Clemson Rocket Engineering Project Technical Reports for the IREC

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Abstract

CU Later is the Clemson Rocket Engineering (CRE) team's entry into the 10,000 foot Commercial Off The Shelf (COTS) category of the 2023 Spaceport America Cup. This past year, the CRE team has had the most growth since its foundation in 2016. CU Later is building off CRE's successes in the 2022 competition, and aims to have more advanced, stand out features. The retention of the motor, avionics, and payload systems have been completely redesigned from the 2022 entry in order to achieve a simplified assembly process. CU Later will have a single ejection for both drogue and main parachutes, with a Tender Descender releasing main at 1,000 feet above ground level (AGL). The avionics will be running two student research and designed (SRAD) raspberry pi boards in addition to COTS avionics. This year's payload is in collaboration with NASA Langley Research Center's effort to release Close-In Covert Autonomous Disposable Aircrafts (CICADAs) via rockets. The team has designed its own small aircraft designated the Clemson Rocket Innovative Cruising Kit for Environmental Testing (CRICKET) and plans to release this aircraft near apogee to collect data on the weather. This technical report is a representation of the CRE teams's work done thus far for the 2022-2023 Spaceport America Cup Competition

I. Introduction

A. Mission Statement

The Clemson Rocket Engineering (CRE) team is the largest aerospace engineering organization at Clemson University. CRE is fully student led and gives students from any major the opportunity to design, build, and launch high power rockets. Since our inception in 2016, the main objective of the team has been to compete in the Spaceport America Cup each year. The team reached many milestones for the 2022 Spaceport entry, including being the 6th team to launch, fully recovering the rocket with no damage, having only a 2.7% error between the simulated apogee and actual apogee, and having fully student made composite body tubes (carbon fiber and fiberglass). Building off these successes in the 2022 competition, the team has strived to make a more advanced rocket for the 2023 competition.

While the Spaceport America Cup is the team's main priority, CRE strives to expand the knowledge of rocketry and aerospace engineering to each member of the team and the surrounding community. There are many ways the team tries to accomplish this; The team had a certification launch day in October 2022, where 22 members attempted their Level 1 certification flight through Tripoli and NAR. This allowed new members to get immediate hands-on experience with rocket engineering, and taught them important terminology which was used throughout the rest of the year. The team also helped to organize and host the second annual Rocketry of the Southern Stars (ROSS) Exposition. This launch in South Carolina allows teams across the nation to test out their Spaceport competition rockets before the competition, and connect with other rocketeers at different universities. Lastly, the CRE team participates in STEM events with local elementary schools and engages in different STEM and art focused programs at Clemson University. CRE wants to inspire the next generation of rocketeers and the team is dedicated to spreading STEM and art awareness.

B. Team Structure

This year, our team has 78 active dues paying members, the highest the team has ever had. The team is split into four different sub teams: Avionics, Flight Dynamics, Payload, and Structures. In addition to the sub teams, the CRE team sponsors internal research and development (IRAD) projects. This year, the Active Aero team is the sole IRAD project being funded. Each sub team and IRAD team has one or two leaders (depending on members' situation with internships and cooperative education). Along with these leaders, the officer title includes the two Managers (the Community Outreach and Safety Manager) and the Business Team. The upper leadership of the team consists of the President, Vice President, Chief Engineer, and Treasurer. The Chief Engineer, Vice President, and Treasurer oversee the Sub/IRAD teams, Managers, and Business Team, respectively. The President oversees the Vice President, Chief Engineer, and Treasurer. While the CRE team is fully student lead, there is a faculty advisor at the head who aids with paperwork and budget allocation. The hierarchy of the team is illustrated in Table 1.

<table>
<tr><td></td><td colspan="4">Faculty Advisor</td></tr>
<tr><td rowspan="2">Upper Leadership</td><td colspan="4">President</td></tr>
<tr><td>Vice President</td><td colspan="2">Chief Engineer</td><td>Treasurer</td></tr>
<tr><td>Officers</td><td>Managers</td><td>Sub Team Leads</td><td>IRAD Leads</td><td>Business Team</td></tr>
<tr><td></td><td></td><td colspan="2">General Members</td><td></td></tr>
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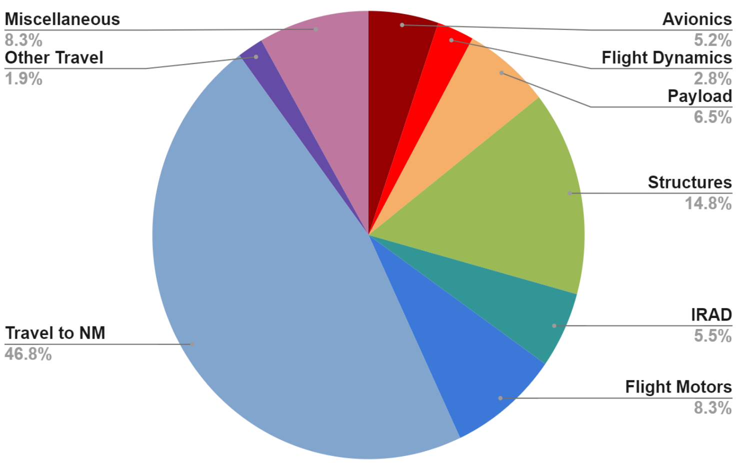
Table 1 – Clemson Rocket Engineering Hierarchy Chart

C. Budget

The CRE team was initially allocated $9,999.08 at the start of the 2022-2023 school year. Through two appeal processes, team member dues, undergraduate research funding, and the College of Engineering Computing and Applied Sciences (CECAS) sponsorships, the team was able to raise the total budget to $38,053.88. Fig. 1 shows the allocation of the total budget among the different subteams, and towards the trip to the Spaceport competition.



Avionics	$1,900.00
Flight Dynamics	$1,000.00
Payload	$2,350.00
Structures	$5,371.06
IRAD	$2,000.00
Flight Motors	$3,000.00
Travel to New Mexico	$16,982.82
Other Travel	$700.00
Miscellaneous	$4,750.00

Fig. 1 - Budget Analysis

II. System Architecture Overview

A. Introduction

The team has elected to compete in the 10k COTS category for the 2023 Spaceport America Cup entry. The main reason for this decision stems from the budget restrictions the team faced at the beginning of the school year. Having extra parts from the 2022 entry would allow us to repurpose those parts and save money on materials.

Due to the successes of the 2022 rocket, similar design principles were maintained, while overhauling many of the internal systems. The standout features for CU Later include revised manufacturing techniques, different material utilization, improved avionics systems, and a deployable payload mechanism. Improved manufacturing techniques for composite body tubes include a layer of woven peel ply to the exterior of the mandrel to improve adhesion of epoxy to the interior of the tube. As a result, the woven peel ply process produces more consistent, circular rocket airframes, and eliminates airframes becoming stuck to the mandrel. Other improvements include precision cut parts, including new carbon fiber and fiberglass bulkheads, which are cut with a waterjet, which lighten the weight inside the rocket. Additionally, the novel avionics bay securing system improves over last year's design by eliminating exterior fasteners and allows for much simpler integration. Finally, in collaboration with NASA Langley Research Center, the payload team has created a launch mechanism that deploys a small aircraft which collects data on humidity, temperature, pressure, and GPS coordinates. A full mission flight profile is discussed in Section III, Mission Concept of Operations Overview and can be viewed prior to Section II.

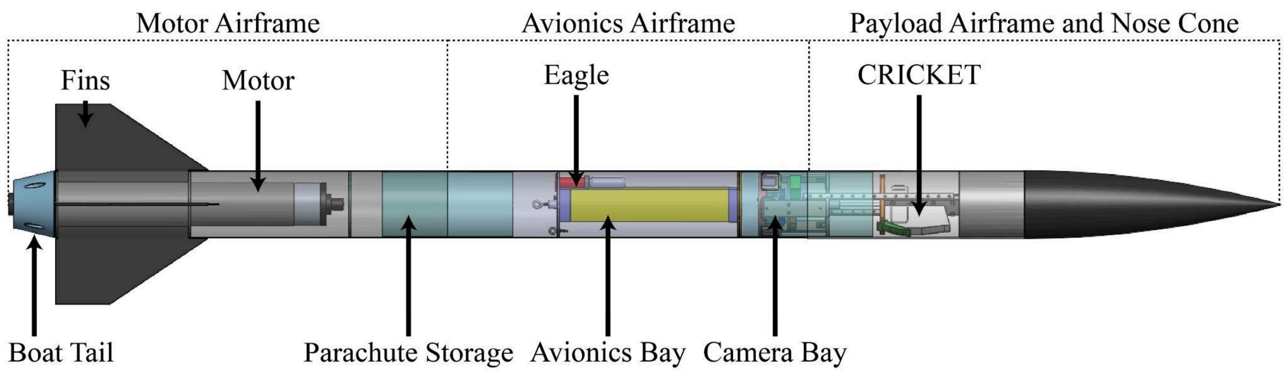


Fig. 2 - Full Rocket CAD

B. Airframe and Structure

1. Motor Airframe

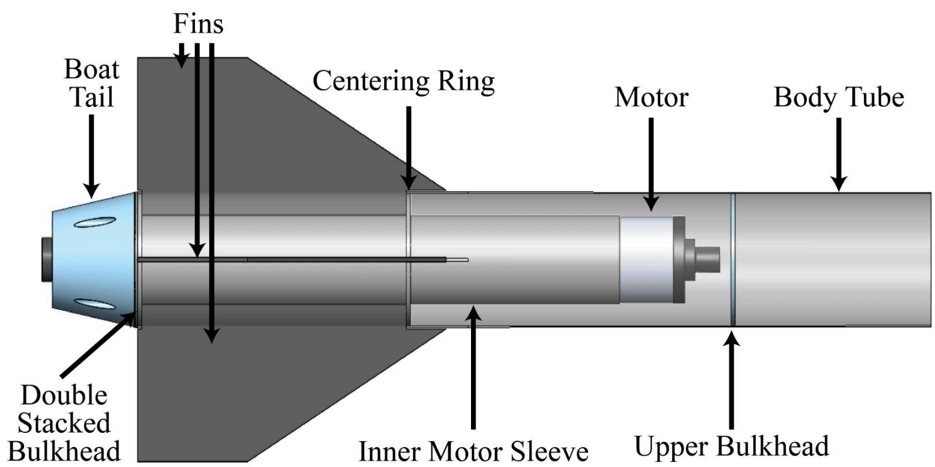


Fig. 3 - Motor Airframe CAD

The motor airframe, or motor tube, serves as the point of attachment for the motor, the fin system, and lower parachute attachment. The motor tube consists of an inner motor sleeve that acts as the main attachment point for the fins and motor. The inner motor sleeve consists of a double stacked bulkhead at the bottom end as a lip for the outer motor tube to sit on, the 4 fins, a pair of epoxy dams on either side of each fin, and the upper centering ring. Both tubes are constructed out of 4 wraps of carbon fiber resulting in a wall thickness of 0.048 in and the bulkheads, centering ring, and fins are water-jet out of 0.197in carbon fiber plate. The fins, epoxy dams, and bulkheads are secured to the motor sleeve with G5000 epoxy. The motor sleeve and fin assembly, as seen in Fig. 4, then fits into the outer motor tube via slots on the end of the outer motor tube. West systems 105 epoxy makes up the fin filets and secures the entire assembly permanently into the motor tube. An additional bulkhead is secured with G5000 into the motor tube above the entire assembly. The upper motor tube bulkhead serves as the mount for the parachute connection eyebolt. A boattail mounts to the rear bulkhead and also serves as the motor retention device.

