Embry Riddle Future Space Explorers and Developers Society

PHOENIX HAS FALLEN

Project Hummingbird Closing Document

Anthony Nichols
(2016 – 2022)

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Project Overview

The goal of Project Hummingbird was to design, test, and fly an experimental rocket that utilized a rotary recovery system to recover the vehicle instead of a standard main parachute. Over the years the scope of the project has remained the same and has been heavily focused on testing flight-critical systems both on the ground and in the air using several different flight vehicles. This project was initially started in 2016 and has been led by multiple leads over its period of operation: Karen Maurer, John Dennehy, Nicholas Butler, and Anthony Nichols.

<u>Karen Maurer</u>

Karen was the lead of Project Hummingbird from 2016 until the fall of 2018 where she oversaw the start of the project and the beginning of its first flight vehicle. During her time as the lead, the project went through its Preliminary and Critical Design phases and constructed the entire first flight vehicle dubbed *Hummingbird 1*. She was the leader of the project for the Hummingbird 1 launch in Fall 2018 which was a shake-down flight to test all of the systems without the rotor hub or the blades to ensure the vehicle properly worked. This flight resulted in a loss of the vehicle that will be covered more in-depth in the Hummingbird 1 section starting on page 5.

<u>John Dennehy</u>

Following the flight of Hummingbird, Karen retired as team lead and John was the one to take her place to help the team recover following the loss of Hummingbird 1 and move forward towards completing the scope. John was team lead for the spring of 2019 and oversaw the construction and first flight attempt of iteration one of the new Hummingbird test vehicle dubbed

Hummingdoot V1. At the end of this semester, John graduated and so a new lead was selected.

Nicholas Butler

Following John's graduation, Nicholas was elected to be the new team lead of the project. Nick was the lead of Hummingbird from the fall of 2019 to the spring of 2021 and oversaw several different Hummingbird vehicles during this time. Following the spring of 2019, Hummingdoot was fixed from its first flight attempt and flown one more time in its iteration one formation. Following this flight, Nick oversaw the modifications made to Hummingdoot into its second iteration for more in-flight system testing and had conducted a total of 2 more flights in this configuration. During the flight testing of Hummingdoot, Nick was overseeing the design and construction of the new full-size flight vehicle for Hummingbird dubbed *Phoenix* (named to represent the new rocket rising from the ashes of Hummingbird 1). Nick was also lead for the construction of the ground testing vehicle *Dootstick V1* used to test hub and rotor theory without the need for flight. In the spring of 2021, Nick wanted to hand the project off to a new lead as he was going to be graduating the following semester.

Anthony Nichols

Anthony was the team lead from the Fall of 2021 to the early spring of 2022. He oversaw the finalization of the full-size test vehicle Phoenix and prepared it for its test flight used to ensure the rocket and airframe operated adequately before adding a hub and blades system. Following this flight, the project began its retirement process due to a flight failure that will be discussed in more detail starting on page 41. During his time as the lead, Anthony had also revived the ground test vehicle Dootstick and oversaw the building of Dootstick V2 but there were no tests of this vehicle. The project was fully retired following this flight.

Design Overview

The overall purpose of Project Hummingbird was to fly a high-powered rocket with a hub and blade setup in which the blades are folded to go down the side of the airframe up to the apogee of the flight. Then, a small 3ft drogue parachute would be deployed for a small period of time to stabilize the vehicle in a vertical orientation with the fin end of the rocket hanging down. Following this, the blades would unfold and the nose cone, along with the drogue, would jettison and continue to land under the drogue chute while the rest of the rocket continued. The blades would then move into a negative pitch orientation allowing for the auto spin-up of the hub and begin gaining momentum. As the vehicle falls it would slow down and gain more speed in the blades which would be utilized to land the vehicle in a vertical orientation by changing the blade pitch to a positive angle of attack to generate lift, enabling the vehicle to land on the ground safely. For this to be successfully done, a custom hinge would need to be added to the rotor hub that would allow the blades to fold down the side of the airframe for the ascent portion of the flight and be deployed when needed just after apogee. Along with this, a custom control system and data acquisition system would be needed to be able to actively take in data to determine when to deploy, change pitch, and activate the emergency parachute if needed. The emergency parachute is needed as a safety measure in case the blades or, the hub system have an issue, or the rocket is falling out of control and not slowing so that the vehicle can be safely recovered without injury or damage in the surrounding area of the launch site. To ensure safety, multiple test vehicles were created to conduct much smaller and much safer scale tests. The original Con-Ops for the project can be found in the additional documents section of this paper.

Test Vehicles

Throughout the project's lifespan, there have been 5 flight vehicles made, all with the end goal of having a vehicle that will be capable of flying with a fully integrated bladed system on board. In the six years that the project has been around, there have been 6 separate vehicles created, Hummingbird 1, Hummingdoot V1, Dootstick V1, HummingDoot V2, Dootstick V2, and Phoenix.

Hummingbird 1

The first vehicle that was produced by Project Hummingbird was Hummingbird 1 and was designed and constructed over the first two years of the project's life.

<u>Airframe</u>

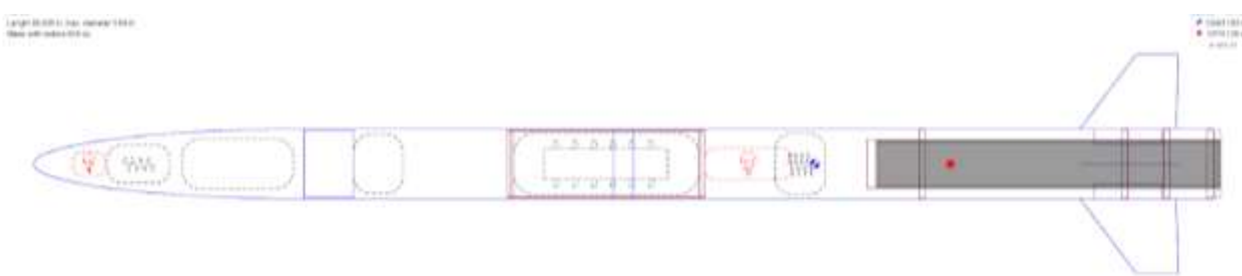


Figure 1 OpenRocket Model of Hummingbird 1

The airframe of Hummingbird 1 was constructed out of fiberglass with the fins being constructed out of carbon fiber and fiberglass in a sandwich configuration (carbon layers in the middle and fiberglass on the exterior). There were a total of two body tubes on the airframe, the lower and upper, which were manufactured by the team in-house. The lower body tube houses the motor retention system as well as the fin mounting points. The motor retainer was epoxied into place within the airframe lower tube using 4 wooden centering rings for support and stability. The 4 ¼ inch fins were also epoxied into place with both internal filets securing it to the motor mount tube and external filets securing the fins to the exterior of the airframe. The upper tube is a hollow tube used to house the simulated mass for the rotor hub and, if successful, eventually the rotor hub itself. Each section of the airframe was coupled together by a switch band coupler that was used to store the main avionics system for the rocket. This `; avionics system consisted of 2 Stratologger CF for redundancy both powered by 9V batteries (Figure 2) as well as a data acquisition system consisting of an Arduino Uno and 3 pressure sensors as well as an IMU (Figure 3).

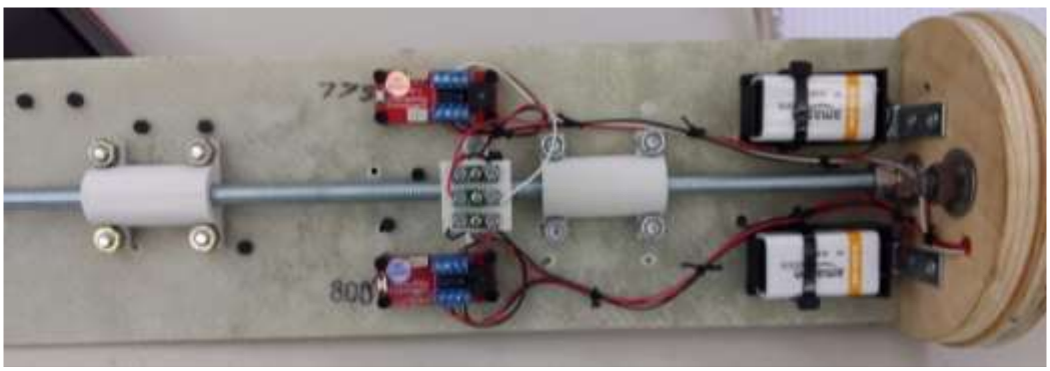


Figure 2 Hummingbird 1 Avionics side of the sled

Figure 3 Hummingbird 1 Data Acquisition side of the sled

This avionics system was responsible for the main parachute ejection during flight. The main parachute was stored in the lower body tube just below the main avionics bay and was a 10ft ripstop nylon parachute that was connected to a 40-foot nylon shock cord.

Nose Cone

The nose cone of Hummingbird 1 was a purchased woven fiberglass nose cone with an aluminum tip that had an eye bolt threaded into the bottom of it. There was also a fiberglass shoulder epoxied to the bottom that allows it to be integrated into the top of the upper body tube of the airframe. The nose cone also had its own dedicated avionics bay to control the drogue parachute deployment. This nose cone was an experimental system as it was cut in half about 9 inches from the tip and a wooden bulkhead was epoxied on the inside of the nose cone precisely 4 inches from that cut. A soft metal shoulder was epoxied in place at the cut to allow the joining of the tip with the rest of the nose cone. This is the section of the nose cone that the 2ft drogue parachute would be deployed from, the deployment of the payload was controlled by the nose cone avionics sled. The avionics sled consisted of 2 Stratologger CF's powered by 2 9V batteries each on a fiberglass plate mounted to a 3D printer sled. This system also controlled the separation of the nose cone from the rest of the airframe. The other side of the sled had a BigRedBee BRB900 GPS receiver (Figure 4) to help locate the nose cone after the flight which connected to the BRB900 transmitter. Two threaded rods go through the center of the sled and two wooden bulkheads, one on the upper half and one on the lower half of the sled. The bulkheads are secured to the sled by using nuts and washers through the bulkheads. The lower wooden bulkhead also has four set screws in the side used to hold the entire avionics bay into the nose cone securely for flight, while the upper bulkhead is there to hold the fiberglass shroud onto the lower bulkhead and keep the sled from wobbling during flight.

Figure 4 BRB900 GPS Receiver(L) and Transmitter(R)

Flight Operations

During a flight, Hummingbird 1 would need to complete six key tasks to be successful.

1. The rocket would need to ascend to apogee in a stable trajectory.
2. At apogee the Nose Cone must deploy the drogue parachute.
3. The vehicle must descend under drogue.
4. Nose Cone separation at 800ft.
5. Main parachute deployment at 700ft.
6. Touchdown and recovery.

Also during the ascent, the rocket was designed with spin stabilization by tilting the fins slightly. More information can be seen on this in Table 1 Hummingbird 1 additional Information below as well as the Con-Ops in Figure 5 Hummingbird 1 Con-Ops on the following page.

Mass Empty	14.83 kg
Motor	M-795
Burn Time	12.4s
Maximum Thrust	1722 N
Minimum Stability	1.94 calipers
Maximum Stability	3.85 calipers
Velocity off 12 ft rail	21.67 m/s
Maximum Velocity	258.2 m/s
Drogue Chute Charge	0.9 g
Nose Cone Separation Charge	1.2 g
Main Chute Secondary Charge	1.5 g
Main Chute Secondary Charge	1.8 g

Table 1 Hummingbird 1 additional Information

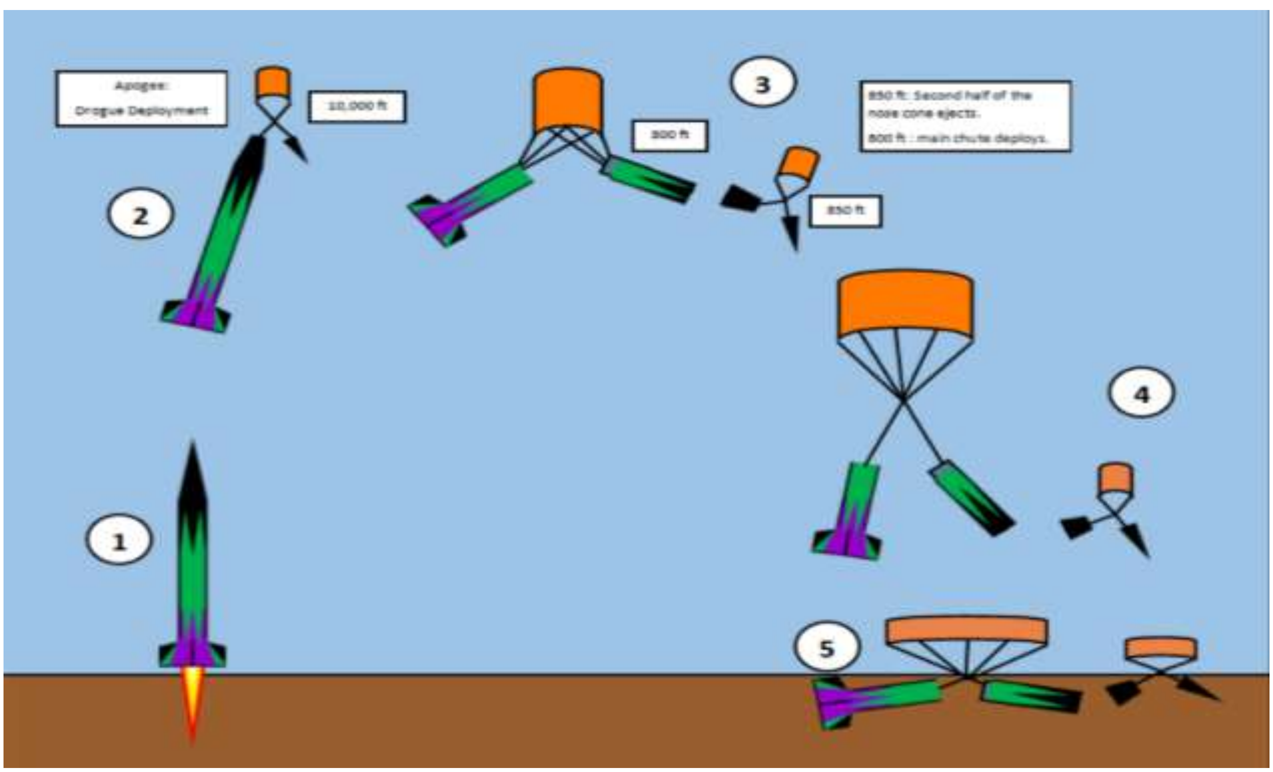


Figure 5 Hummingbird 1 Con-Ops

November 17 2018, Flight Results

The first and only flight of Hummingbird 1 took place at the SRA launch site in Palm Bay, Florida in 2018. After a successful assembly and pad preparation, the vehicle launched and had a successful ascent with the spin stabilization creating a very stable flight with a small amount of wobble following motor burnout. At apogee, the nose cone successfully deployed the drogue parachute but the weak drogue chute shroud lines along with the sharpness of the nose cone tip shoulder caused the drogue parachute to tear off. Following the loss of the drogue chute, the rocket continued on its descent and went ballistic for the entirety of its descent. Once the rocket reached 800ft in altitude it successfully ejected the nose cone which flew past the airframe and bounced off of the fin while passing. The vehicle was still moving too fast and could not deploy the main parachute causing it to hit the ground at an estimated 320 mph and drive itself into the ground 3 feet. The nose cone then landed in a bush at an estimated 280 mph and took no damage from the impact. This failure resulted in the total loss of the airframe and avionics with the nose cone being the only part that was fully recovered.

