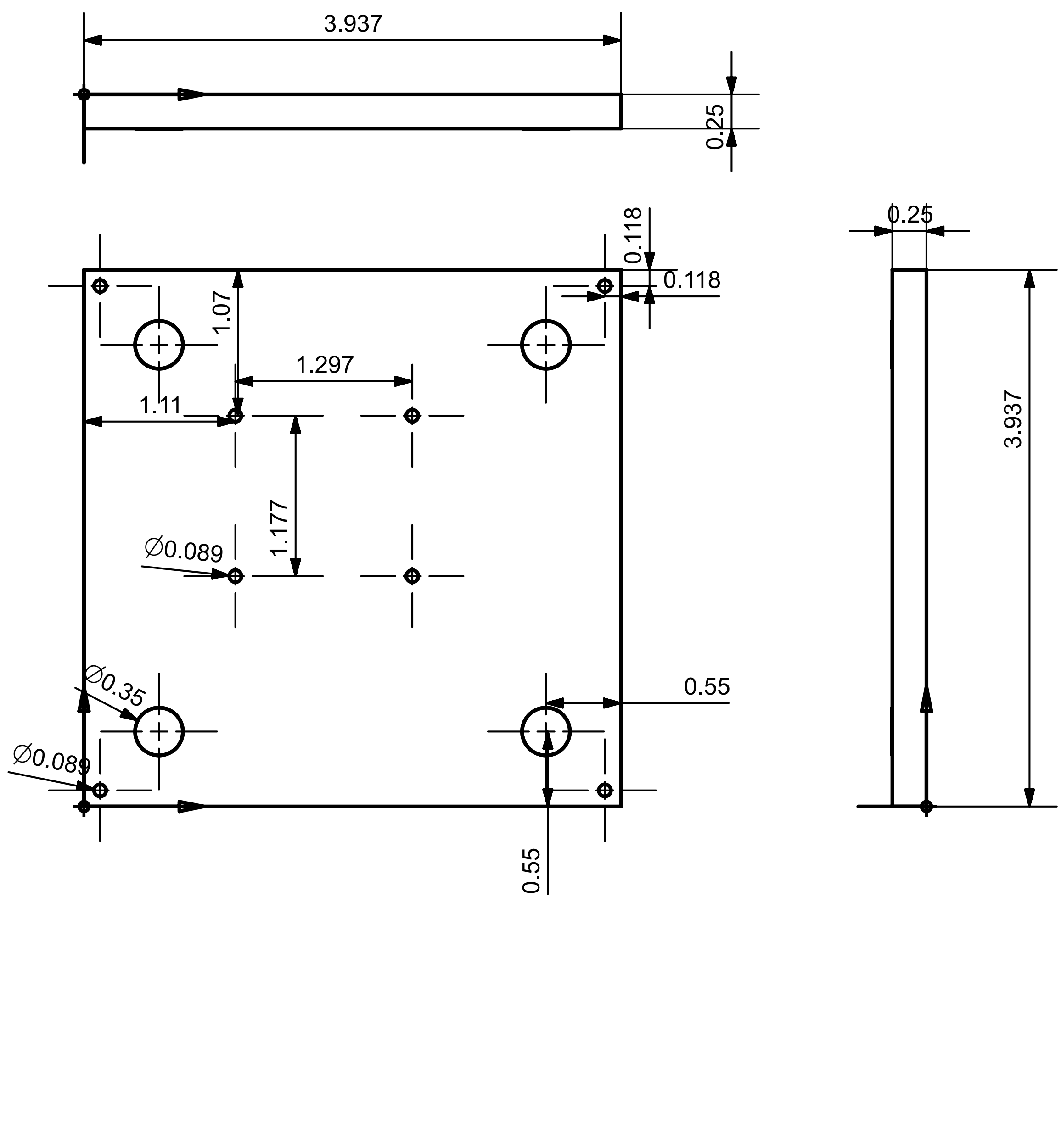
All units in inches



Ballast



Frame Bottom



Solenoid Mount

All units in inches