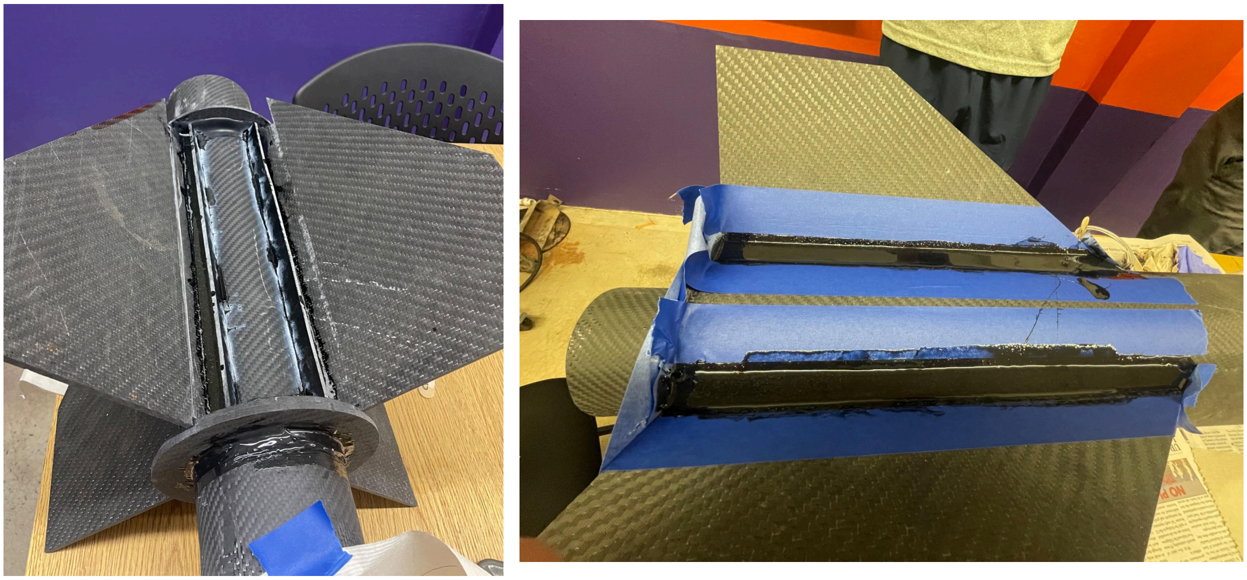


Fig. 4 - Motor Sleeve and Fin Assembly (Left). Outer Motor Tube Fin Fillets (Right)

2. Avionics Airframe

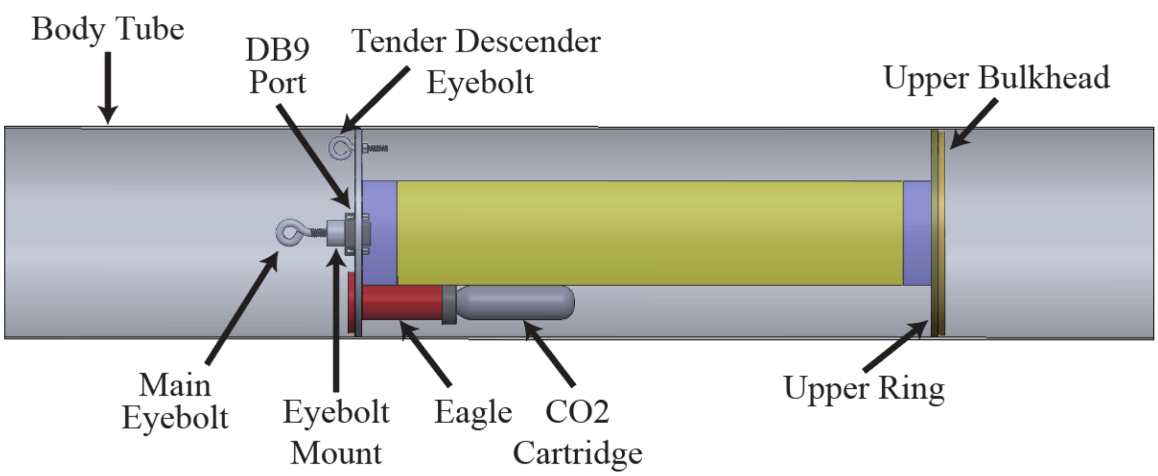


Fig. 5 - Avionics Airframe CAD

The avionics airframe, or avionics tube, houses the avionics bay, serves as the upper parachute attachment, and interfaces with the payload tube and the camera bay. The avionics tube is constructed of 4 wraps of fiberglass. Fiberglass was deemed the best material due to its RF transparency which allows for consistent long-distance telemetry and data transmission.

In order to allow a quick assembly of the avionics tube, the team improved how the avionics bay is mounted to the tube. Our past avionics tubes have used screws mounting through the composite material into each bulkhead. The result of multiple individual screws is high stress concentrations at the attachment points, and difficulty during assembly due to the avionics tube not being a highly rigid structure. It was determined to have two bulkheads epoxied in the tube. The upper is a ring made of fiberglass with an inner diameter of 4.65in, allowing the avionics bay to pass through and attach to the bottom bulkhead using the originally designed and manufactured eye bolt mount. The eyebolt mount has both male and female threads. The male side screws into the bottom of the avionics bay, so when the bay is lowered down through the ring, the casing of the female threads can slide through the hole in the bottom bulkhead. With the innovation of the eyebolt mount, the upper eyebolt can now be screwed in (used as the upper parachute attachment) into the eyebolt mount; this effectively frees up more room on the bottom bulkhead for the ejection system components.

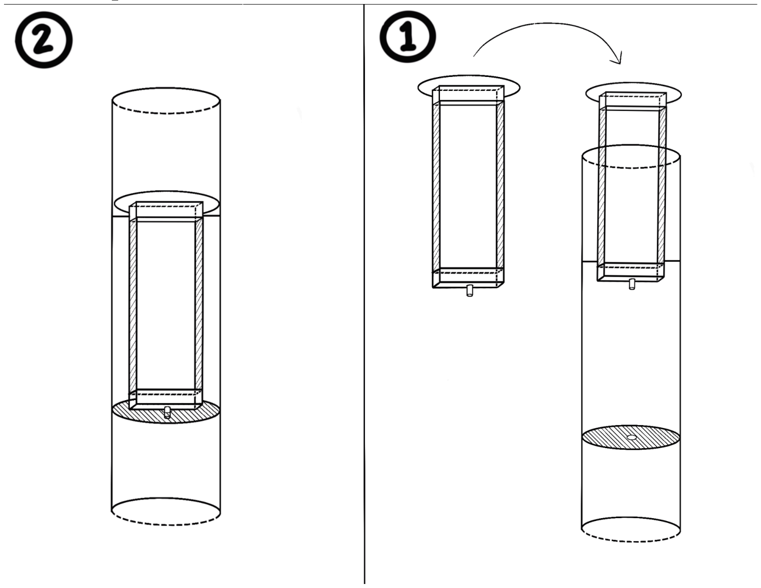


Fig. 6 - Assembly Diagram of the Avionics Bay

In order for the avionics bay to fit through the upper ring, it must be confined to fit through the inner diameter of 4.65in. The bay is made up of two fiberglass plates (where all the avionics components are attached), two plate mounts, and an upper bulkhead. The upper bulkhead is attached to the upper plate mount, and when the bay is lowered through the upper ring, the upper-bulkhead will overlap with the upper ring allowing them to be attached together with threaded inserts and screws. The plates will be parallel and 2 inches apart; they will be screwed into the mounts at the ends. The bottom mount will have the eyebolt mount screwed into the bottom.

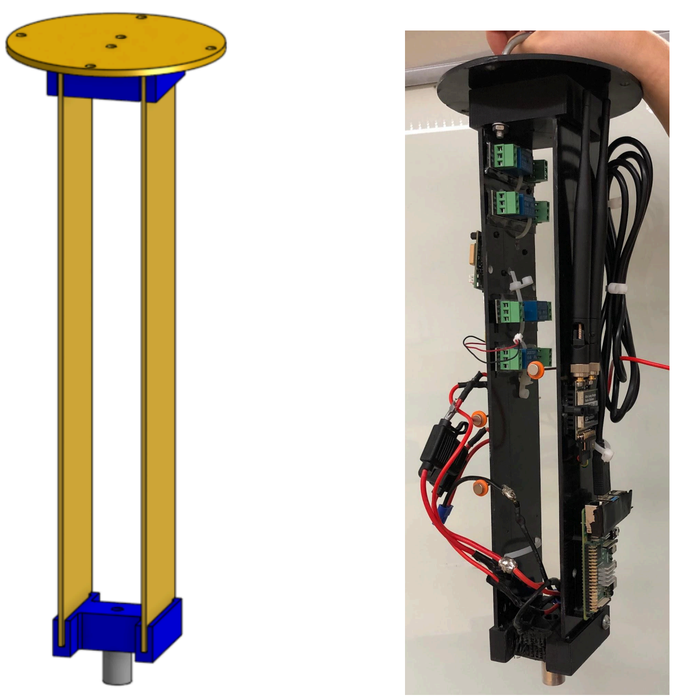


Fig. 7 - Avionics Bay CAD (Left). Avionics Bay Manufactured (Right)

For the manufacturing of the bulkheads and the avionics bay. The bulkheads are both secured to the tube with G5000 epoxy, carefully spaced to share the load of the avionics bay and the 600N force caused by the parachutes. The avionics bay comprises two sheets of 0.118in fiberglass plate, two 3D printed ASA mounts, and a fiberglass upper bulkhead water jetted from a 0.118 in plate. The bottom bulkhead is carbon-fiber water jetted from a 0.197in plate, and the upper ring is fiberglass water jetted from a 0.118in plate. Overall, The avionics components are attached to the two fiberglass sheets, and the entire bay can be lowered in from the top of the tube through the ring bulkhead, where it attaches to the bottom bulkhead with the eyebolt adapter, and the ejection charges can be inserted and screwed into the bottom bulkhead.

3. Parachute Ejection System

The parachute ejection system consists of three separate charges, a drogue chute charge, a backup drogue charge, and a main chute charge. The drogue charge uses 45g of CO_2, while the backup drogue uses 7g of black powder, and the main chute mechanism is set off with 0.5g of black powder. The CO_2 drogue is initiated by an Eagle from Tinder Rocketry [1] and an e-match, while the backup charge uses only an e-match. The main chute mechanism is a separating link which holds together two quick links. The quick links, while connected, prevent the main chutes bag from opening. The main chute mechanism is called a tender descender and is also a product from Tinder Rocketry [2]. The tender descender has two prongs which hold the quick links together; the prongs are disconnected by a black powder charge. The ejection occurs between the motor and the avionics tube with four #2-56 shear pins keeping the two tubes together during flight. The e-match for the Eagle and the main deployment system must be placed in the motor tube rather than the avionics tube to not damage the delicate components in the avionics bay. This means several wires must pass through the bulkhead, which would be difficult and tedious to achieve a proper seal every time an e-match must be replaced. To overcome this, a DB-9 connector is installed on the bulkhead to act as a passthrough for the wires. This allows for a significantly quicker e-match installation because the DB-9 connector has screw terminals, and wires are not required to be routed back to the avionics bay. Sealing putty is then placed between the components of the Eagle, the DB-9 connector, and the bulkhead to ensure a proper seal is achieved between the two tubes to have a successful separation. Finally, proper lubrication and cleaning of the Eagle is done to make the piston slide effortlessly inside the Eagle to puncture the CO_2 cartridge with ease.