What Was Learned

From this flight, the team had learned that the nose cone needed some lower altitude flight tests with a smaller vehicle. This would allow any issues that occurred on this flight to be fixed and tested before flying it all on a larger rocket again. The main things learned from this flight included,

- A drogue parachute with tougher shroud lines
- The nose cone shoulder needs to be duller to prevent cuts
- Smaller scaled flight tests to confirm system operation

- More analysis on designs with stricter safety policies

Hummingdoot V1

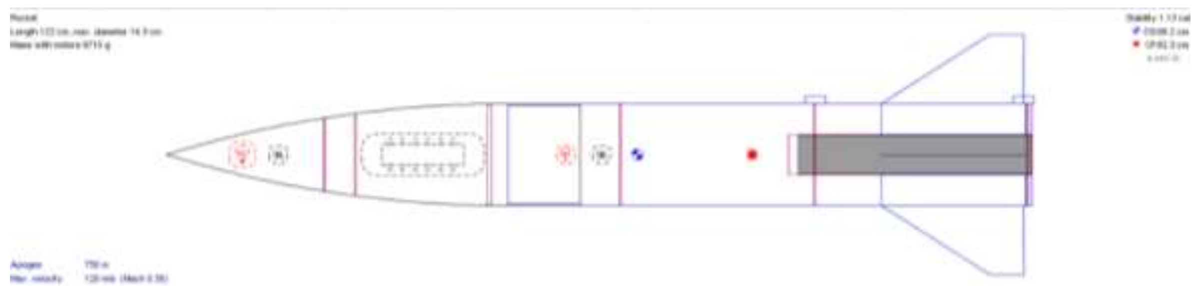


Figure 6 Hummindoot V1 OpenRocket

This is the second vehicle made in project Hummingbird and the first iteration of this test vehicle. This vehicle was made specifically for flight test systems and hardware. Its first use was a flight test of the experimental nose cone from the Hummingbird 1 flight. This vehicle was made using Pathfinder 8's airframe in order to cut down on costs and re-use older club airframes that are just being stored.

<u>Airframe</u>

The airframe of Hummingdoot V1 was a full fiberglass airframe with carbon fiber reinforced fins. The airframe body tube was the 5.5 inch upper body tube from Pathfinder 8 that was modified to fly on its own. A fiberglass motor (54mm) tube was installed with two half inch centering rings and epoxy securing the tube to the centering rings and those are then epoxied to the interior of the airframe. On the bottom centering ring a motor retainer was installed to hold the motor in during a launch.

Nose Cone

The Nose Cone used on Hummingdoot V1 was the same nose cone that had flown on Hummingbird 1 and was fixed up and modified very slightly in order to continue testing with it. After the crash of Hummingbird 1 the nose cone luckily landed in a bush and was structurally sound with the only issue being the loss of the drogue parachute. A new 3ft drogue parachute was added to the nose cone to replace the one lost in flight and had a much more reinforced set of shroud lines to prevent tearing on deployment. Another modification made was that the 2-inch shoulder for the nose cone tip was cut down to about 1 inch to allow the parachute to have a cleaner exit from the nose cone. The last modification was a 1kg mass attached to the bottom of the lower ebay wooden bulkhead as a small, simulated hub mass. Other than this, the nose cone had the same avionics bay, construction, and structure as discussed in the Hummingbird 1 section on page 7.

Flight Operations

The flight operations for this vehicle are very different from Hummingbird 1 due to the substantially smaller size. For test flights, Hummingdoot V1 needs to complete different tasks for each flight as the vehicle was designed to test several different systems over several different flights. For the first two flights, a successful flight needs to complete the following milestones,

- The rocket launches and reaches apogee in a stable fashion
- Drogue parachute is deployed at apogee
- Descend under drogue until desired altitude
- Deploy main parachute and separate nose cone
- Land safely and be recovered

This vehicle had an estimated apogee of only around 2,000 feet and more information pertaining to this vehicle can be found on the next page with the Con-Ops and Table 2. All separation charges are successfully ground tested prior to launch.

Motor	J-760
Burn Time	1.75 s
Max Thrust	937.3 N
Stability	1.22
Max Velocity	131.98 m/s
Drogue Chute Charge	0.9 g
Main/Sep Charge	2.0 g
Empty Mass	8.56 kg

Table 2 Hummingdoot V1 additional information

April 2019 Flight Results

The first launch of iteration one of the Hummingdoot test vehicle had an on-pad failure which was caused by a manufacturer defect in the Cesaroni 54mm motor used. Once the countdown reached zero and the launch button was pressed the motor's ejection charge was detonated rather than igniting the motor. Which caused the motor to eject out of the bottom of the rocket while still on the pad. The motor never ignited and was safe after this incident but the aluminum bulkhead that was at the forward closure portion of the motor mount was destroyed and the flight was scrubbed due to the amount of damage done.

What was learned

Nothing was learned in this flight as the failure was caused by a manufacturer defect in the motor causing the vehicle to never be able to leave the pad.

Launch 2 Flight Results

The second and final flight of the first iteration of Hummingdoot was at the SRA launch site in Palm Bay, Florida. This flight had a successful take-off with a fully operational motor as well as a successful drogue parachute deployment. When the main parachute was deployed an issue occurred in which all of the pressure from the charges vented out of the nose cone and the rocket proceeded to land under only drogue and damage one of its fin filets. The cause for this failure of separation was caused when the drogue parachute was deployed at apogee. After a lengthy analysis, it was determined that the force of the drogue chute opening, the weights of the nose cone avionics, and the one-kilogram mass put too much stress onto the lower wooden bulkhead that was holding the ebay in place. Three of the four set screws ripped through the upper portion of the bulkhead allowing the ebay to slide back into the airframe and hang. Once the main charges fired, the pressure escaped through the pressure relief holes made for the altimeters and the nose cone tip. After recovery, the damage was assessed, and the only damage done to the rocket was a cracked fin filet and the wooden avionics bulkhead.

What Was Learned

From this flight, it was determined that the 1 kg weight on the bottom of the lower wooden bulkhead was not needed as the rocket was too short and the extra weight added to the instability. Another change that was to be made was to replace the wooden bulkhead on the bottom of the avionics bay with a machined one made out of Aluminum alloy 7075. More changes were made to the airframe and nose cone following this flight but they were not related to this flight and were simply added for additional testing.

There are no further documents on Hummingdoot V1

Hummingdoot V2 Phase 1

The V2 variant of Hummingdoot had many changes made to it between its two flights so to make it easier to understand they will be separated into their own sections. This first flight of Hummingdoot V2 had many changes made to it to fix the nose cone problems that caused problems on the last Hummingdoot V1 flight. These modifications were made to continue testing the functionality of the nose cone before a full-scale flight of the next vehicle to prevent any further issues.

Airframe

The airframe of Hummingdoot V2 reused the booster section of Hummingdoot V1 after repairing the cracked external filets. The only other change to the airframe was the addition of an additional body tube to help stability and add room for additional testing since a similar tube would be added just below the nose cone on the Phoenix test vehicle. This tube was rolled by the team, cut and sanded, and fit into the booster with a blue tube coupler. This tube would only be housing a quarter inch PLA bulkhead in the lower half of the rocket in order to reduce the volume that needs to be pressurized for this flight (shown in Figure 7). The area above this bulkhead and below the nose bulkhead is empty space for this flight. With the new tube the total height of the airframe is 5 foot 2 inches.

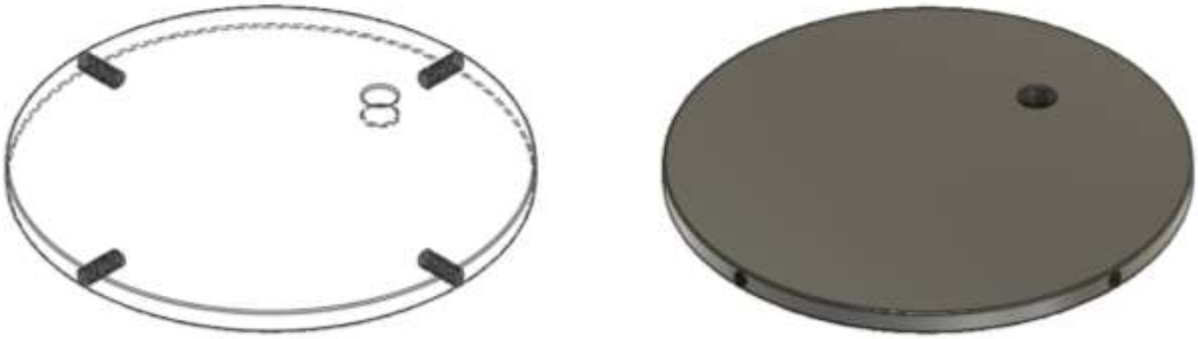


Figure 7 PLA bulkhead for new tube

Nose Cone

The Nose Cone had the most changes made to it for this flight with a total redesign of the avionics sled as well as a new lower bulkhead. The sled redesign was a modification of the previous sled design that allowed for better wire management since the previous sled allowed the wires to hang anywhere. This sled was made to hold the same electronics as the original sled, two stratologger CF and an XBee GPS unit as well as two key switches which were mounted through the new tube. The whole sled was 3D printed in PLA at 80% infill and held the four nine volt batteries within it using two PLA caps to hold them in place. The redesigned sled can be seen in Figure 8.

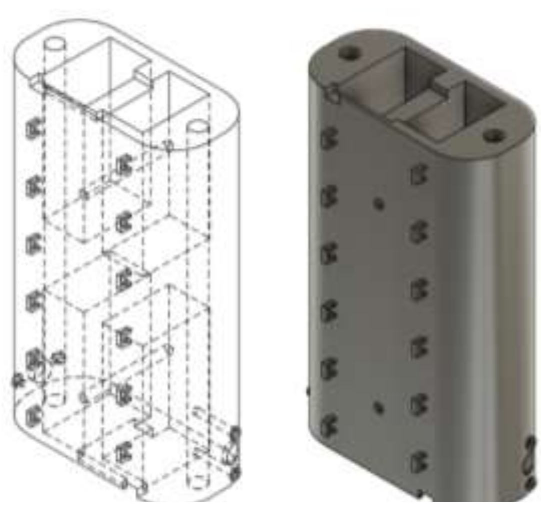


Figure 8 Nose Cone Sled model

Each of the loops seen on the face of the sled were used for zip-ties to help run the wires around the two altimeters and to the ends for the charges (top for drogue and bottom for mains). The two ends each hold the 9V batteries and are capped off with the caps shown in Figure 9.

Figure 9 Nose Cone Sled Cap

This was assembled with the avionics and mounted to the two threaded rods used in the original sled along with two fiberglass plates. The plates were mounted directly to the PLA sled on either side and the avionics and GPS were mounted to the fiberglass plates. The original wooden upper bulkhead was also installed back onto the threaded rods as well as the new aluminum lower bulkhead. The new bulkhead was machined out of quarter inch aluminum alloy 7075 and can be seen in Figure 10.

Figure 10 Aluminum Bulkhead model

This bulkhead was attached with the threaded rods to the ebay sled and utilized the center hole for the charge wires so they could reach the main parachute charges at the bottom on the new body tube. This bulkhead also used the threaded inserts to set in set screws which are used to hold the sled into the nose cone during flights. To aid in preventing any possible shorts on the aluminum a thin PLA disk was printed to go between the aluminum bulkhead and the sled.

Flight Operations

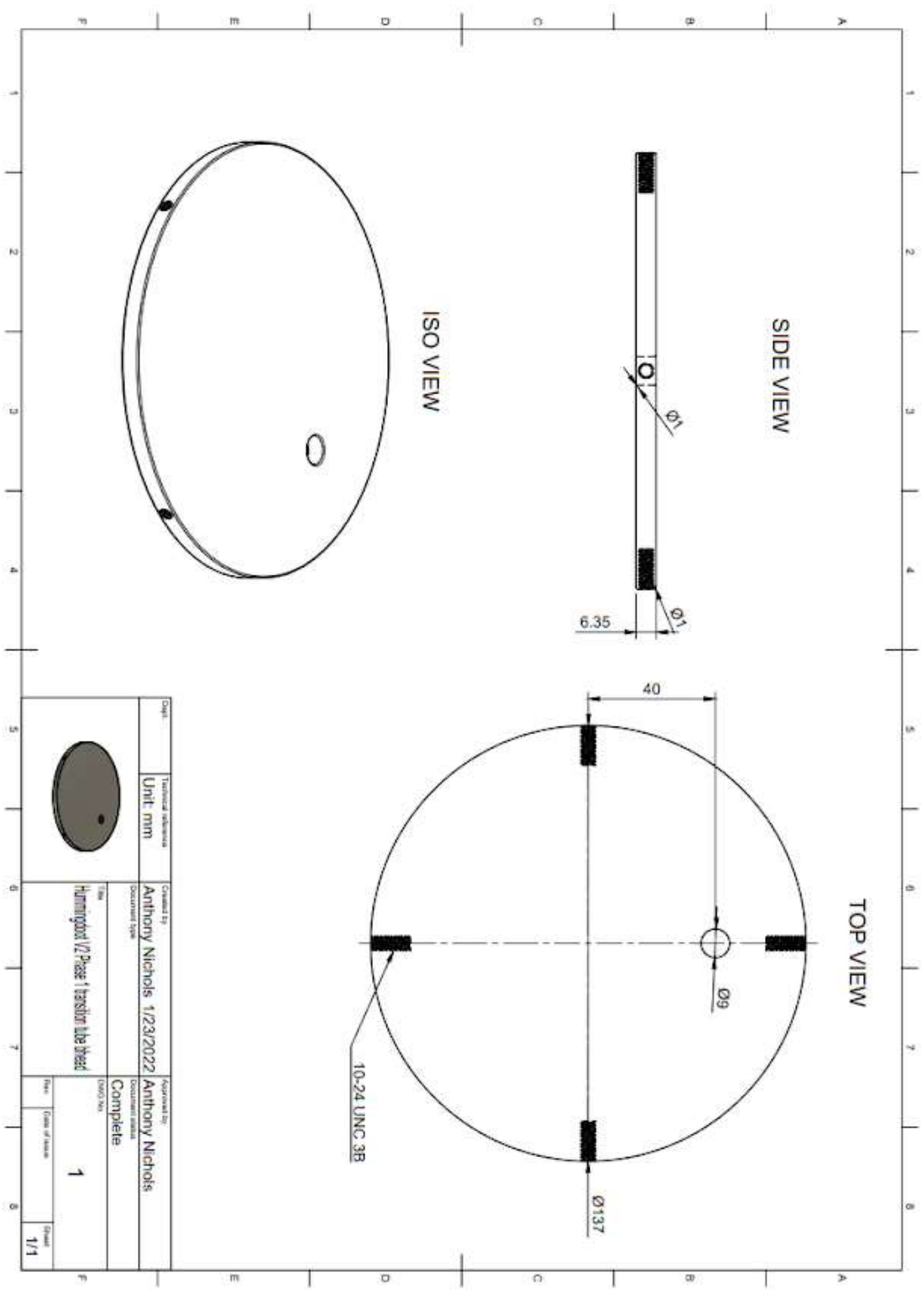
This flight of Hummingdoot V2 had the same objective and flight operations as the previous flight of Hummingdoot V1. The main objective is to successfully deploy a drogue chute and nose cone with a completely successful recovery. All separations were successfully ground-tested.

September 16th Flight Results

The first flight of Hummingdoot V2 took place at an SRA launch in Palm Bay, Florida with a 54mm Cesaroni J760. The ascent of the launch was a very smooth and stable flight and reached apogee with a successful drogue deployment. The vehicle descended under drogue until its nose cone separation point in which the nose cone fully separated successfully followed closely by the full deployment of the main parachute. Both parts of the vehicle landed safely and were completely recovered and marked the first and only successful flight of a Hummingbird vehicle.

What was Learned

Though the flight was successful, a few issues occurred pre-launch and post-launch with the vehicle that needed to be prevented on the full-scale flight of Phoenix. First, during pad operations it was discovered that one of the key switches were aligned with the launch rail not allowing the primary altimeter to be powered on while on the pad. The rocket needed to be removed and brought back to the tent and fixed so that it was no longer an issue. Another issue was that the GPS in the nose cone was not connected to the receiver prior to putting the rocket on the rail. This resulted in a slightly difficult with locating the nose cone post flight. For future flights all key switches were placed to face away from the rail and each GPS would be connected while at the tent.



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Anthony Nichols 1/23/2022
Anthony Nichols
Complete
Hummingbot V2 Phase 1 transition tube thread
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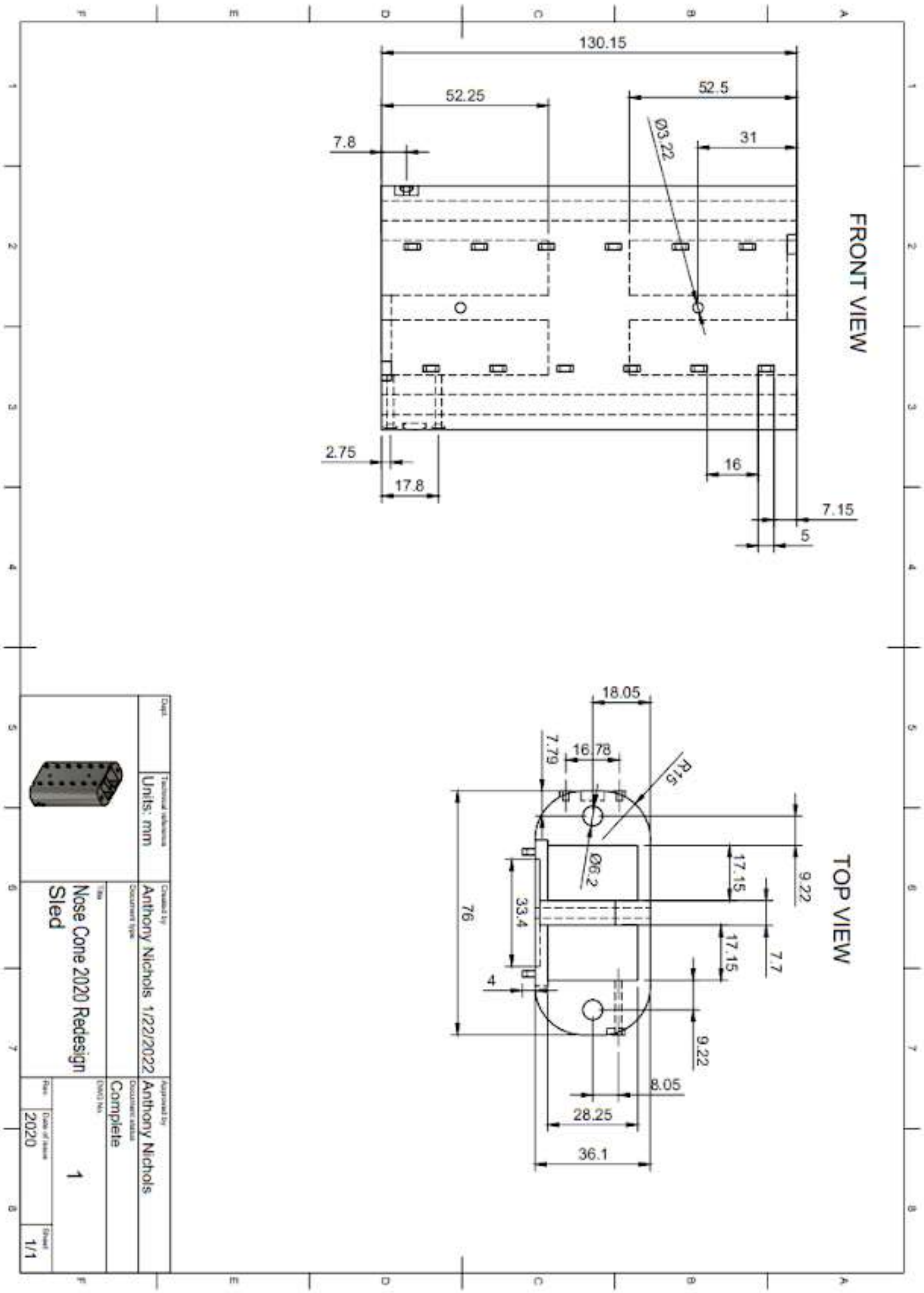

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Units: mm
Anthony Nichols 1/22/2022
Anthony Nichols
Nose Cone 2020 Redesign Sled
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Figure 12 Hummingdoot V2 Phase 2 Main Avionics

Figure 11 Hummingdoot V2 Phase 2 XBee GPS System

Hummingdoot V2 Phase 2

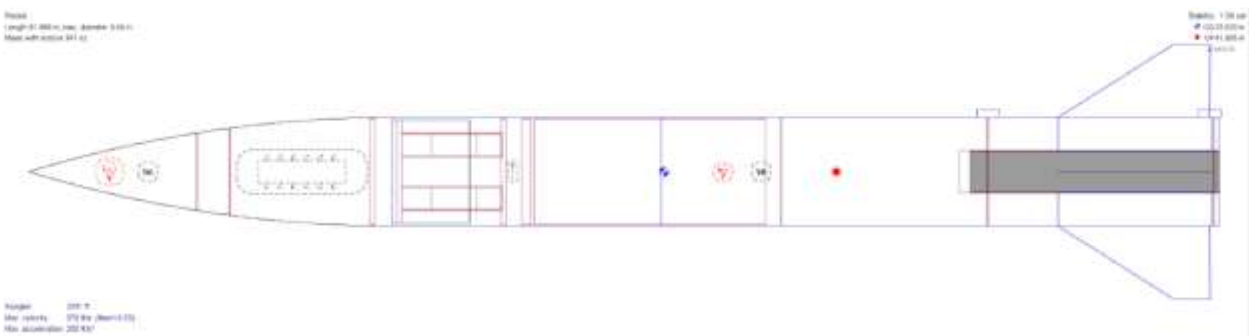


Figure 13 Hummingdoot V2 Phase 2

The second phase of the Hummingdoot V2 vehicle was a launch designed to test a new experimental ejection system. This system was a new piston system that was designed to fit around the rotor hub which allowed the separation of the tubes to free the hub for spinning while also isolating the pressurization of that section of tubing. This was needed because the hub would be sticking through the side of the airframe so when the charges would go off all of the pressure would escape through those holes. This piston system would allow smaller tubes to pressurize and push themselves apart, requiring much less black powder due to the smaller volume. This will be the new separation point, meaning the nose cone will be separating on its own and not with the new tube from phase 1. This required a new avionics bay as well to fire the main parachute after the nose cone separates.

Airframe

The airframe of Hummingdoot V2 Phase 2 was the same exterior as phase 1, but it required a new temporary avionics bay on top of the transition bulkhead from phase 1. This avionics bay was mounted to the top of the PLA bulkhead with an eye bolt. The eye bolt part of the bolt was on the booster side of the bulkhead allowed the bolt to go through the bulkhead and the new ebay holding it in place with a washer and nut. This new avionics sled consisted of two stratologger CF's and 4 9V batteries and is shown in Figure 14,

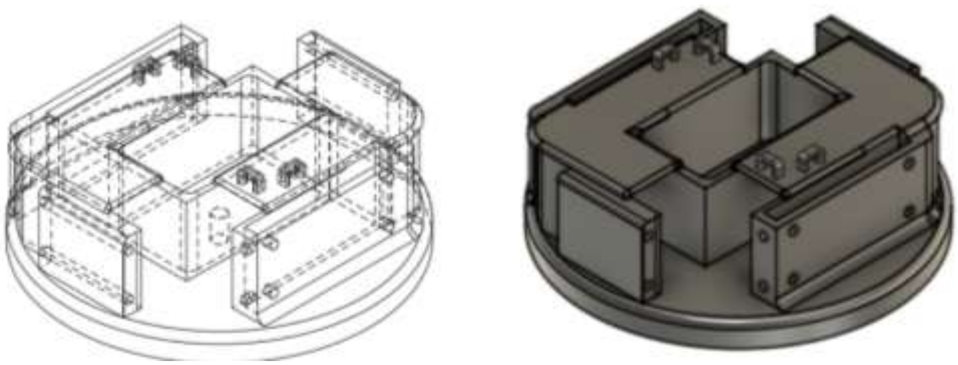


Figure 14 Temp Ebay Model

The final change to the airframe of Hummingdoot V2 Phase 1 is the addition of a new 3D printed bulkhead that has the lower half of the new piston system and is set screwed into the airframe. Each half of the pistons are rolled 29 mm fiberglass tubes that were epoxied into the bulkhead and coupled with a 29 mm blue tube. The lower bulkhead in the airframe was a half an inch PLA bulkhead and can be seen in Figure 15.

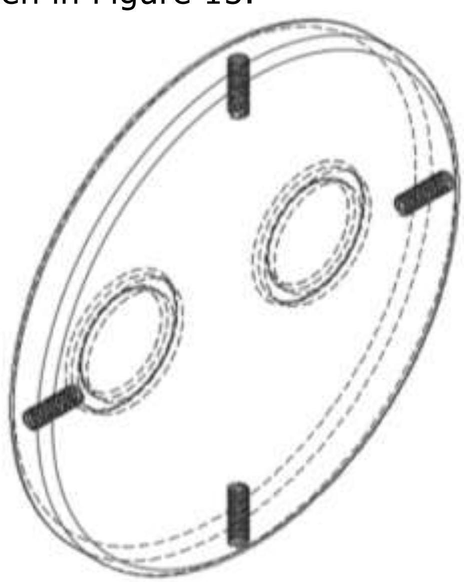


Figure 15 Lower Piston Bulkhead

Nose Cone

The nose cone of this phase of Hummingdoot V2 has only two changes made to it with the addition of the upper piston system mounted to the bottom of the aluminum bulkhead on the ebay and a newer stronger shock cord for the drogue parachute. The shock cord was replaced with bright orange half inch nylon shock cord (22ft) in order to prevent any possible tears during deployment and a longer shock cord to help with descent stabilization. The upper half of the piston system was attached to the aluminum bulkhead by fitting onto the threaded rods that hold the ebay together and being tightened on with a nut and washer. The pistons, like in the lower section discussed in the airframe portion, are epoxied onto the 3D printed mount with the blue tube coupler for them also epoxied into place. This upper bulkhead was a half inch PLA 3D printed oval with spots for the piston tubes to be epoxied similar to the spots shown on the lower bulkhead.