4. Payload Airframe and Nose Cone

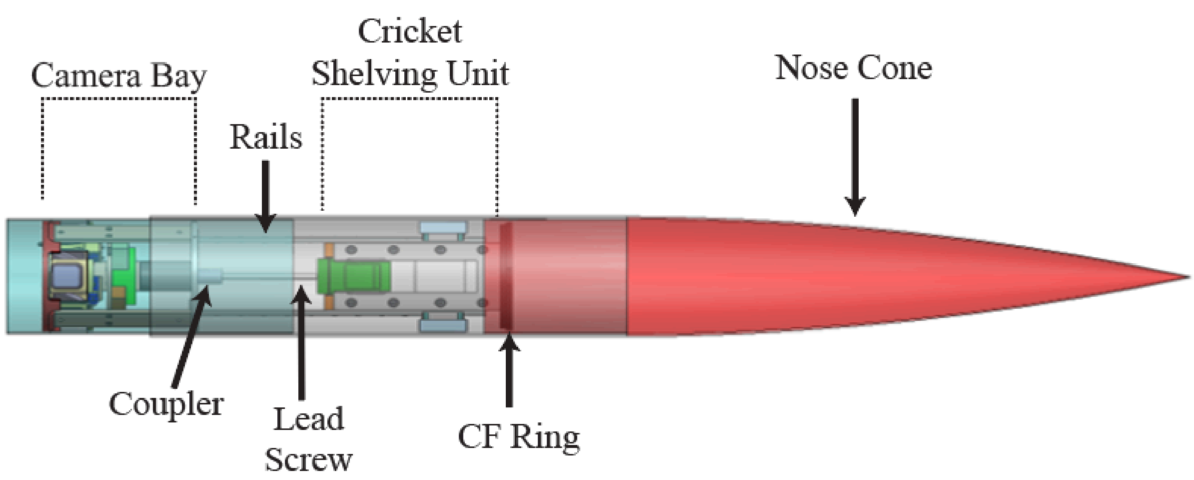


Fig. 8 - Payload Airframe CAD

The payload airframe, or payload tube, is composite fiberglass and houses the payload actuation mechanism, the CRICKET shelving unit, and a camera bay. The payload tube itself is secured to the avionics tube through eight, #4-40 screws through the airframe and coupler tube into two threaded bulkheads. The two aluminum bulkheads are located above and below the payload camera bay (the upper and lower payload bulkheads, respectively). The motor which actuates the CRICKET shelving unit and nose cone is attached to the upper payload bulkhead.

During the actuation of the payload mechanism, the nose cone will extend from the payload tube, allowing for the CRICKET to exit the rocket, and then retract back into the payload tube. A carbon fiber ring, manufactured via water jetting a carbon fiber plate, is attached to the nose cone with G5000 epoxy. The top of the CRICKET shelving unit is secured to the fixed carbon fiber ring by four #8-32 screws. The CRICKET shelving unit is secured to two linear rails. These rails allow the shelving unit and nose cone to translate up and down a lead screw when a motor activates. The rails also allow the shelving unit to be centered within the tube. Each rail is secured to the payload airframe by two M3 screws through the composite tube into a 3D printed adapter that is secured to the outer edge of the rail. The closed and open configurations of the payload airframe is illustrated in Fig. 9.

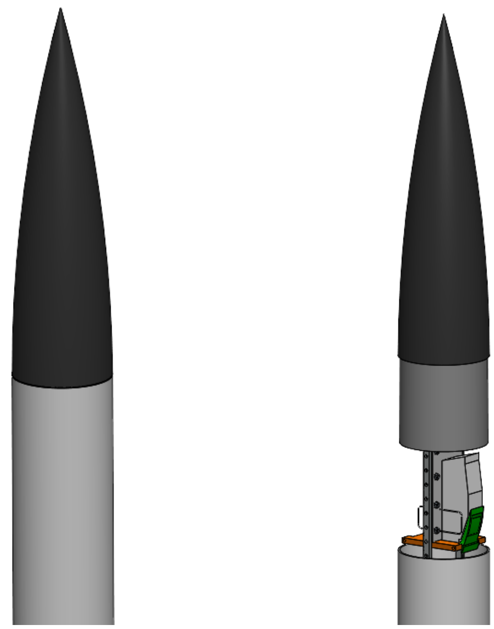


Fig. 9 - Payload Shelving Bay Closed (Left), Payload Shelving Bay Exposed (Right)

C. Avionics

1. Hardware - General:

The hardware system of the avionics system on the rocket consists of three main systems, a COTS system complete with dual deploy altimeter and live GPS transmitter, and two SRAD systems, one transmitting telemetry (SRAD 1) and the other controlling deployment events for the payload (SRAD 2). While each system acts as equals to deploy the main parachute, SRAD 1 is considered the dominant system for drogue chute deployment as it indicates when SRAD 2 may deploy the payload. While SRAD 2 does have an override of this, it is still dependent on SRAD 1. Both SRAD systems consist of a Raspberry Pi (4B for SRAD 1, and 3B for SRAD 2), as well as a custom designed printed circuit board containing the IMU, altimeter, GPS, power step-down regulation, deployment lines for ejection charges, and the optically isolated buddy-comm system.

The COTS system consists of one Stratologger CF as the dual deploy altimeter, as well as one Featherweight GPS tracker, and associated ground station. The Featherweight GPS tracker is powered by one 400mAh battery, rated by Featherweight to last for 16 hours on a full charge. The Stratloggger CF is powered independently by one 9V 1Ah battery, rated to last 20 hours on a full charge. Connected to the battery is a single pole, double throw (SPDT) pull pin switch that is rated for 5A. When the pin is in the switch, the normally open (NO) pin is connected to the battery, and is left as an open circuit so that no connection to the system is made during that state and no power is used. When the pin is pulled, the normally closed (NC) pin is connected, and current is allowed to flow to the Stratologger. All flight critical systems, COTS and SRAD are powered independently, and activated with independent power on switches. Each pin is friction fit within a 3D printed holding for the power on switch, and is tipped with a magnet so that the team member may pull the pin from outside the rocket using a magnetic pole, while the pin itself does not extrude from the rocket. Both COTS devices were used at the 2022 Spaceport America Cup and have been revalidated for the 2023 competition.

Each SRAD system is powered by one 12V 4Ah 3s lithium polymer battery, which has been tested to last 5 hours on full charge during full systems on. Like the COTS power on switches, each SRAD system is connected to an SPDT switch, preventing system power from being supplied until desired. Following each switch is a fuse rated to 5A, to protect the SRAD system in case of a short by removing power to the system. The voltage is then stepped down to the Raspberry Pi's supply voltage of 5V using a TSR 3-24150 converter. A capacitor is attached in parallel with the regulator to maintain a constant supply voltage to the flight computer when a deployment line for an ejection charge is fired.

A custom printed circuit board (PCB) is mounted on top of the Raspberry Pi in each SRAD system, consisting of an LSM6DSOX + LIS3MDL 9DoF IMU recording acceleration, angular velocity, and magnetic fields in all three axes. A BMP 180 is used for altitude measurements, as well as an Adafruit GPS breakout board for GPS connection. Each sensor sits on the board on top of the Pi, allowing for easy repairs if a replacement is needed. Deployment lines for both the drogue and main parachute are run through the board, as two MOSFETs rated to 47 A are able to be toggled by the flight computer during flight. When the MOSFET is set, the deployment line is connected to the 12V input voltage of the board, supplying power directly to the line. Additionally, a backup drogue charge of black powder can be fired by triggering a 3V3 logic relay on board the bay, connecting the 12V supply to the backup line.

All ejection charges are routed through an RS-232 DB9 connector located in the center of the avionics bay. Each system connects their representative deployment line into one main line connecting to a pin on the DB9 connector. Five main pins are used, drogue supply, drogue backup supply, drogue ground, main supply, and main ground. Each deployment line connects directly to each PCB of each SRAD system through sets of EC5 connectors. This allows for quick rewiring of the deployment lines if needed during assembly, while maintaining a strong connection while wired together. The drogue supply line wires the pyro charge within the Eagle [1] , while the drogue backup supply line is wired to black powder charges, as a secondary line in case there is some failure on the primary line. The DB9 connector connects to another DB9 connector and screws into place, ensuring that ejection lines do not backout during flight.

In order to allow for live data from the rocket as well as remote diagnostics, the SRAD 1 system is equipped with a telemetry link via a pair of RFD900x 1W modems. Operating in the 900MHz ISM band, the Raspberry Pi is connected to the onboard modem through a USB to serial connection, secured to protect against backing out due to vibrations. Onboard the system uses two ½ wave dipole antennas to communicate with the ground. On the ground, one ½ wave dipole and one Yagi Uda antenna are used to maintain connection with the rocket throughout the flight.

SRAD 1 and 2 use an optically isolated message passing system to communicate between systems while remaining electrically isolated. Using the opto-isolators present on each board, each SRAD system is able to transmit both a data and clock signal between systems, allowing for electrically isolated intersystem communication of commands and flight event indications such as drogue deployment, payload deployment, and remote onboard camera start.

The SRAD 2 system is in charge of deploying the CRICKET drone payload. Since the payload deployment system relies on a singular brushless DC motor, the interface between the avionics system and the payload consists of a singular signal line and a shared ground. When SRAD 2 is given permission to deploy the payload, it sends the signal line high, which, internally to the payload system, begins deploying the payload. When SRAD 2 begins deploying the payload, it uses BuddyComm, see Software Design - Flight Computer, to signal to SRAD 1 that it is doing so. SRAD 1 then relays this message to the ground station operator through the telemetry system, where it can be read out and reported in real time. SRAD 2, through testing, has determined the amount of time that it will take for the payload system to fully open and deploy all of the CRICKET drones. From here, the SRAD 2 system sets the signal line high again to retract and store the payload deployment system. Once the system has been retracted, SRAD 2 uses BuddyComm to relay to SRAD 1 that it has completed the payload deployment, which, again, is sent in real time to the ground station operator at base camp.

2. PCB Design

The PCB serves to streamline the process of running the Pi, sensors, and organizing the electronics of SRAD 1 and SRAD 2. It not only supplies power to the Pi it sits on top of but also connects a gyroscope, accelerometer, magnetometer, altimeter, and GPS to the Pi. As well as adding relays, mosfets, and optoisolators that can be used to control and trigger events in the rocket. While the IMU and altimeter are connected on an I2C (SDA/SDL) bus, the GPS uses UART to communicate with the flight computer. The relays are controlled by separate MOSFETs that allow 5v to flow into the coil in order to activate or deactivate them. Furthermore, all MOSFETs on board are connected to a RPi logic pin with an output of 3.3v and a max current pull of 15 mA paired with a 10k ohm pulldown resistor wired to the gate input of the MOSFET. The optoisolators are also connected to the 5v power and have 220 ohm resistors protecting overcurrent of the signaling side with header pins on the receiving end for quick plug and play with other microcontrollers.