Flight Operations

For the final flight of the Hummingdoot test vehicle several milestones needed to be completed during the flight. For a successful test the drogue parachute needs to successfully deploy at apogee and later the piston system must successfully separate the nose cone from the airframe. For a successful flight the main parachute had to deploy and every part of the rocket needs to be completely recovered. The order of milestones during flight are as follows,

- A successful and stable ascent to apogee
- Successful deployment of drogue parachute at apogee
- Smooth descent under drogue chute

- Successful separation of nose cone from airframe
- Full main Parachute deployment
- Touchdown and recovery

Success of milestones 1-4 deems the tests of the rocket successful while the completion of all milestones deems a fully successful flight. The Con-Ops and additional flight details can be viewed in Figure 16and Table 3,

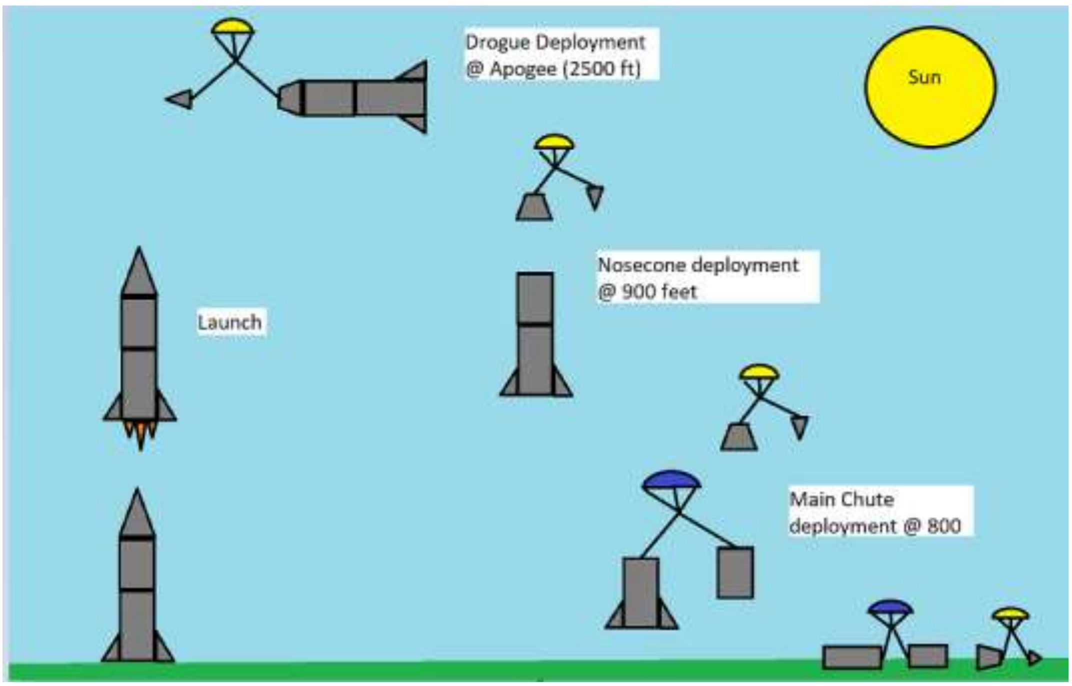


Figure 16 Hummingdoot V2 Phase 2 Con-Ops

Motor	J-760
Empty Mass	7.76 kg
Max Thrust	937.7 N
Stability	1.59
Velocity off 10 ft rail	21.21 m/s
Max Velocity	112.78 m/s
Drogue Chute Charge	2.4 g
Main Chute Charge	3.5 g
Piston System Charge	0.5 g

Table 3 Additional Information

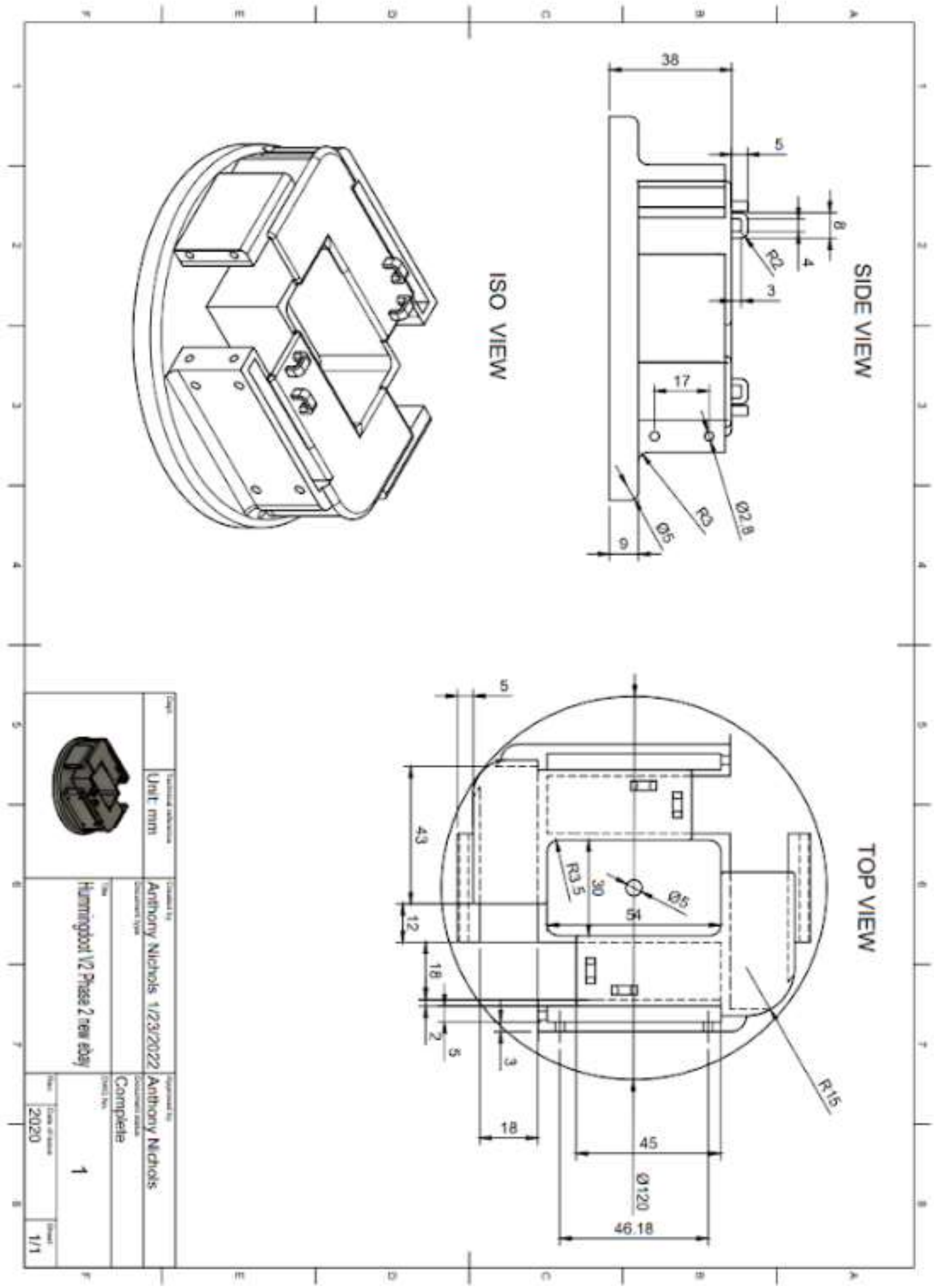
Flight Results

After lift off the vehicle followed a stable ascent to its apogee just over 2,000 feet and successfully deployed its drogue parachute. It then proceeded with a mostly stable descent until a successful piston ejection system. The main parachute also deployed at its designated time but due to a folding error, it tangled and was not able to properly open. The airframe continued its descent into the ground while the nosecone was able to descend under the drogue and land safely.

What was learned

The only take away that occurred from this launch was to ensure that every parachute is properly folded before packing to ensure that no tangles happen during a flight following this.

Additional Documents for Hummingdoot V2 Phase 2


SIDE VIEW
ISO VIEW
TOP VIEW
Unit mm
Anthony Nichols 1/23/2022
Anthony Nichols
Complete
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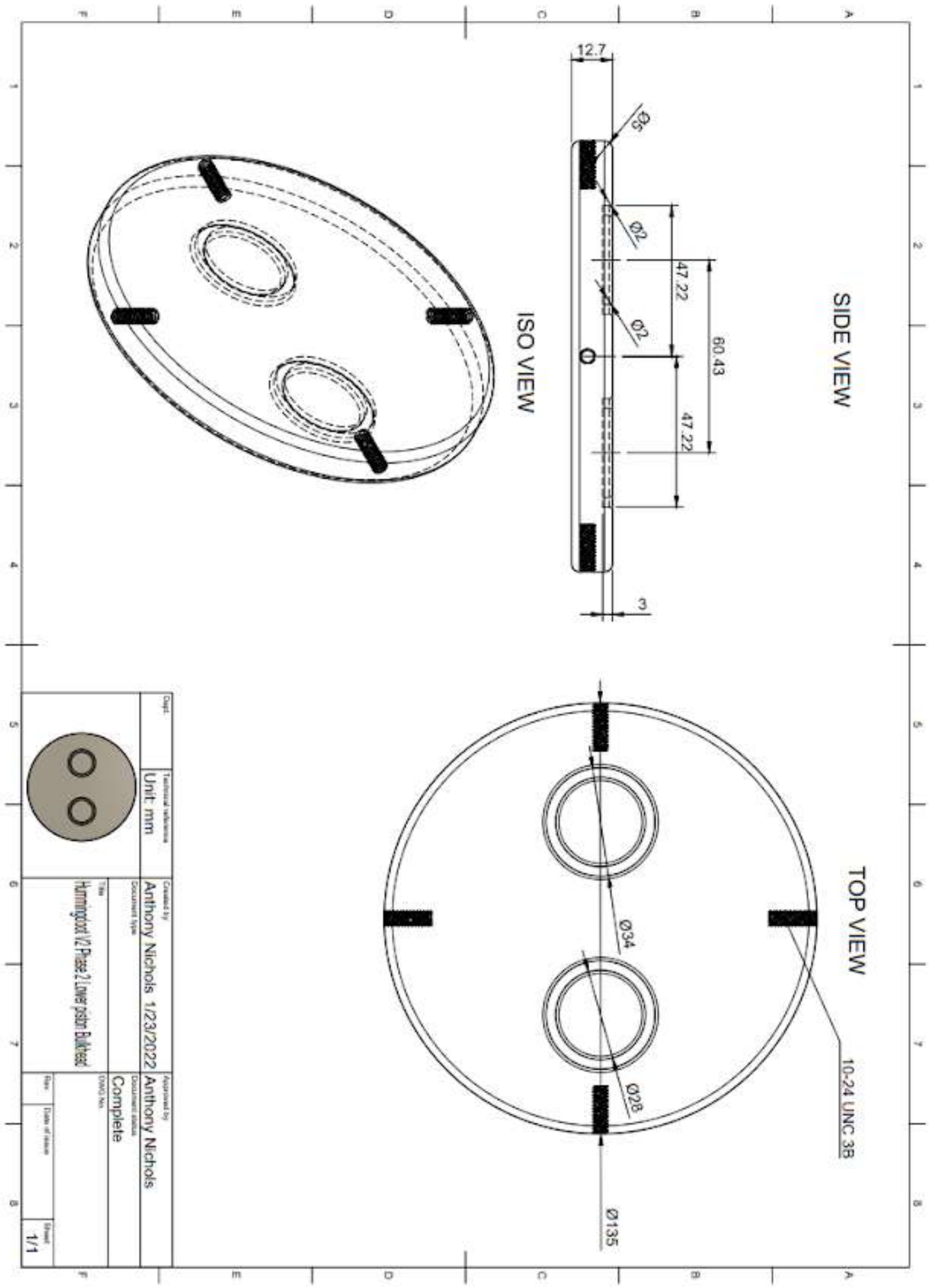
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Hummingbird V2 Phase 2 Lower piston Bulkhead
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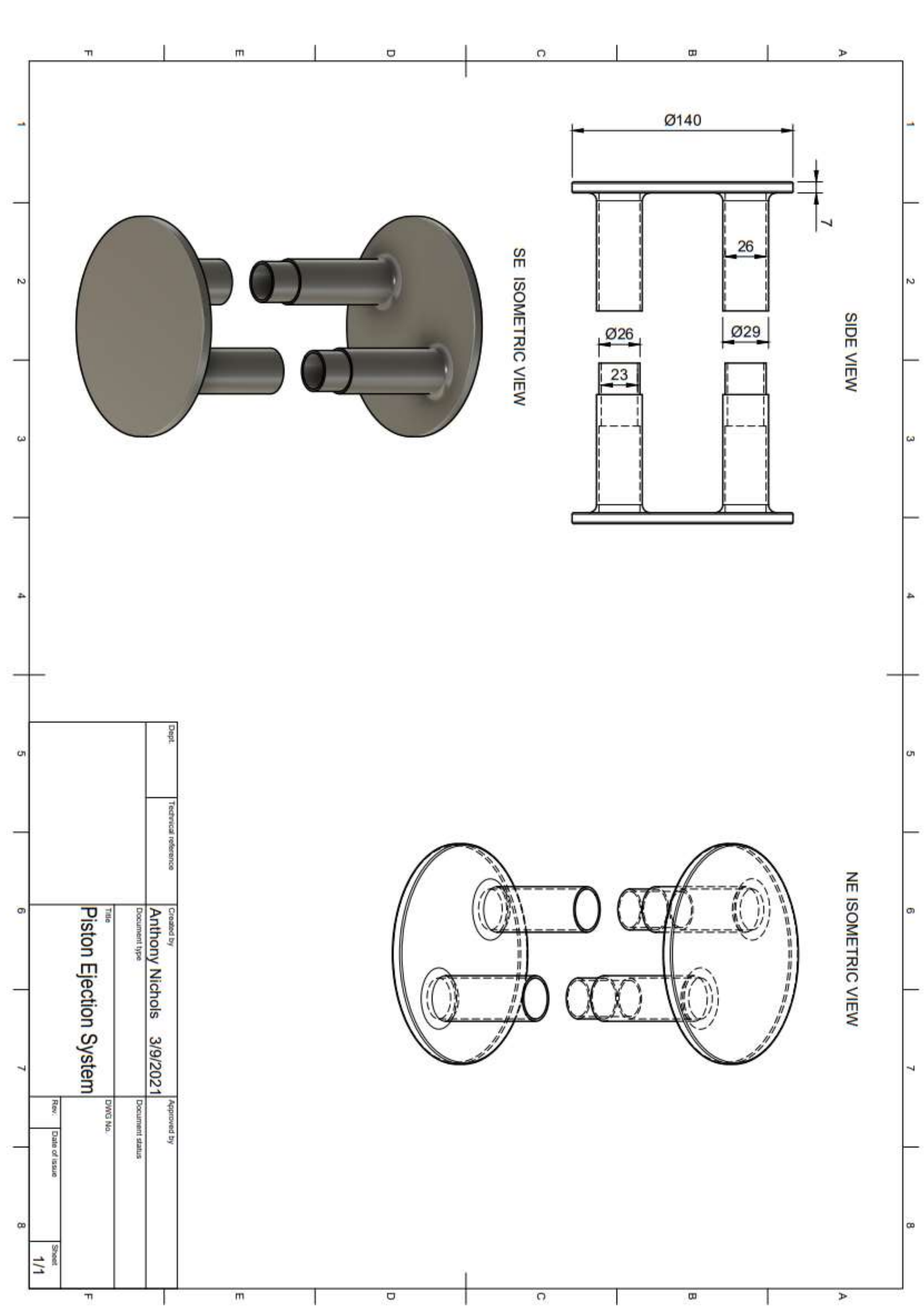
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Created by
Anthony Nichols 3/9/2021
Approved by
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Doot Stick V1

Doot Stick V1 was created in order to help complete smaller scale ground tests to test the autorotation theories of the project. This vehicle was the first iteration and was built in a very crude fashion in order to keep it cheap and quick.

Airframe

The airframe for this vehicle was created by rolling a foam board into a tube and hot gluing it together. Following this a small radio controlled helicopter hub was hot glued into place using a popsicle stick as a stabilizer. To finish it off, several nuts and bolts were duck taped into the bottom of the foam tube to ensure stability by making it bottom heavy. This was needed to keep the blades at the top during descent.

Nose Cone

There was no nose cone for this test vehicle as it would not be flying with a motor.

Flight Test Results

This vehicle was flight tested by simply spinning up the blades slightly and dropping the vehicle off of the third floor of the Lehman building. Multiple videos were taken from the side and above in order to do analysis of the blade spin. The video analysis showed that the hypothesis that the blades would increase in rpm as it descended was correct as the blades had gained spin during its descent.

What was learned

This test has shown us that autorotation is possible for our larger vehicles once rotation begins. Due to the state of the test vehicle and highest point we can drop from, we did not have the ability to drop without rotation as there would not be enough airtime to allow the effect to begin.

There are no additional documents that were recorded for this project.

Doot Stick V2

Doot Stick V2 was the second iteration of the Doot Stick test vehicle and was designed for larger height testing to determine if the vehicle can start rotation on its own. This was designed to be much more refined as well as a directly scaled-down model of the Phoenix flight vehicle.

Airframe

The airframe for this iteration of Doot Stick was made out of a 75mm Blue Tube that was cut in lengths to match a half scaled version of Phoenix. To couple the two airframe pieces together a 3D PLA coupler was made and set screwed into place since there were no separations on this vehicle during flight. The hub was from an Align T-Rex 500X RC helicopter and was installed using a custom made hub mount as shown in Figure 17 Doot Stick V2 Hub Mount.

Figure 17 Doot Stick V2 Hub Mount

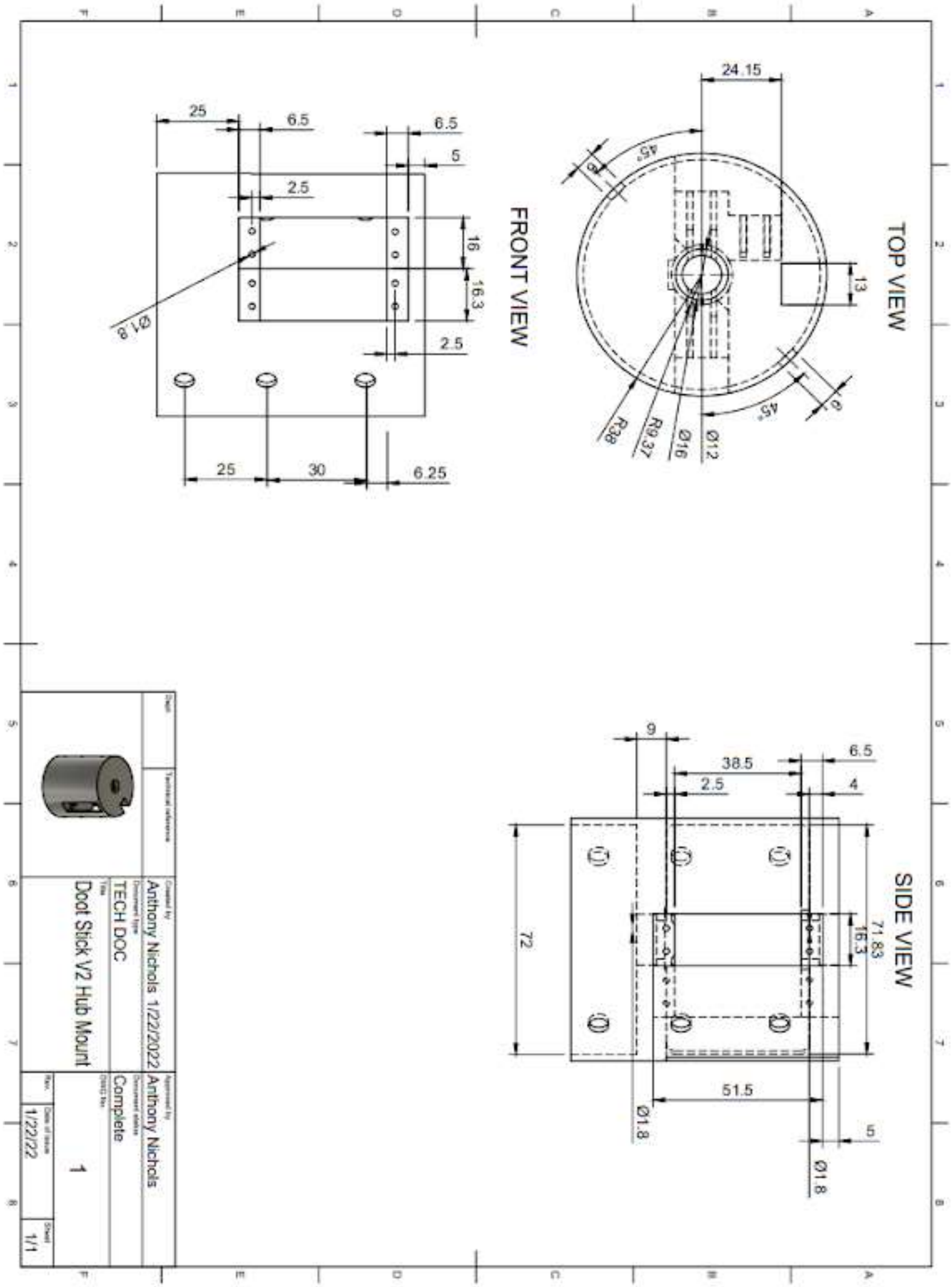
Nose Cone

There was no nose cone for this vehicle due to it not flying with a motor.

Flight Results

There is no flight test data for this vehicle as after it was finished, construction of the project was halted in order to finish and prepare Phoenix for its Flight Readiness Review (FRR) and launch in November. Now that the project has come to an end the vehicle will not be used for any further testing.

Additional Documents for Doot Stick V2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Phoenix

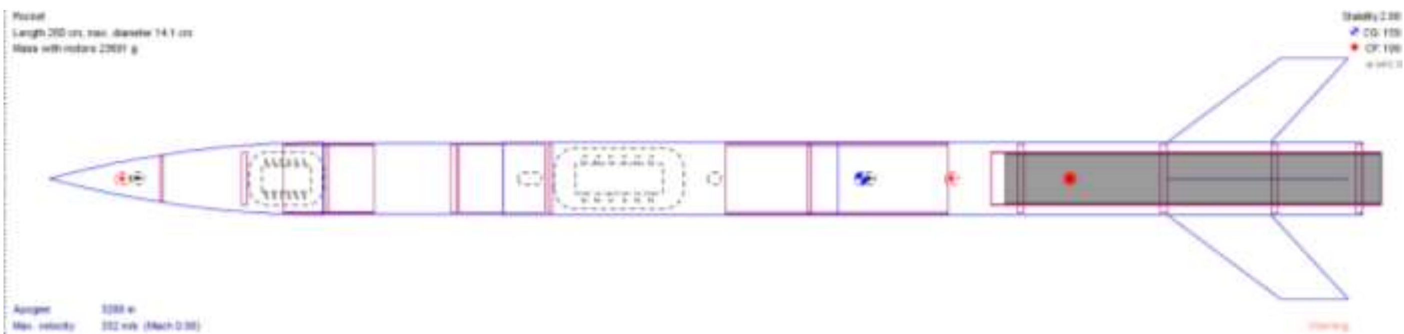


Figure 18 Phoenix OpenRocket

This is the final vehicle that was made by this project following the loss of the Hummingbird 1 launch vehicle. This airframe utilized parts of Pathfinder VIII in order to help cut the costs of building a new airframe. Other than the airframe itself, every system in the vehicle was made from the ground up with all new electronics, parachutes, and the same nose cone used on both Hummingbird 1 and the Hummingdoot flights. This vehicle, like Hummingbird 1, was designed to have the hub and rotor blades integrated into it following the success of the first test flight. The implementation of all successfully tested systems from the Hummingdoot program was completed over the course of two years, with very small changes made to them so that they fit into the airframe. The biggest addition to this vehicle was the addition of the Data Acquisition System (DAQ) which was made by the Hummingbird avionics/DAQ team along with vast amounts of help from Project Cerberus. This vehicle had also been the first of the Hummingbird vehicles to have a completely airbrushed livery made using stencils and an airbrush.

Airframe

The booster and lower body tube of Phoenix were repurposed from the older Pathfinder VIII rocket. The booster tube was rolled fiberglass that had slits for the fins, which were ¼ inches thick, made from carbon fiber between layers of fiberglass. They were then mounted through the body tube, connecting to the motor mount. Internal fillets were made on the motor mount tube, and external ½ inches fillets connected the fins to the outer fiberglass tube. The team also repaired a small hairline fracture in one of the external fin fillets by sanding away the cracked portion of the fillet, re-epoxying it, and sanding it flush with the older, non-cracked portion.

The motor retention system in the airframe was permanently installed into the main body tube using four centering rings and epoxy. It was made from a fiberglass tube that had 4 wooden ½ inch centering rings around the outer diameter of the tube, which were epoxied to the tube it. These centering rings had an outer diameter matching the inner diameter of the body tube and were epoxied to the body tube with one at the bottom, one at the top, and one just above and below the fins. At the bottom of the motor mount tube, located at the bottom of the rocket, was the aluminum motor retainer which was bolted to the bottom bulkhead. This whole assembly was permanently fixed to the airframe body tube with epoxy.

The lower body tube which housed the main avionics bay was also sourced from Pathfinder VIII. It was also a rolled fiberglass tube. This tube was attached to the main body tube using a blue tube coupler that was screwed into this tube and used shear pins to connect to the booster. This tube had an aluminum bulkhead with a U-bolt in the center to which the main parachutes were attached. The bulkhead was machined by Bill out of aluminum 7075 alloy. This bulkhead was secured using 4 set screws that screwed directly into the bulkhead through the fiberglass and blue tubes. This tube housed all experimental systems that test the theories of the project.

The transition tube sat under the nose cone and was a rolled fiberglass tube made for Phoenix. It housed the upper piston and charges for the separation mechanism, with the lower portion housed in the body tube just below it. Other changes include the addition of a new 8ft main parachute as well and 27 feet of half inch nylon shock cord which is attached to the U-bolt and the eye bolt attached to the top of the motor casings forward closure.

Nose cone

The nose cone that was used on Phoenix is the nose cone that was used on every airframe since Hummingbird 1 and has very little changes made between the last Doot and Phoenix.

The new hardware inside the nosecone consisted of a 15-inch chute protector and an aircraft plug used to connect the ebay to the nose cone charge wires in an easier fashion than running the wires on site. There was a primary charge of 2.4 grams and a redundant charge of 2.6 grams to separate the nosecone tip and deploy the drogue. Also, at the top of the nose cone there was a newly machined washer made 7075 aluminum. This washer was put into place in order to reinforce the wooden bulkhead that was epoxied into the nose cone just below the cut so that the eye bolt connected there could not pull through the wood. There were two 1 gram charges in the piston system connecting the transition tube to the main body tube to help fully separate the nosecone from the main body to help with blade deployment during a bladed flight.

Figure 19 Nose Cone Drogue System

The avionics in the nose cone are all the same from previous flights and consist of the 2 stratologger CF's and the XBEE GPS. A new upper bulkhead that was 3D printed out of PLA was added to house the new aircraft plug for charge connections. Finally, the fiberglass tube that was placed over the sled was removed as it served no purpose and added unnecessary weight to the top of the airframe.

Main Avionics

The main avionics on Phoenix was a similar system to what was on Hummingbird 1 but in a much more thorough and complex way. The main sled consisted of the flight altimeters for main parachute deployment as well as the Data Acquisition system (DAQ) for post flight analysis. The DAQ was planned to become a control system as well to control the hub and blades during a bladed flight.

This electronics bay is designed to fit within the upper body tube of the airframe and be mounted just below the lower piston system bulkhead, which is supposed to be the hub bulkhead in a bladed flight. The ebay consists of two 10 inch by 5 inch ¼ inch thick fiberglass plates that are mounted using 3 3D printed PLA mounting blocks. The blocks have holes that were used to run a threaded rod through which held the entire sled together and to the airframe. The plates are then mounted to these blocks and secured with nuts and bolts which are all secured with blue Loctite and then tightened. The threaded rods were then passed through the aluminum hub bulkhead (Figure 20) into the piston tubes and secured using a washer and nut with Loctite.

Figure 20 Aluminum Hub Bulkhead

The bottom of the threaded rods went through a 1/4 inch PLA 3D printed bulkhead that housed the FeatherWeight GPS, holes for charge wires, and set screws to attach to the airframe directly which was also secured in place using a nut and washer. The FeatherWeight GPS Transmitter was mounted to the PLA bulkhead using standoffs with a dedicated spot for the battery to be stored (Figure 21). Both of the bulkheads were designed to secure to the airframe using set screws to ensure that there was as much support on the system as possible as during a bladed flight the hub and blades would have been directly connected to the upper aluminum bulkhead.