3. Software - General

There are four main pillars of the software architecture to the avionics system, sensor data sets, live telemetry data, onboard camera footage, and the BuddyComm communication system. The source code for all software can be found on the team's GitHub repository here. Since the flight computers run on a Raspberry Pi, Python was selected as the programming language, as it allows for greater flexibility and abstraction. Although Python has performance limitations, the team determined that this was acceptable, as it provides a baseline for development of future avionics systems. In the coming years, the team expects to move to C++ for increased performance while maintaining components of Python's emblematic abstractions.

In the realm of software development/architecture, our goal was to design a multithreaded modular flight computer that can be duplicated across SRAD 1 and SRAD 2 with minimal changes to the specific code for differing system capabilities (payload deployment for example). Through a modular top down design, development could be sectioned off into discrete sections and delegated throughout the team, allowing for members to have dedicated projects within the software. Secondly, this style of design allows the team to work on individual sections of the flight computers while ensuring that the changes made in one module will not cause another to become broken.

In order to distribute the computational workload across systems, the SRAD avionics systems, SRAD 1 and SRAD 2 use an intersystem communication protocol called BuddyComm. Through this, both systems are able to communicate with each other to share data on flight status, and commands sent via telemetry. Since each SRAD system maintains independence in their collection of data, BuddyComm allows each system to maintain cohesion as an overall avionics platform, while keeping their distinct states. BuddyComm works by sending a predetermined set of binary numbers, zero through three, across a data line one bit at a time. When the sender desires for the receiver to read the data on the line, the clock line is pulsed high, triggering an interrupt on the receiver's end that reads the data on the line. This is done twice to build a two bit binary number, which corresponds to one of four different messages.

The avionics system is in charge of managing all cameras onboard the rocket. While two of these are Raspberry Spy cameras, which are activated purely through software, and three are GoPros that must be mechanically activated through the use of a servo motor controller. To control these cameras, the SRAD 1 flight computer receives a telemetry message from the ground station, where it either executes the camera command locally, or passes the message through BuddyComm to SRAD 2. In order to turn off each camera, the ground station can repeat the message, and turn each camera off.

The avionics system is able to converse with a set of three sensors, the IMU, altimeter and GPS. Each sensor, within the flight computer, is represented as its own process and object. By maintaining the internals of the object within the object, also known as encapsulation, all that is required by the core of the flight computer is to interface with said object in order to get new data. This enhances the modularity of the design as encapsulation of each sensor allows for isolation between parts of the flight computer, increasing reliability and ease of design. The avionics telemetry system allows a live downlink with the ground station through the aforementioned RFD 900x which sends packets of sensor data through the pyserial library, to be decoded and sent to the ground. The flight controller downlink software simply works by taking in all the sensor data and then converting them into an explicitly binary representation of the data by creating a byte object that represents the number in a specific datatype of either a half int or float depending on the type of data and the precision required. Once it has a list of bytes representing the sensor data, 3 sync bytes, and a byte used as an XOR checksum the software concatenates them into an array and utilizes pyserial to feed it through the serial bus to the modem where it is then transmitted to the other linked antenna, in this case the ground station.

4. Software Design - Flight Computer

The optically isolated message passing system, BuddyComm, enables communication between the two avionics flight computers. This facilitates a division of labor between the two flight computers. Since both computers collect flight data independently, BuddyComm allows the flight computers to provide inter-system logic for payload deployment. Since SRAD 1 is the dominant system for the drogue chute deployment, SRAD 2 waits for a zero (0) signal on its BuddyComm connection in order to begin deploying the payload. SRAD 2 must wait for this so that the payload does not begin deploying before apogee or while not under drogue, thereby posing structural risks to the rocket. If the two systems agree, then SRAD 2 will deploy the payload. If SRAD 2 never hears that SRAD 1 has detected apogee, possibly due to a failure on SRAD 1's part, then SRAD 2 will fall into a failsafe of deploying the drogue chute if not already deployed by the COTS system, and then beginning deploying the payload, once it can confirm it is under drogue. While SRAD 2 manages the payload, SRAD 1 is devoted to communicating to the ground station via telemetry. Therefore, all information must be relayed between SRAD 1 and 2 using BuddyComm. This feature is used when deploying the payload as well as when remotely activating two of the three onboard GoPros. Commands sent by the ground station are passed from SRAD 1 to SRAD 2 via BuddyComm for execution.

BuddyComm uses four pins on each flight computer. Two pins are required for communication in one direction. The first of these pins is the data pin, which can be either a logic 1 or logic 0. The other pin, the clock pin, when the clock pin is set high, the value on the data line is read as either a one or zero. These bits are read to build a binary number that is then mapped to a specific command.

To ensure consistency of the system, BuddyComm operates at a low rate of bits per second, only two hertz. This is only a minor drawback, as each message is only two bits wide, and therefore can be sent in one second. Since BuddyComm's main commands are only somewhat real time dependent, this does not decrease the overall performance/reliability of the avionics system.

There are a total of five cameras controlled by the avionics system. Two of the cameras are Raspberry Pi Spy Cams which connect directly to the board and are activated once launch is detected. The three other cameras are GoPros which are activated with a servo when a message is received from the ground station. One of the three GoPro servos is activated with SRAD 1, while the other two are activated with SRAD 2. Having some of the GoPros be activated by a different computer improves the chance that at least one of the GoPros activates even though one of the SRADs may fail. Once SRAD 1 believes a GoPro has been activated, it sends a message back to the ground station indicating which GoPro is ready.

If a GoPro needs to be stopped and started again, the ground station sends another camera activation message which will cause the servo to activate again, stopping the GoPro's recording.

Each SRAD system contains three main sensors, an Adafruit LSM6DSOX + LIS3MDL 9DoF IMU, a BMP 180 barometer, and Adafruit Ultimate GPS breakout board. The LSM6DSOX provides the accelerometer and gyroscope of the IMU, while the LIS3MDL provides the magnetometer capabilities. The BMP 180 supplies barometric pressure and altitude data to the flight computers, while the GPS breakout board provides real time GPS location. Each sensor is polled asynchronously in their own process within the flight computer. Each time the flight computer wants a new piece of data from a sensor, it grabs the most recent piece of data from each process. Through this process, the sensors can be separated in software, where the failure of one sensor does not affect the rest of the system integrity. If a sensor fails to provide data, then the flight computer automatically tries to reset the sensor and reestablish it. This allows a sensor to fail for part of the flight, but still provide data for all of the time of which it is active, despite it being "unplugged" and plugged back in while the system is running.

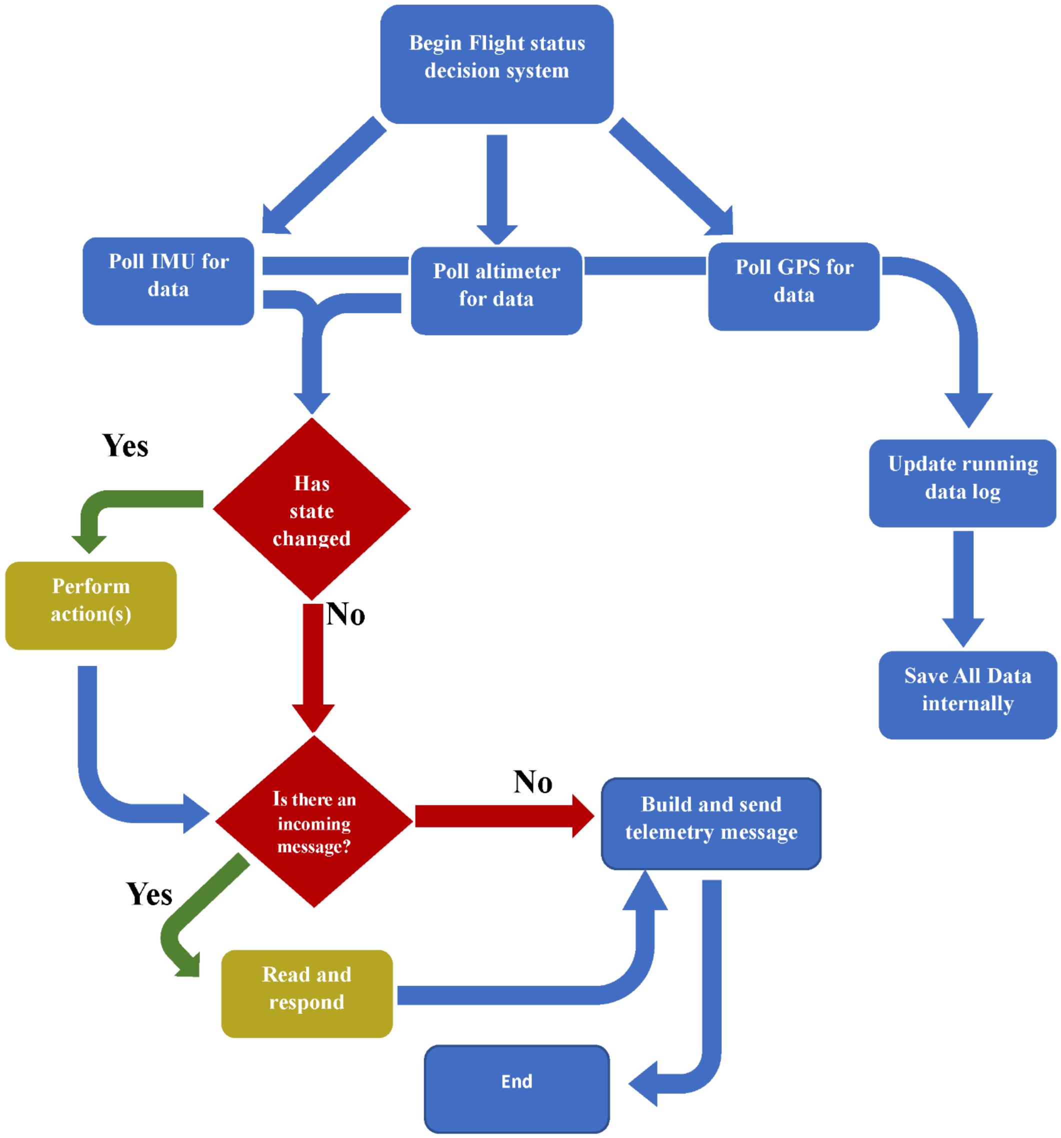


Fig. 10 - Flight Status Decision System Flowchart

The main flight computer requests new data from the sensors as fast as possible, saving each data set to an onboard log file. Every eighth of a second, the current set of data is given to the flight status decision system, which uses the data set to update the flight status. The flight status decision system stores the previous eight seconds, or 64 samples of data from the altimeter, and IMU. By weighting the data from the last eight seconds in different ways, the flight computer is able to account for sensor noise and outliers in data.