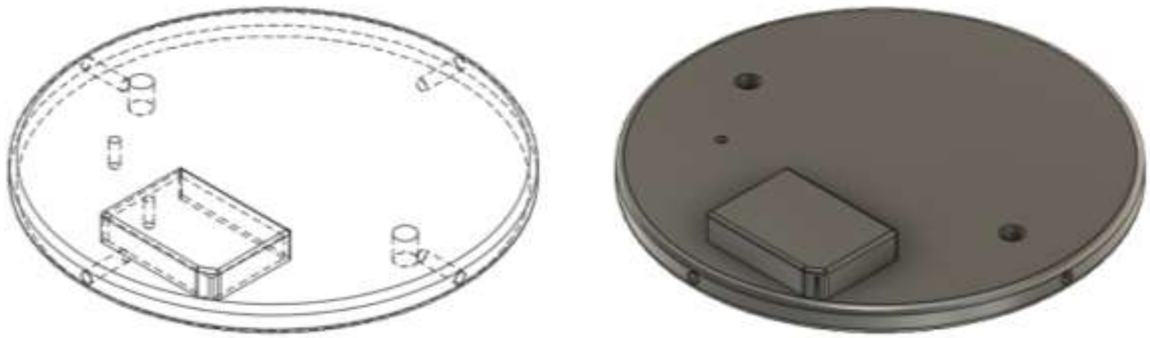


Figure 21 Main Avionics Lower Bulkhead

The holes for the main parachute charge wires were drilled in place after printing of the bulkhead. Key switches were also utilized to power both the altimeters and both DAQ's separately which required a key switch mount. The decision was made to make two identical mounts (Figure 22), one for each side of the sled, so that 4 large holes were not needed in the side of the airframe right above one another. This mount was capable of holding two key switches and mounted to the fiberglass plates using nuts and bolts.

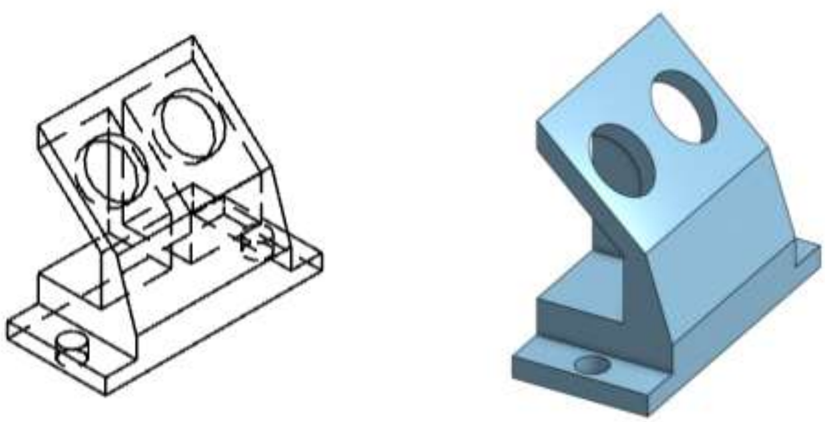


Figure 22 Key Switch Mount

All of the electronics were mounted to each fiberglass sled using standoffs and the batteries have their own mounts discussed in the coming sections.

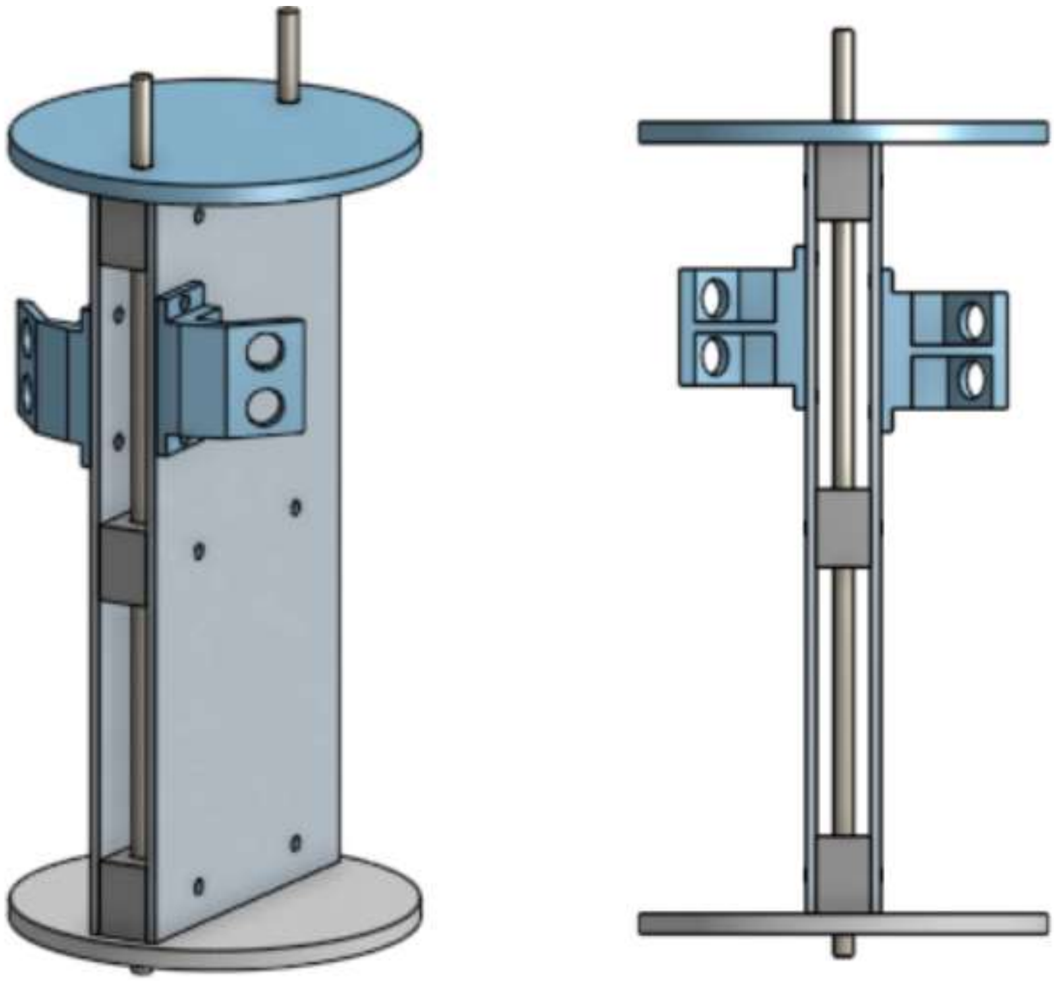


Figure 23 Ebay assembly without electronics or upper and lower bulkheads

The flight altimeter side of the sled consists of two FeatherWeight Raven 4 flight altimeters with their own Lithium Polymer (LiPo) 1500 mah two cell battery. There are two for redundancy as main parachute deployment is a priority for safety and recovery of the rocket. Each altimeter uses their own battery as added redundancy in case of an event where a battery disconnects, dies, or simply cannot put out the necessary voltage to fire the charges. This allows one altimeter to still work if one of the batteries are no longer operational. The batteries for this side of the sled are mounted using a custom 3D printed PLA double battery mount (Figure 24) that is attached to the sled using nuts and bolts.

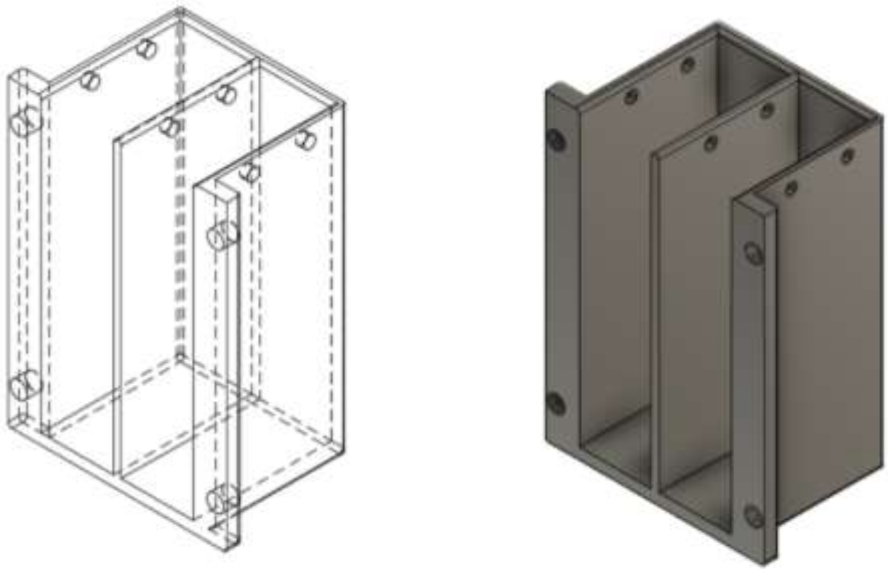


Figure 24 Altimeter Side Battery Mount

Using the holes on the forward opening of the battery holder allowed the use of zip ties to secure the batteries into place while also allowing for removal. The completed flight altimeter side of the ebay can be seen in Figure 25.

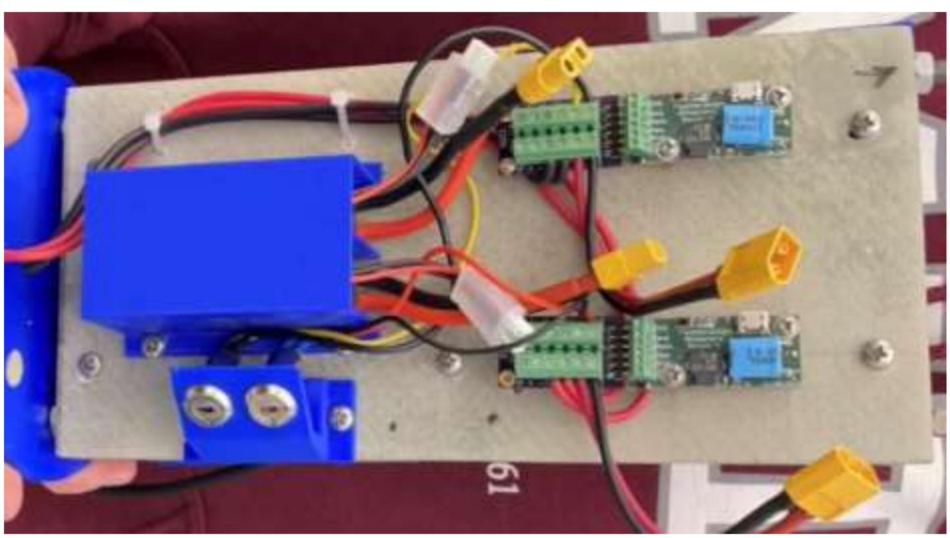


Figure 25 Assembled Avionics side of Ebay

Each Raven altimeter on the sled also is using a terminal extension to allow for the use of larger charge wires, and better connections. Each altimeter had power connected to it through a plug that plugged directly into a LiPo battery, and the key switches were wired directly to the designated switch terminals. Finally, the charge wires were connected to the *Main* terminals and ran out the bottom of the sled. Holes were drilled into the fiberglass along the wire path in order to utilize zip ties for wire organization.

The Data Acquisition side of the sled is much more crammed and complicated due to the number of components that had to be fit on it. On this side there are two DAQ's for as much data recovery as possible, and the team had the extra components to do so. The components in the primary DAQ were a Teensy 3.6 microcontroller, a BMP280 pressure sensor breakout, and a 9 Degree of Freedom (DOF) Inertial Measurement Unit (IMU) breakout which would be soldered to solderable breadboards and wired practically due to lack of knowledge and time for creating a custom PCB. These breadboards were then mounted to the sled using standoffs. The secondary DAQ was made of the same components except for a 6 DOF IMU breakout. The two Teensy's were then powered by a single LiPo that goes through two separate power regulators that dropped the 7.4 volts down to a usable 5 volts which was provided by Project Cerberus. Each system was activated using key switches which were mounted using the key switch mount shown in Figure 22. The LiPo battery on this side was mounted using a different battery mount which was also 3D printed in PLA and mounted using nuts and bolts, Figure .

All breakouts and Teensy's purchased from Adafruit

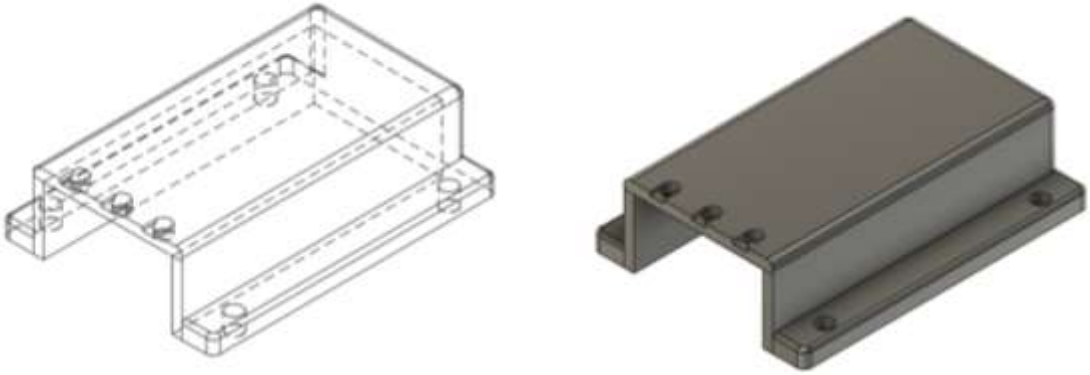


Figure 26 DAQ LiPo battery mount

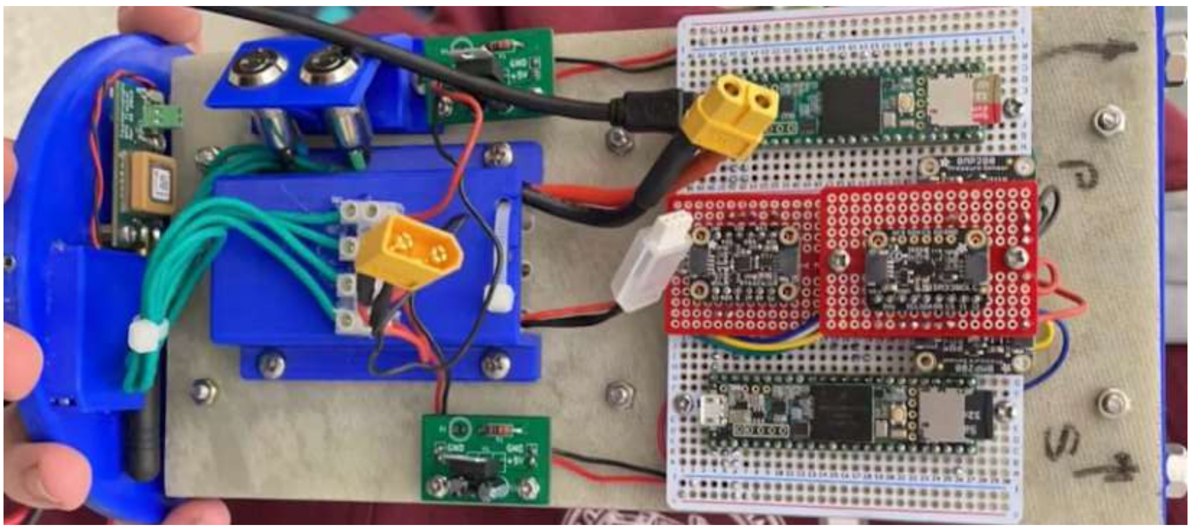


Figure 27 Assembled DAQ side of Ebay Sled

The DAQ itself had many unique decisions that were made during its development process and were very insightful on how to properly log and save a live data feed. For the wiring of the DAQ a communication protocol needed to be selected and the team decided to use Serial Peripheral Interface (SPI). This was chosen due to its ability to run multiple sensors on “buses” allowing for less connections being needed. Each sensor could share a Data in, Data out, and Serial Clock (or Miso, Mosi, and SCK) while needing their own individual Chip Select (CS) and power.

The code for the DAQ also took several iterations for it to be operational and allow proper recording of the target data. The iterations worked through coding in the Arduino IDE using the example codes provided in the libraries for each component. The final code also implemented a launch detection section that actively read the acceleration from the IMU and once this passed 3G's the data will begin logging onto the SD cards. This was put into place in order to not fill the SD cards (32Gb Class 4) while sitting on the pad and risking not getting any of the wanted flight data. The code for each DAQ is the same except for the included libraries due to the secondary DAQ having a different IMU than the primary DAQ. Additional information for the DAQ can be found in Table 4 and both the Primary and Secondary Codes can be found in the additional documents at the end of the section.

Primary and Secondary	Teensy 3.6
Primary and Secondary	BMP 280 Breakout
Primary 9 DoF IMU	ICM200948
Secondary 6 Dof IMU	ISM330DHCX

Table 4 Additional DAQ Information

Flight Operations

During the flight, Phoenix would need to complete six key tasks to prove itself as a viable vehicle to test the rotor descent system.

- First, the rocket would need to ascend to apogee (10,000ft) in a stable orientation.
- At apogee, Nose Cone must deploy the drogue parachute.
- The vehicle must continue a stable descent under drogue.
- The nose cone would separate at 1,000 feet.
- The main parachute would deploy at 950 feet.
- The rocket would then safely touch down and would be recovered.

At apogee, the tip was meant to separate from the base of the nosecone pulling a drogue chute out. There was a redundant charge 1 second after apogee. The airframe was supposed to descend under drogue until around 1050 feet with a redundant separation charge at around 1,025 feet where the nose cone and transition tube would separate from the rocket with two 1-gram charges in a piston system to isolate the pressure as in a full experimental flight there would be two holes in the airframe for the hub to go through allowing normal charge pressure to vent. The Con-Ops of this flight can be viewed in Figure 28 Phoenix Con-Ops, and any additional flight data can be viewed in Table 5.

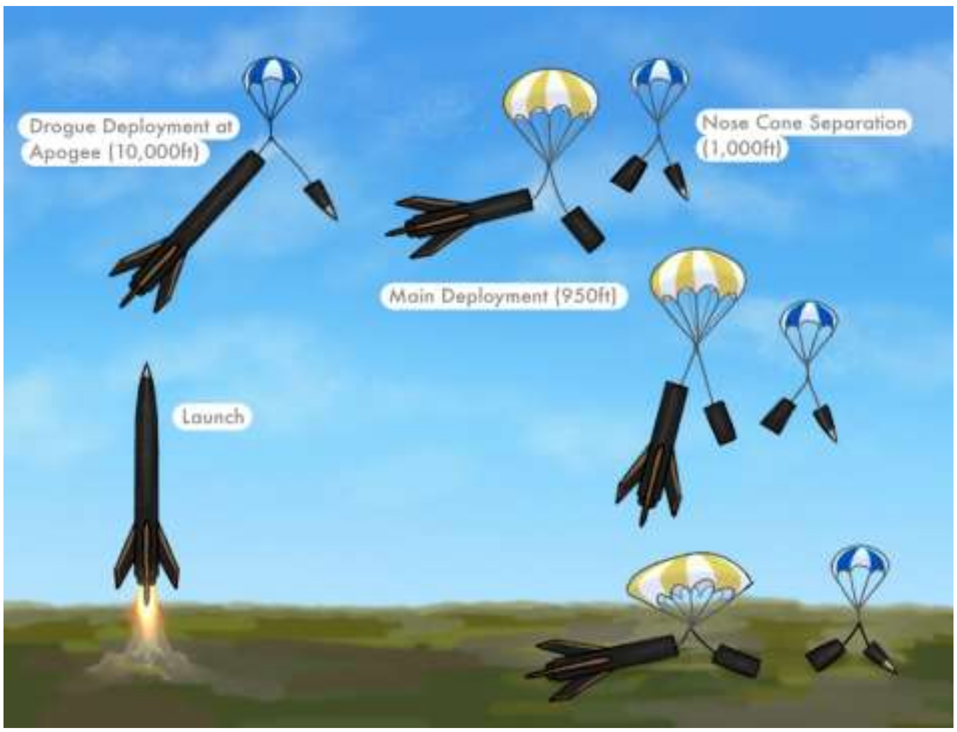


Figure 26 Phoenix Con-Ops

Motor	M2000-R
Wet Mass	24.5 kg
Burn Time	4.5 s
Max Thrust	2327 N
Stability	2.88
Max Velocity	Mach 1
Drogue Chute Charges	2.4 g and 2.6 g
Main Parachutes Charges	3.4 g and 3.7 g
Piston Charges	1.0 g and 1.0 g

Table 5 Additional information

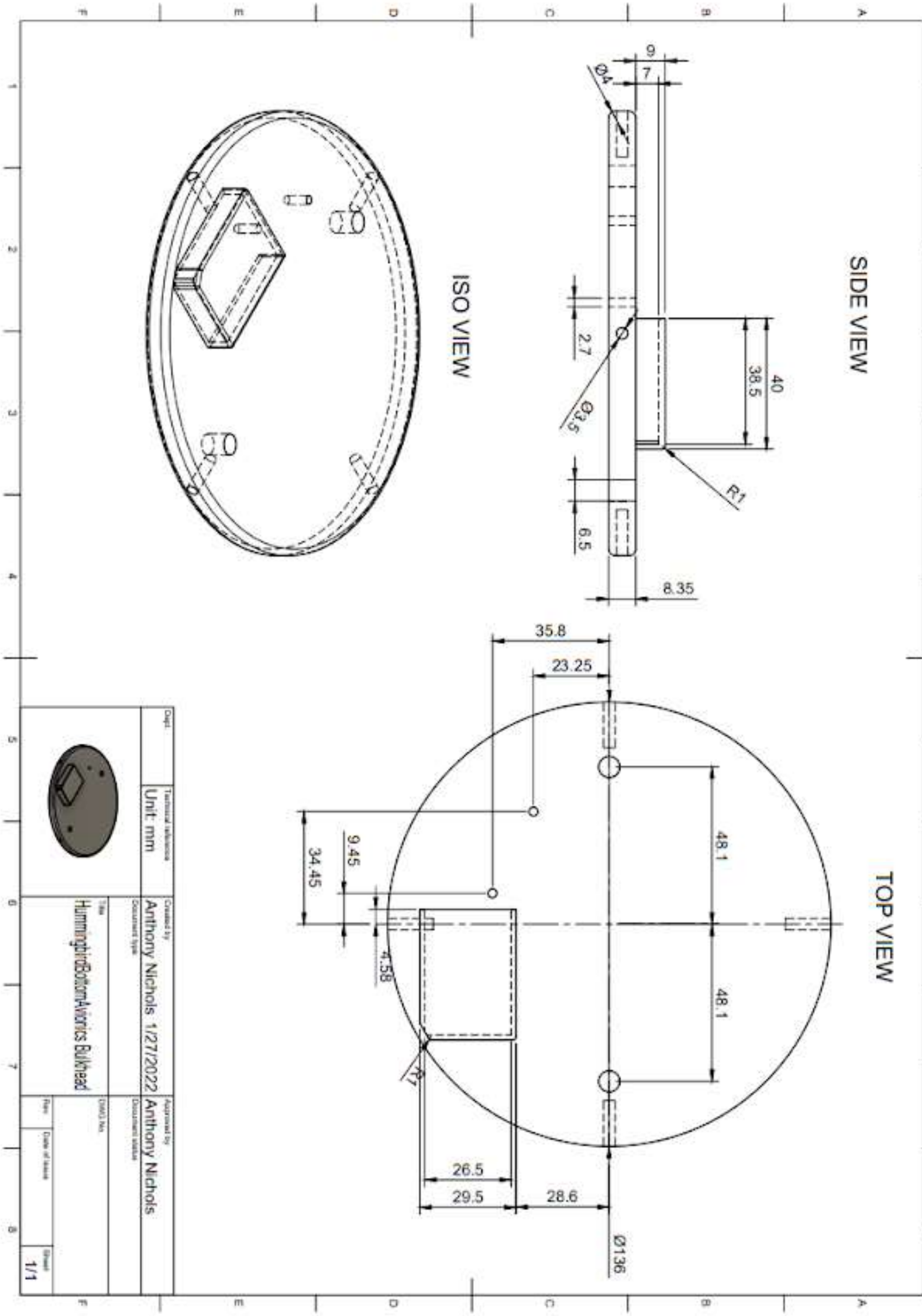
January 15th, 2022 Flight Results

The day of the launch was a very clear day with minimal 5-10 mph winds with no clouds in the sky. The vehicle left the pad in a very stable fashion with no wobble or deviation until a critical error that occurred with the nose cone about 3-4 seconds into the flight. The nose cone tip was torn off on ascent just at the end of the motor burn. Since the drogue chute is located in the tip of the nose cone, the drogue deployed during ascent when the tip came off and immediately sheared the shock cord connecting it to the rest of the rocket. The rocket then proceeded to apogee while still being stable and the drogue deployment event was witnessed on the ground with a large puff of smoke. Due to no drogue chute being present, nothing was deployed and the rocket promptly arched over and continued its descent ballistically. Once it reached the main deployment altitude the main was able to successfully deploy despite the speed of the airframe but tore through the connection points on the airframe. The shock cord connected to the forward closure ripped on deployment and the other end pulled the aluminum bulkhead that was in the airframe out. The main chute inflated and drifted off and landed somewhere unknown while the rocket body also landed in a field in Palm Bay and has yet to be recovered. The drogue chute also drifted to an unknown location. As of 2/21/22 the only parts of the airframe to be located in the tip of the nosecone.

What Was Learned

No parts of the vehicle were able to be recovered post flight so no in flight data was recovered. DAQ data as well as video data would have been a massively useful tool for post flight root cause analysis as to why the nose cone failed. The prevailing theory is that the vehicle had flown much faster than it should have. The motor purchased for this flight was a mistake due to a flawed simulation model and was going to be pushing the vehicle to Mach 1. The nose cone, though has been flown many times, ws never flown to Mach 1 or even in the transonic region. This leads the team to believe that the nose cone tip could not handle the speeds and air flow going over it causing it to be pushed off of the rest of the nose cone and causing the flight failure.