The flight computer has five different flight states, preflight, inflight, descent, and on-ground. Starting in preflight, the system performs a variety of tasks to prepare the flight computer for flight. The flight computer establishes connection with the three main sensors, spawning a child process for each one. Using the BMP 180, the flight computer collects sixty-four (64) samples of altitude, performing a fit of the data, it finds an estimated base altitude from which it will reference for all calculations. If any sensor fails upon startup, then the flight computer resets the sensor and attempts to connect to the sensor again, and repeats one more time if it fails again. If the flight computer fails to establish a connection with a sensor after three tries, then this indicates this failure on its startup diagnostic beeps. If the IMU has failed, then the buzzer will begin its diagnostic output with one long beep. If the altimeter has failed, then two long beeps will be output, and three long beeps for a failed GPS.

BuddyComm, the diagnostic buzzer, and telemetry system are set up by designating the associated pins to the flight computer. The telemetry system is set up by opening the virtual COM port (VCP) to the modem, and the flight computer prepares to write telemetry messages to the port. If all sensors successfully connect to the flight computer, then the first buzzer output will be three short beeps to indicate successful power on and boot of the flight computer. Then, the buzzer outputs a series of short beeps, one for every one hundred feet of the main parachute deployment altitude, ten in this case. This sequence is repeated by the flight computer.

After the instantiation of all flight systems has finished, the flight computer begins logging data from each sensor. The flight computer will begin to actively transmit telemetry data to the ground station located at base camp. After the team has returned from the pad, and the launch is expected soon, a remote command will be sent by the ground station operator to the flight computer to activate each GoPro camera. SRAD 1 will activate GoPro 1 by actuating a servo, while passing BuddyComm messages to SRAD 2 for GoPros 2 and 3. Additionally, the ground station operator will send a ready command to the system. This is NOT an arming command, and does not affect the system's ability to deploy recovery events. Instead, it is used to remotely verify correct system operation across SRAD 1 and 2.

Since the flight computer power on event occurs after the rocket is vertical at the pad, no special logic or indication is needed for an arming sequence. The flight computer waits for a large and sustained level of vertical acceleration, and uses that to determine lift off from the pad. Upon entrance into the inflight stage, the onboard Raspberry Spy cameras begin recording and videoing internal flight events.

The flight computer uses altitude measurements as the primary method of detecting that the rocket has reached apogee. By taking the median of the altitude readings from the current second, and comparing them to the median from the previous second, and the second before that, the system is able to consistently detect apogee even with bad and outlier sensor readings. Using these three aggregated data points, one can determine when the rocket has reached apogee. While the flight computer does detect apogee slightly late, this system has consistently provided accurate apogee indications and deployments. To deploy the drogue, the flight computer sets a pin high to flip the deployment line MOSFET and fire the drogue parachute.

If SRAD 1 detects apogee before SRAD 2 does, then it deploys the drogue parachute and relays this information to SRAD 2 via the BuddyComm system. Upon receiving the message from BuddyComm, SRAD 2 begins deploying the payload by sending a signal to the payload electronics. If SRAD 2 detects apogee before SRAD 1, then it must wait to deploy the drogue chute and deploy the payload. If SRAD 2 does not receive a message from SRAD 1 after it has detected it has begun to descend, rather than approach/be at apogee, then it will override the need to have received the command from SRAD 1 on the pretenses that SRAD 1 has malfunctioned in some manner. It will deploy the drogue chute, if not done already by the COTS altimeter, and then deploy the payload.

Post drogue deployment, the rocket is now in two possible states, either the drogue has deployed correctly, and the rocket is coming under a stable velocity, or the drogue has failed in some manner. If the drogue has failed, then the rocket is at risk of returning to the earth in a ballistic reentry. This can be countered by deploying the main early, but this must be done early enough in the descent so that the rocket's velocity is not high enough to where the force of deploying the main chute would cause the chute to shred or disconnect from the rocket, thereby guaranteeing a ballistic reentry. Post drogue deployment, if the flight computer detects the downward vertical velocity to be above 50 m/s and growing, then it will deploy the main chute at whatever altitude it is currently at. This is greater than the expected drogue descent rate and indicates to the flight computer that the drogue chute has not deployed correctly, or at all. If the main chute does not deploy early, in that the drogue deploys correctly, then it deploys at 1000'. When altitude has reached a relatively constant value and acceleration is 1g for an extended amount of time, the stage is changed to on-ground. Data collection and other processes continue while on the ground until the system is unpowered.

In the event that the launch is scrubbed, and the rocket must be pulled off the pad, SRAD 1 and 2 may be disarmed and placed in a safe mode to ensure that no deployment events can occur while the rocket is being removed from the pad. The disarm codes are sent via telemetry with the ground station. When SRAD 1 receives the disarm message, it relays the message to SRAD 2 via BuddyComm. This disarm message will only disarm while the rocket is in preflight mode, to prevent accidental disarms during flight. If the rocket believes it has launched, and has not actually, then a separate override code must first be sent via telemetry in order to enable the primary disarming code. Once disarmed, the cameras are stopped, and after 5 seconds, SRAD 1 is shut down.

Reading	Data Type	Description
Sync 0	Char	Zeroth sync byte – 'C'
Sync 1	Char	First sync byte – 'R'
Sync 2	Char	Second sync byte – 'E'
MFC1	Uint short	Major frame counter 1 – Increments every message and resets every 4095 messages
MFC2	Uint short	Major frame counter 2 – Increments every time MFC1 resets
Altitude	Float	Current altitude in meters [m]
Acceleration X	Float	Acceleration on X axis $[m/s^2]$
Acceleration Y	Float	Acceleration on Y axis $[m/s^2]$
Acceleration Z	Float	Acceleration on Z axis $[m/s^2]$
Gyro X	Float	Angular velocity on X axis $[°/s]$
Gyro Y	Float	Angular velocity on Y axis $[°/s]$
Gyro Z	Float	Angular velocity on Z axis $[°/s]$
Magnetometer X	Float	Magnetic field on X axis $[\mu T]$
Magnetometer Y	Float	Magnetic field on Y axis $[\mu T]$
Magnetometer Z	Float	Magnetic field on Z axis $[\mu T]$
Temperature	Float	Temperature $[°C]$
Predicted apogee	Float	Predicted apogee [m]
GPS Latitude	Float	GPS latitude in decimal minutes $[D°\ M.M']$
GPS Longitude	Float	GPS longitude in decimal minutes $[D°\ M.M']$
GPS Altitude	Float	GPS altitude in meters [m]
Time of data collection	Long	Time that data was collected at to 3 decimal places of a second. Uses 1Hz update rate GPS time and interpolation to determine time of message.
Status	Uint short	16-bit field indicating status messages from the rocket – see proceeding figure
Checksum	Uint short	Checksum generated by bitwise XORing each byte in the message. Used for error detection during transmission

Message indicators/error correction	Message Counters and status	Altitude and related measurements
IMU Data	GPS Data	

Fig. 11 - Telemetry Downlink Message Formatting

Bit Number:	Message:
0	Active aero status: Green – Running, Red – Disabled
1	Excessive spin detected: >720°/s
2	Excessive vibration detected: >10g in either Y or Z direction
3	SRAD2 ready
4	System disarmed
5	Launch detected
6	Apogee reached
7	Drogue deployed
8	Main deployed
9	Touchdown
10	Payload deploying
11	Backup drogue charge fired
12	Null
13	GoPro 1 On
14	GoPro 2 On
15	GoPro 3 On

Flight Events	Warnings/system status	Camera Data

Fig. 12 - Telemetry Downlink Bitfield

5. Ground Station Telemetry Software Design

The ground station software of the telemetry system uses C# in combination with Windows Presentation Foundation (WPF), and DevExpress to build an interactive graphical user interface (GUI) that allows for the user to see live data from the SRAD 1 system in real time. In addition to receiving data, the user can send a variety of commands to the SRAD 1 system. This allows the user to observe and relay recovery events to the team as they happen. Using the RS-232 communication protocol at 57.6k Baud, the program uses a VCP to manage the incoming stream of data by writing all of the data into a buffer file, from which Bytes can be read in.

The GUI consists of two main screens, the "Home" screen and the "Telemetry" screen. The Home screen has three main technical components to it, the altitude graph, the data quick view, and the control panel/message box. The altitude graph shows the current altitude of the rocket as well as all past data from the last thirty seconds. This allows for a clear and visual indication of the rocket's trajectory during flight. The data quick view gives the user three main pieces of information needed for understanding the rocket's state at a glance, altitude, acceleration, and GPS location. The altitude panel in the UI provides a more in depth view of the altitude than the aforementioned graph does. As can be seen in Fig. 13, the current altitude, change since last message, current apogee, and predicted apogee can all be seen. Extending this to the acceleration, one can see the current acceleration, in m/s^2, across all three axes, as well as the change in acceleration across the axes. Lastly, one can see all of the current GPS coordinates of the rocket.

The control panel and message box allows the user to see the current status of the rocket before and throughout the flight, as well as sending any preflight commands. When a status is set to true by the SRAD 1 flight computer, the according light on the ground station software will turn from red to green. Using the message box below the control panel, the user can type commands for the SRAD 1 system to execute, as mentioned prior, these include activating/deactivating the GoPro cameras, performing a diagnostic check on the SRAD 2 system, and disarming the avionics system, if the rocket must be pulled from the pad for any reason.

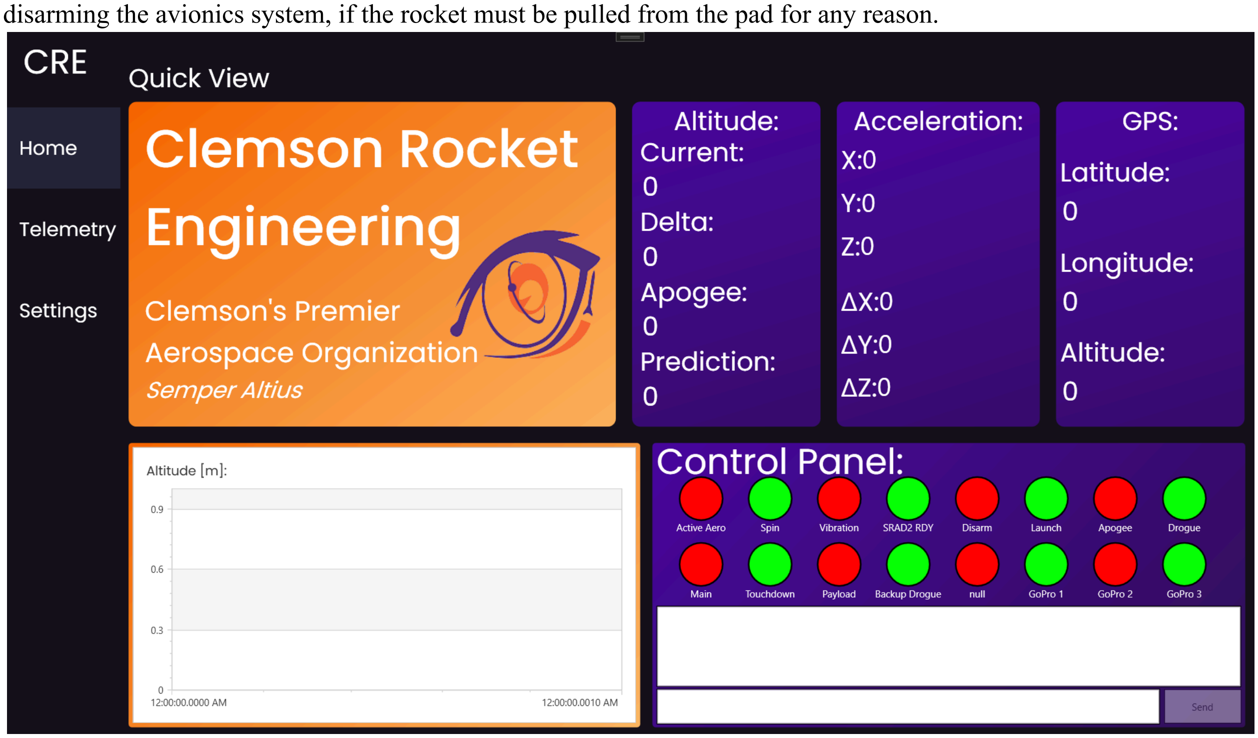


Fig. 13 - Home Screen of Ground Station Software

The telemetry screen of the ground station telemetry software allows the user a more indepth and bare bones view of the system. The user can see all of the current readouts from all sensors. Additionally, the user can see graphs for both altitude and all IMU measurements across all three axes concurrently. When a message is found to be corrupt, the background of the page will turn red until a new valid message is read by the interpreter. The user can also visually observe the signal reliability by referring to the valid messages percentage readout, that indicates the percentage of found messages that were corrupted in some form or another.

At the top of the screen, the user can find the controls for the data stream. The user must select a COM port before opening the link to the data, and can refresh the found COM ports as needed. The user may reset the stream at all times, setting all values to zero/null, and resetting the state of the interpreter. Upon opening the data link, the program creates and writes to a new data file that contains the data collected while the link is open. The name of the data file corresponds to the date and time of the link being established so that each file has a unique name.

The ground station telemetry software uses multithreaded asynchronous programming in order to process multiple different tasks in concurrence. A thread is dedicated solely to message interpretation, while others are tasked with handling data and updating UI elements. In order to do this with ease, the program uses a set of background worker objects that operate on different threads automatically.

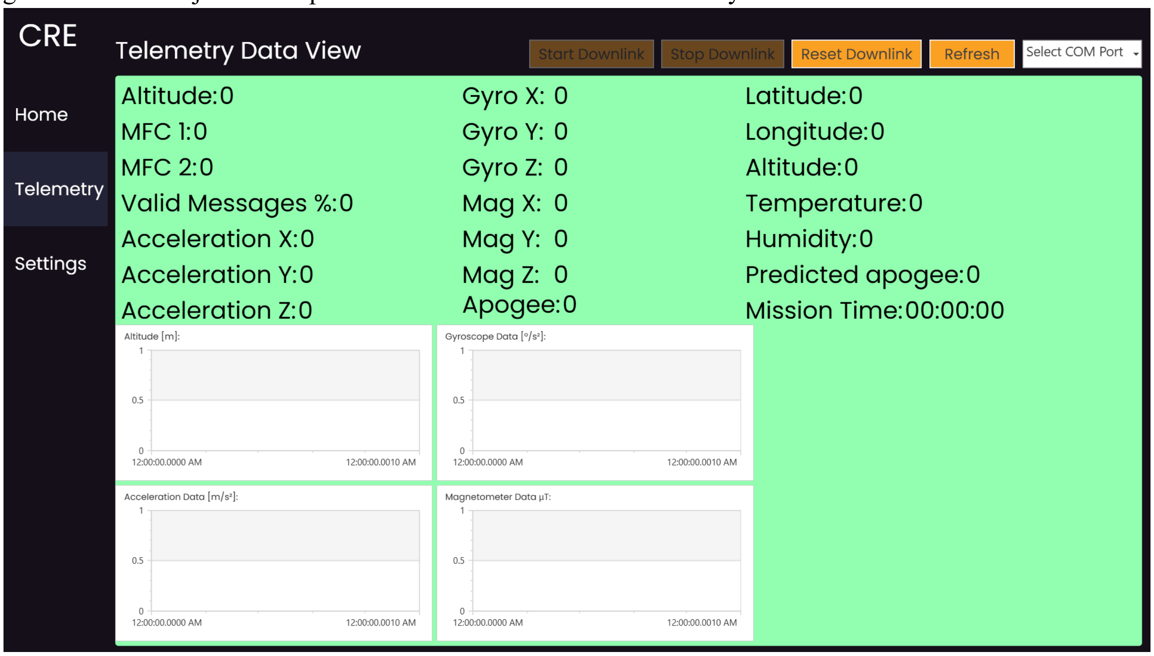


Fig. 14 - Telemetry Screen of Ground Station Software

In order to search for and read in messages sent via the SRAD 1 system, the ground station software uses a dynamic interpreter and three sync characters/bytes, ‘C’, ‘R’, and ‘E’, to latch onto and bring messages in. When the data stream, or buffer, fills with enough data for there to be a message, 80 Bytes, then the interpreter’s asynchronous process is automatically called. The interpreter scans the buffer for a ‘C’ character and records where it is found, investigating all found locations, it checks for the two remaining sync characters. If those are found, then the interpreter knows it has a message, reading in any extra data from the buffer if needed. When the entire message has been read in, the interpreter checks the checksum of the message by calculating the bitwise XOR operation of all of the bytes in the message in ascending order, and comparing that result to the final byte of the message. If the two match, then the message is uncorrupted, and the interpreter can read the rest of the message, calculating values using the agreed upon message formatting.

The telemetry system uses a system of major frame counters, MFC 1, and MFC 2, to assign discrete numbering to each message. Each time the SRAD 1 system sends a message, it increments the MFC 1 variable, until it reaches 4095. When MFC 1 reaches 4095, SRAD 1 resets the value to zero, and increments the MFC 2 value by one. This gives a total of 1,679,025 messages, or 582 hours at a rate of 8 Hz:

$$\left(\frac{(2^{12}-1)^2}{8}\right) * \frac{1}{3600} = 582.258\ hrs$$

Fig. 15 - Unique Message Values Time Equation

While the interpreter reads each value in the message, the values are automatically pushed to the UI for the user. Once the interpreter reads in the 16 bit status field, it uses bitwise operators to scrape off each bit from the message and adjust the control panel lights accordingly.

Once the data link is closed, the user can access the data through the saved data log in the form of a CSV file. From here, data can be analyzed for post flight analysis/performance reviews.

D. Flight Dynamics

1. Motor Selection

The motor selection is critical to determining how much a rocket can weigh, how stable it will be during flight, and what apogee it can reach. It was determined that CU Later would need to lift 66lbs to an apogee of 10,000ft for the competition. After analyzing thrust curve data for all of AeroTech's class N and M rocket motors, it was decided that a M2500T AeroTech motor should be used. There were several reasons for this. First, the team has experience with the M2500T from the 2022 Spaceport competition launch, which was on a rocket of similar shape and weight as this year's design. Second, the thrust curve of the M2500T allows for the rocket to reach a velocity close to 100 fps when it leaves the launch rail. This is crucial for stability during launch. It also provides a near constant thrust of 2,700N for the first three seconds of its burn time, reducing stresses that would have been increased by a more variable rocket thrust curve and therefore increasing the chance of success.

2. Fin Design

When determining the shape of the fins, several variables needed to be considered. Design consideration includes needing to move the center of pressure further towards the end of the rocket to increase stability, having low-drag principles, and being relatively easy to manufacture. These necessities instantly eliminated elliptical, trapezoidal, and rectangular fin shapes from consideration. This left clipped delta, swept, and tapered swept shapes for testing. After the overall profile of the rocket had been designed, flight dynamics experimented with these three fin shapes using OpenRocket and RASAero computer simulations. While swept and tapered sweeps have benefits, it was determined that a clipped delta design would be the best choice. Such a design has low-drag and is typically used on high-performance rockets. It is also relatively easy to build, and the team has used similar designs in the past. As shown in A.1.1, the fins allow for the stability margin of the rocket to stabilize around 2.8, ensuring that the flight is a smooth one. The engineering drawing can be viewed in A.6 for specific dimensions.

3. Nose Cone

The selected nose cone design is tangent ogive-van karmen. The tangent ogive-van karmen was selected because the balance between drag and pressure it provides is optimal at the velocities the rocket is operating at. This was confirmed through computational fluid dynamics simulations. Tangent ogive-van karmen has also been used by the club in the past, which was a contributing factor to its selection. The cone itself is COTS and is made of carbon fiber to ensure that it would be light-weight and durable. The tip of the cone was replaced with aluminum to protect the rest of the nose cone from shattering on landing. Aluminum was selected as it is a less dense metal and easily machined and thus easily replaceable.

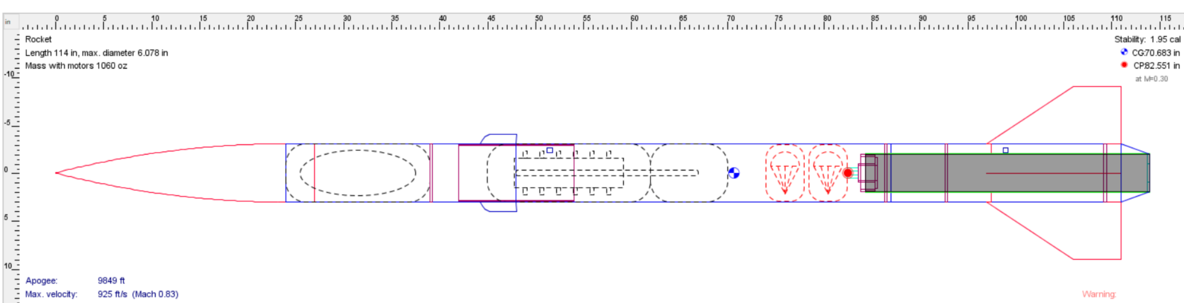


Fig. 16 - OpenRocket Design of CU Later

E. Payload

1. Mission Overview

The payload mission was inspired by a partnership between CRE and NASA Langley Research Center (LaRC). NASA LaRC currently has a research project revolving Close-In Covert Autonomous Disposable Aircrafts

(CICADAs). These CICADAs are equipped with environmental sensors to monitor the atmospheric conditions upon descent. Currently, these gliders are released via rotary drones and small aircraft at varying altitudes to collect data on pressure, temperature, humidity, GPS, and more. Early this year, the CRE contacted NASA about acquiring CICADAs and using them as an ejectable payload at apogee. NASA LaRC has aided in the development mechanism for deployable payloads, however, due to long waiting periods for a Space Act Agreement between NASA and Clemson University, the CRE team has elected to create similar small aircraft, designated the Clemson Rocket Innovative Cruising Kit for Environmental Testing (CRICKETs). Similarly to the CICADAs, a single CRICKET is to be released following apogee at 10,000ft. The descent of these CRICKETs will provide NASA LaRC with new data to further aid their mission. In order to accomplish this, CRE's payload design was designed to withstand the forces of the rocket's launch as well as reliably release CRICKETs while the rocket is still in flight.

Fig. 17 - NASA Research with CICADAs [3] (Left), 3D Printed CICADA Model (Right)

2. Actuation Mechanism Selection

In order to release the CRICKET at apogee, the nose cone will extend from the payload tube (while still maintaining a connection), allowing for the CRICKET to eject from the rocket. Two different actuation mechanisms for this separation were explored: a pneumatic system and a motor system. The pneumatic system uses compressed air to actuate pneumatic pistons, moving the payload shelving unit (fixed to the nose cone) up and down. The motor system configures a lead screw and a DC motor to translate the payload's shelving unit up and down.