Additional Documents for Phoenix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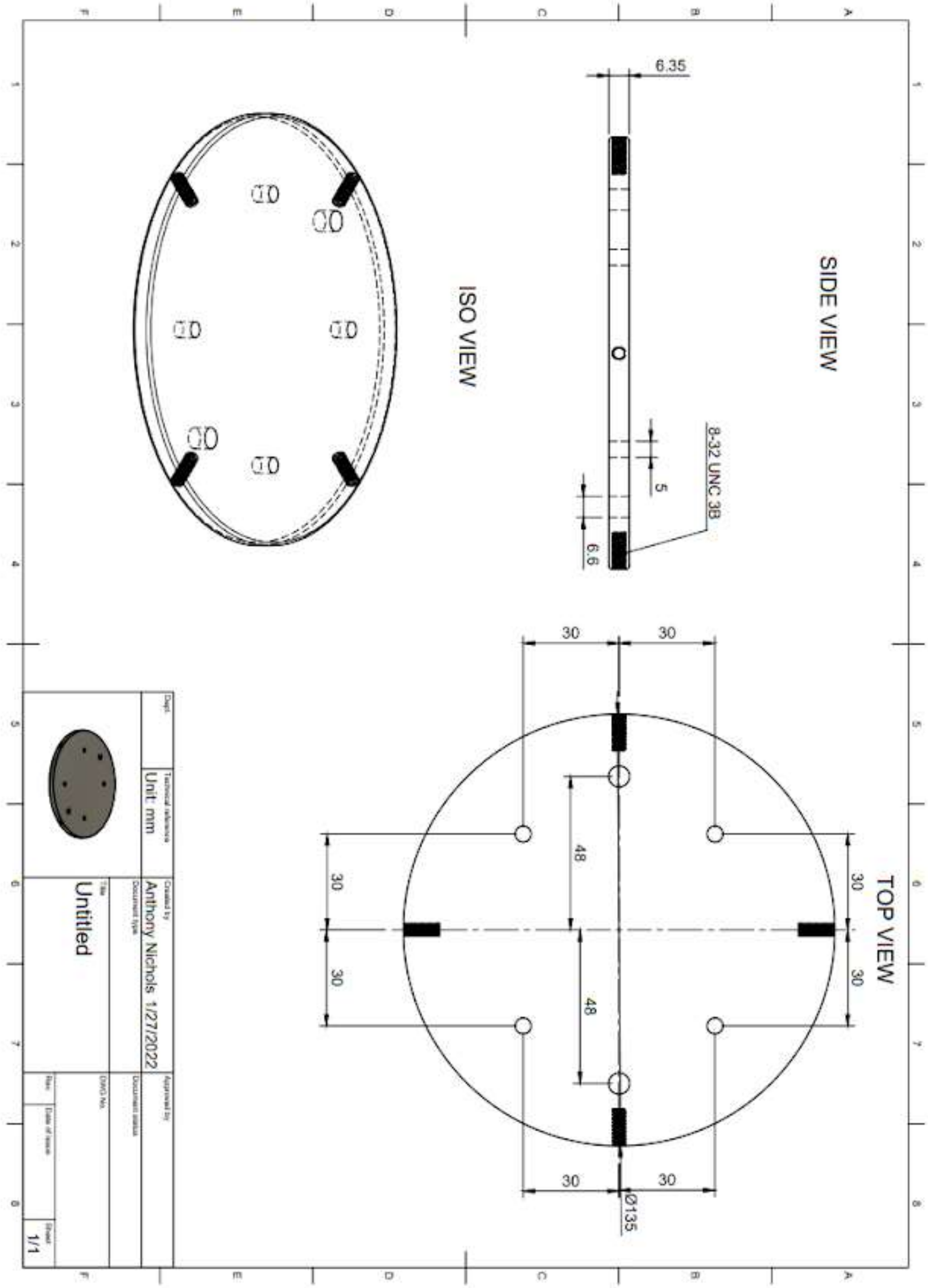
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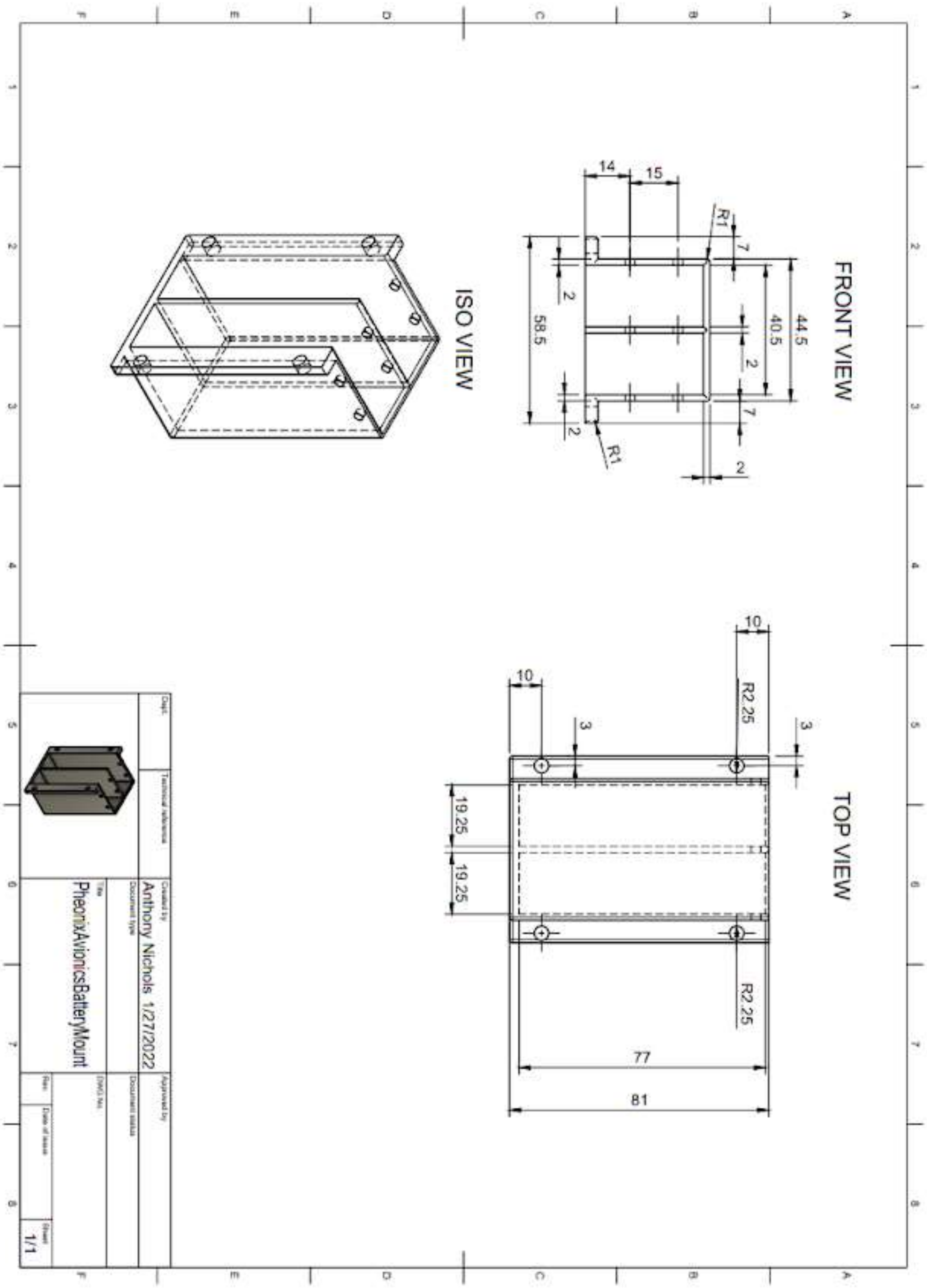
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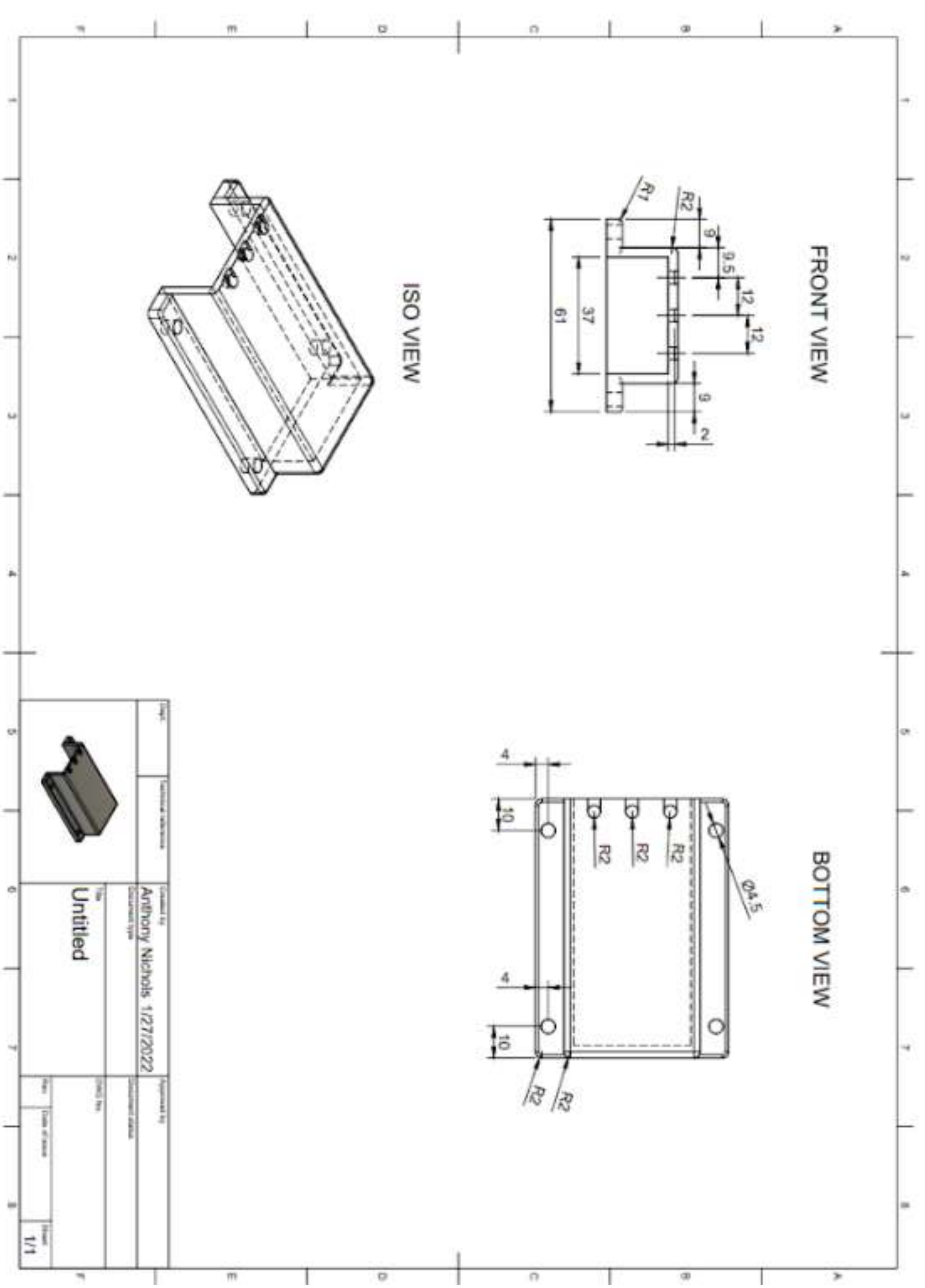
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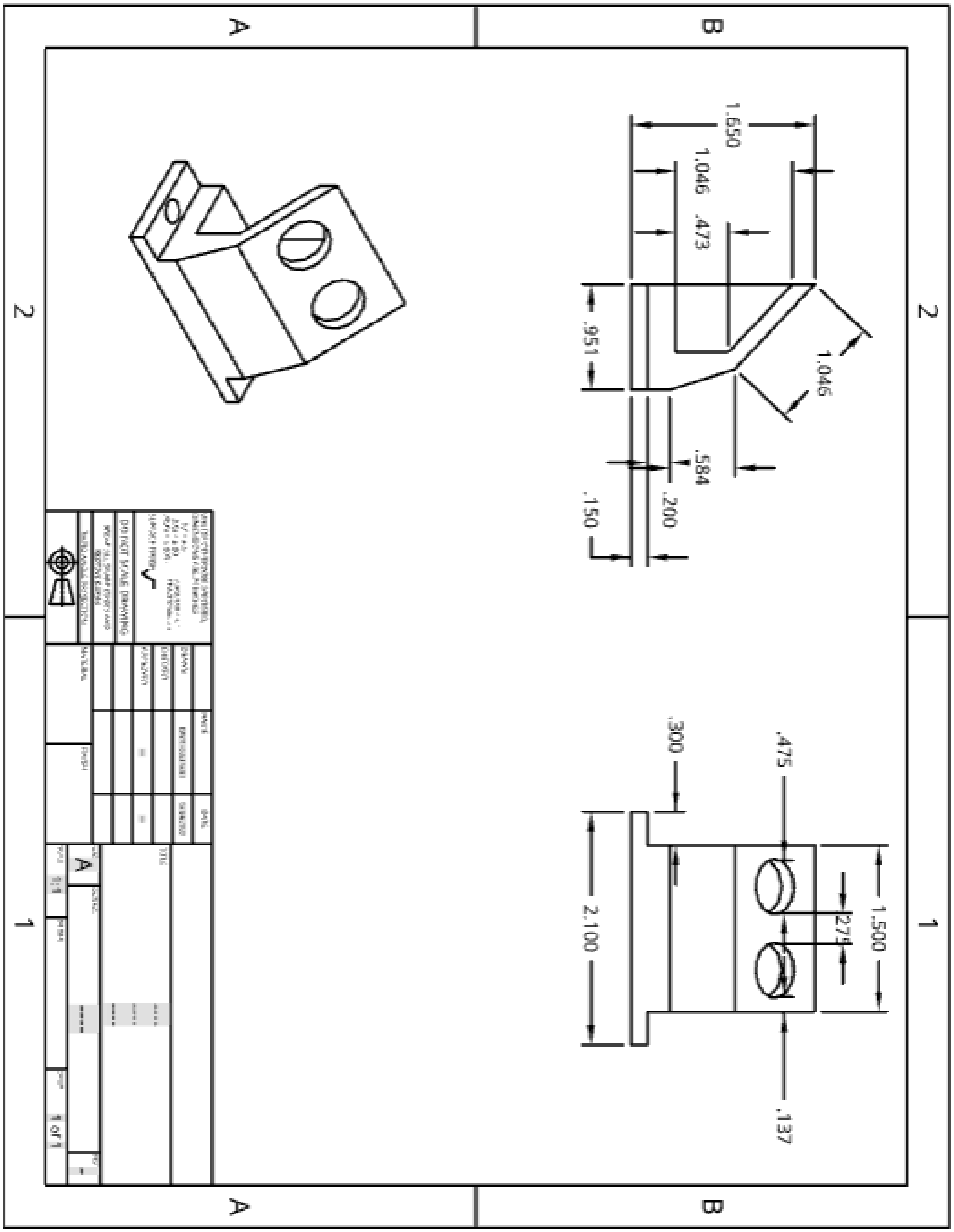

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Reason For Project Closure

Project Hummingbird is no longer continuing due to the loss of its second full-size vehicle *Phoenix* during its flight on January the 15th of 2022. The project itself was started in 2016 and lost its first flight vehicle *Hummingbird 1* in the fall of 2018 during its test flight due to a drogue parachute failure. The following years were followed with test vehicle flights, a pandemic that halted work for a while, and eventually the loss of *Phoenix*. The project has been around for six years, one of the longest-lasting projects, and has led to very little data being collected for the actual scope. It was determined that the loss of the latest vehicle would be the perfect stopping point as another airframe would cost the club a substantial amount of funding and more room needs to be made for new projects to help the club expand. The ending of this project was a unanimous agreement between X-team and the project team lead. Project Hummingbird's official last meeting was January 28th 2022.

Conclusion

Throughout the last six years the project has been able to do a substantial amount of testing and construction on multiple different airframes as well as several flights. Though the project was never able to achieve its goals and complete the scope it was able to provide a learning experience that allowed its members to prepare for industry. High detail Standard Operating Procedures (SOP) became a standard as well as testing all aspects of the vehicle prior to a flight. A more in-depth design should have been made and all possible issues should have been considered as several design decisions made in the past were poorly thought through and led to many failures throughout the project's life.

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https://shop.bigredbee.com/products/brb900-transmitter

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