For the pneumatic system, a series of tests were initially conducted to determine the range of compressed air required to fully actuate the pistons up and down (A.2.1). Starting at 30 PSI, there was no initial movement. When 40 and 50 PSI were tested, one complete actuation was completed, however, the speed was significantly slower than the payload system required. When 60, 70, and 80 PSI were tested, three complete actuations were completed. It was observed at 90 PSI that four complete actuations were ompleted. At both 100 and 110 PSI, five complete actuations were recorded. When determining the PSI range which should be tested with the shear pins, both 100 and 110 PSI were selected because of the excess amounts of compressed air build up within the pistons. As seen in A.2.2 (testing with shear pins), neither PSI amounts were capable of breaking a single #4-40 shear pin screwed through a composite tube into a threaded bulkhead. Since the pistons were not able to break a singular shear pin, it was concluded that they pneumatic system could not break four #4-40 shear pins. Additionally, the pneumatic system consumed a significant amount of space within the payload section due to the size of both pistons and the air tank.

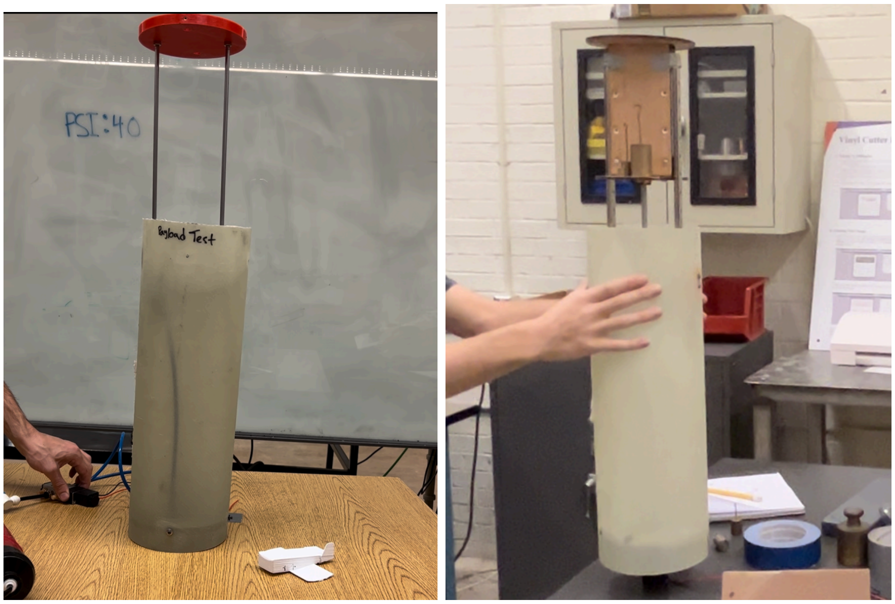


Fig. 18 - Pneumatic Testing at 40 PSI (Left), DC Motor Weight Testing (Right)

When investigating the motor system, a GoBilda MATRIX 12VDC Motor was used initially. This motor has a max torque of 1.47 kg.cm. When testing this motor specifically, it was determined that a more powerful motor was required. As seen in A.2.3 (dc motor testing results table), the MATRIX motor was only able to handle actuating the shelving unit with an additional 440 grams fixed to it (without the nose cone fixed). This prompted the team to explore the INJORA RC Motor 550 21T Brushed Motor. The INJORA motor allows for either a 2S or 3S lipo battery, operates at max efficiency at 310 g.cm of torque, and also is easily programmed with a QUICRUN 1060 Brushed ESC. The lead screw system was able to operate at a faster rate than the pneumatic system, occupy less space within the payload tube, and was a simpler system to prepare before flight, the lead screw with DC motor was chosen to be the actuation mechanism.

3. Shelving Unit

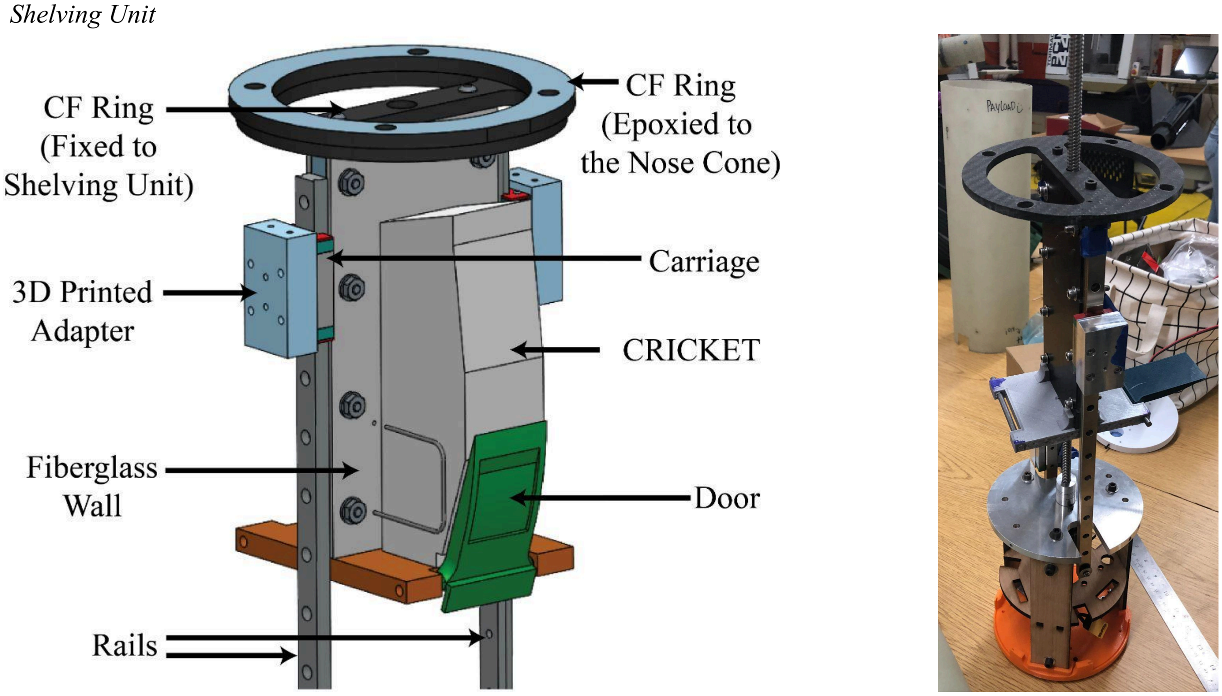


Fig. 19 - Shelving Unit CAD (Left), Shelving Unit and Camera Bay Manufactured (Right)

In order to accommodate either actuation mechanism, the shelving unit was designed to have open spaces to allow for either mechanism to work with it (Fig. 19). This mainly included leaving space to the left or right of the unit to allow for either linear rails or the pistons to fit alongside it. Along with this, the shelving unit needed to also throw the CRICKETs away from the rocket after the actuation mechanism exposed the CRICKETs to the air stream. This was designed to be completely mechanical as this would increase reliability and decrease the number of communications between the avionics section and the payload section of the rocket.

The outwards ejection system of the shelving unit was initially integrally designed into the part the CRICKETs rested on and would rotate outwards to throw the CRICKET pair away from the rocket. By having this mechanism, the shelving unit could take up less space inside the airframe and allow for more total CRICKETs to be carried in one launch. However, this initial design used many moving parts to hold comparatively fewer CRICKETs, and many of these parts were difficult to manufacture. The new design borrows heavily from this initial design, primarily the vertical orientation of the CRICKET and the upward motion of the shelving unit to push a pin or the upper lip of the airframe moving out of the way of the shelves to allow for CRICKET ejection. The next major design iteration removed the rotating mechanism of the first in favor of constantly having a spring push the CRICKET outwards from the center of the rocket. This way, when the system was in its stowed state, the CRICKETs would be firmly pressed against the airframe, not only keeping them inside the rocket but also protecting them from vibrations and from wandering out of place during launch. The removal of the rotating mechanism also allowed for a simpler and stronger platform for the CRICKET to rest on as the load generated by the high G forces would not have to go through a critical moving part. When the system would have to deploy, the shelving unit would move upwards until the bottom of the CRICKET cleared the upper edge of the airframe, at which point the spring would push the CRICKET out of the rocket and into the airstream.

After this, the shelving unit will then move back down into its stowed state to protect itself from the impact on touchdown. The third and final iteration of the shelving unit (Fig. 19) coincided with the switch from using CICADAs, the intended payload to the use of the in-house developed CRICKETs as the CRICKETs could be better tailored to suit the ejection system. This final iteration kept the same overall architecture of the second iteration with the non-rotating shelf and upwards motion of the entire unit, but also included new features such as a flap between the payload and the airframe wall. This flap was added to decrease the amount of friction between the body tube and the payload and also prevent the motion of the body tube relative to the payload from damaging either of the two. Along with this, the spring was removed from the system to reduce complexity and instead the CRICKET itself will use its folded parachute as a very short spring to push it into the oncoming airstream. The drag generated by the now-exposed parachute would then pull the CRICKET out of the ejection system. This reduction in part count and complexity allowed for a far simpler to manufacture final part and increased reliability.

4. CRICKETs

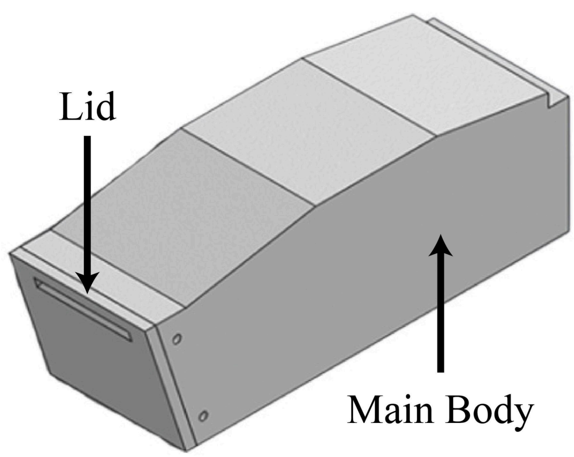


Fig. 20 - CRICKET CAD

The CRICKET device was designed according to guidance from aerodynamic principles. This device is intended to endure a high-altitude drop as it is ejected from the rocket and is expected to be recoverable. The outer shell of the CRICKET is made up of two main components: the main body and a lid. A model of the design is pictured above in Fig. 20. Inside the model will be a COTS Featherweight GPS (COTS) powered by a 400mAh battery and a SRAD PCB. This device is meant to communicate with the base station throughout the flight and give an estimate of its location to assist the recovery team.

Using the dimensions of the Featherweight GPS, the battery, the PCB, and the allotted space in the shelving unit, the model was developed around these constraints. The Featherweight GPS is intended to be mounted on the lid side of the model to assist with assembly. There are two slits located on the front and back sides of the model which is intended to allow airflow throughout the device as it experiences the drop; this airflow is for the sensors on the PCB. To create drag on the device and decrease its terminal velocity, a 12in parachute is to be attached on the lid side of the outer shell. The cords will be secured on the inside of the device. Lastly, to assist with the recovery of the CRICKET, a ribbon made of reflective material is meant to attach to the lid side of the cricket.

For the SRAD PCB, the electronic internals of the CRICKETs were selected to be cheap and energy efficient. The internals can be split into three groups: power, sample acquisition and processing, and transmission. For power, the PCB uses a single common 9v battery. The voltage is regulated and dropped down to 3.3V. This is handled by the ST715M33R linear voltage regulator and supporting capacitors. Originally, the design called for a CR3032 coin-cell battery. However, during testing it was discovered that these batteries could not provide enough current for the expected duration of the flight. The design calls for temporally spaced samples of humidity, temperature, pressure, and position. A Bosch BME280 three-in-one sensor is used to measure humidity, temperature, and pressure. For position data, a PA1616D GPS module from Adafruit is selected. The BME280 sensor communicates via I2C and the GPS uses a two wire interface (TWI). These sensors are controlled by an ATTINY441 microcontroller. This microcontroller was chosen for its low cost, power usage, and ease of operation. Transmission of sample data is achieved through the TXM-433-LC transmitter from Linx Technology. This transmitter uses the 433MHz radio-frequency (RF) band. The data is packaged into a binary representation and transmitted. On the ground, a software defined radio records the signal for later processing.

5. Cameras

The CRE team has the goal of capturing as much footage of the launch, flight, and recovery process. This led the team in the direction of using both exterior and interior cameras in order to properly capture the flight of our competition rocket. The exterior cameras consist of two Runcam 2 4k Editions. These exterior cameras are mounted to the side of the rocket (on the avionics airframe) capturing the fin and ground view as the rocket is launched. Due to the drag that these would produce on the rocket, a shroud made of fiberglass was produced in order to reduce the force on the rocket created by the camera. These cameras are to be manually turned on prior to the CRE Pad Team leaving the launch site. The RunCams are able to capture 1080p video 60 frames per second for an average of 3 hours before the battery dies. In case of a low battery these cameras are wired into a portable battery bank within the rocket which can supply the power for over 5 full recharges of the camera. In addition to this, a 128 GB micro-SD card will store the footage data.

An internal camera bay is to contain 3 GoPro 5 Session cameras. These cameras are to be started via servos controlled via live telemetry with SRAD 1 and 2. Prior to ignition, the team will send a message to the rocket to start these cameras. These cameras do not require shrouding, because they are within the rocket and look horizontally out through a clear screen within the body of the rocket. Each of the GoPro 5 Sessions will store the video data to 64 GB micro-SD cards within each individual system. This allows for easy retrieval and viewing of the footage nearly immediately after the collection of the rocket. The CAD model of the camera bay is presented in Fig. 21.

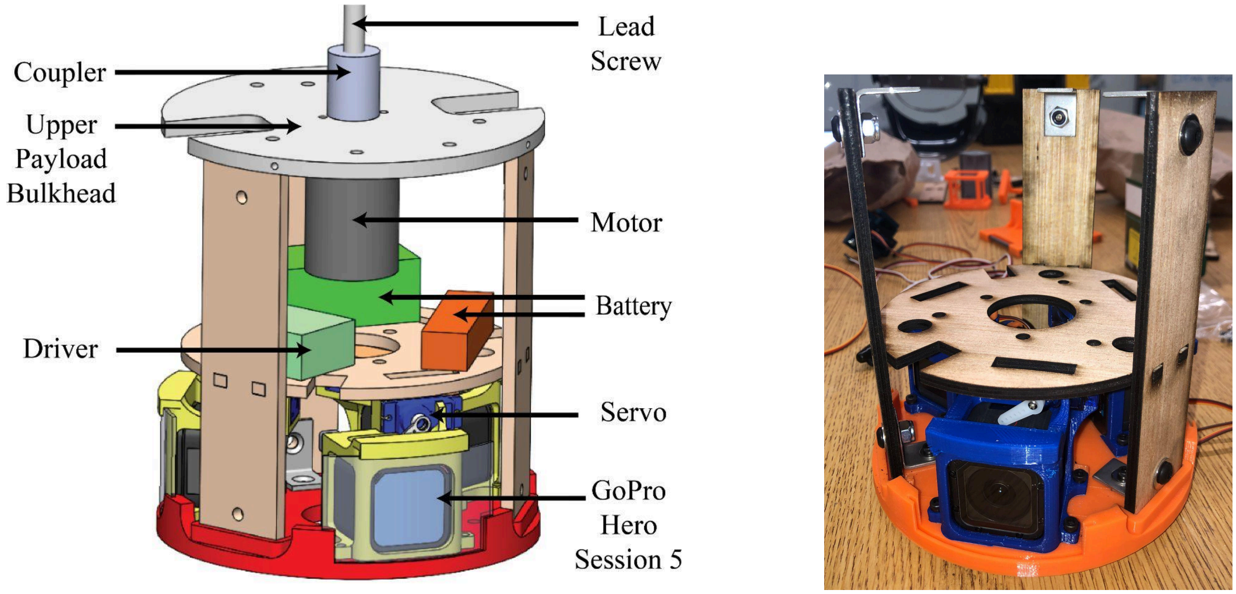


Fig. 21 - Camera Bay CAD (Left), Camera Bay Manufactured (Right)

III. Mission Concept of Operations Overview

A. Overview

The design of CU Later is meant to streamline the assembly, integration, and flight processes. Fig. 22 displays an overview of the mission concept of operations (CONOPS). The white steps labeled 1 through 8 are each of the flight phases of the rocket. The black steps lettered A through C are specifically the flight phases of the CRICKET. Prior to the launch rail integration, the assembly, preflight checklist, safety review, and transportation to the launch pad must take place.

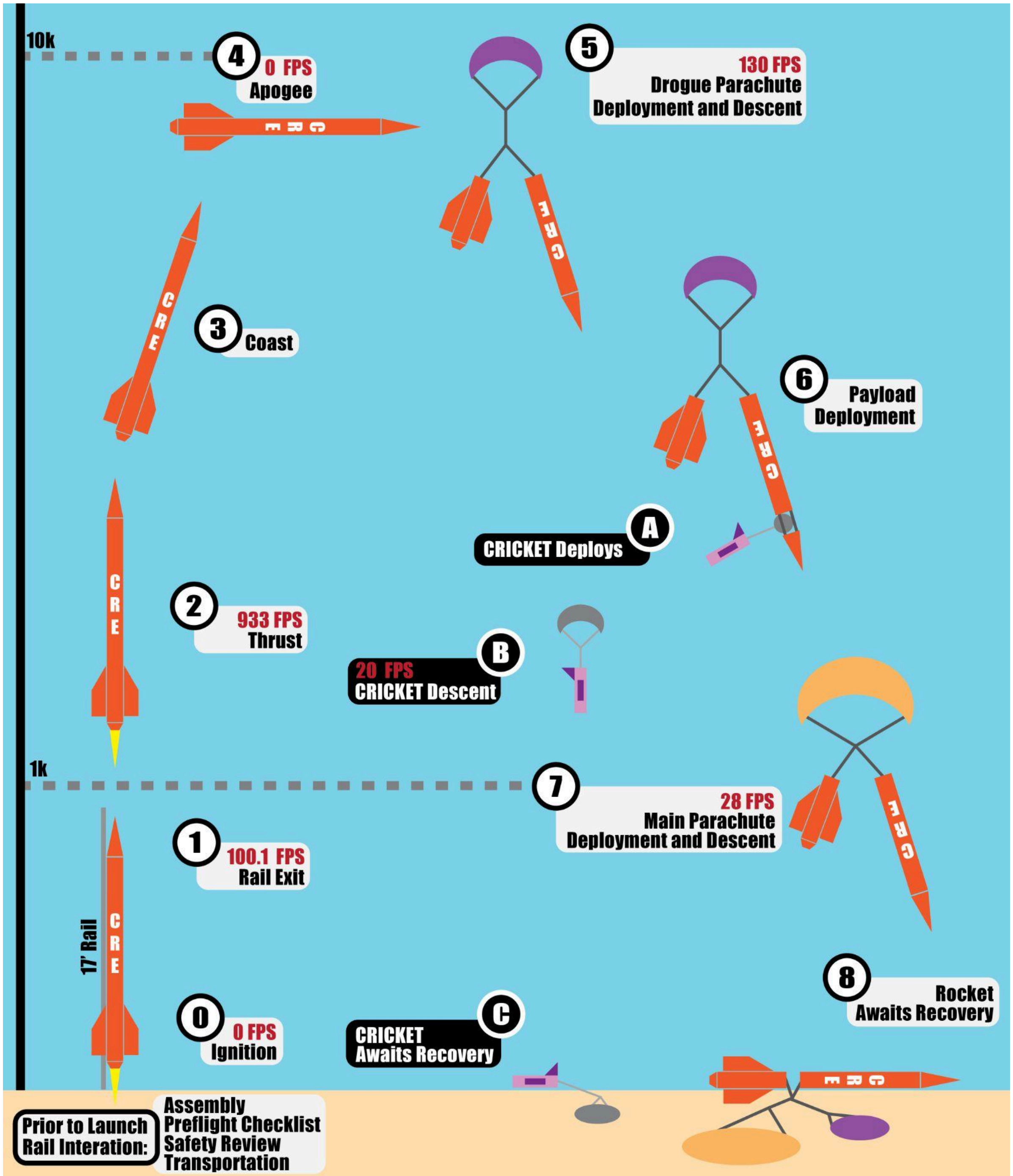


Fig. 22 - Mission Concept of Operations

B. Preflight

Before the launch of the rocket, it first must undergo assembly, review, and transportation. During the assembly phase, the preflight checklists outlined in Appendix A.5 will be utilized to ensure each aspect of the rocket has met satisfaction and is properly integrated. The motor, avionics, and payload airframe sections can be worked on independently until integrated with one another. While three different teams work on each of these sections, other team members can simultaneously work on folding the parachutes, fastening the tender descender, running flight simulations based on weather conditions and documenting the process.

Once each of the sections are fully integrated with one another, the rocket will undergo a preflight readiness review. During this review, the center of gravity, center of pressure, and proper integration will be verified (design elements will have been approved prior to this process). Once this review is complete, the rocket will be loaded into a transportation vehicle and will be taken to the launch pad. From here, the rocket will be loaded onto the rail horizontally, and lifted into its vertical position. Live telemetry will then be established with the rocket. Before ignition (Step 0), a message to the servos via live telemetry will be sent, thus turning on each of the GoPro cameras in the camera bay. External cameras will be set up to ensure footage of the launch is captured.

C. Full Launch CONOPS

0. Step 0

Until the ignition phase is reached, the rocket will sit idle on the pad. The ignition phase will begin the instant the motor grains are ignited for M2500. This will happen once the fire signal is sent to the igniter. Once vertical motion occurs, the rocket will enter liftoff and begin traveling up the rail. Once there is detection of motion, the raspberry pi cameras will turn on. Liftoff will cease once the rocket exits the rail.

1. Step 1

The rocket will exit the rail traveling at approximately 100.1 feet per second (FPS). The motor will continue to burn during this stage. Once the rocket fully leaves the rail, it has exited this phase and has entered the thrust phase.

2. Step 2

The thrust phase is determined by the burnout time of the motor. The M2500 has a burn time of 3.9 seconds from ignition. While this is occurring, a thrust force will cause the rocket to continuously accelerate. The peak velocity during this phase will be 933 FPS. Once the motor has fully burnt out, the thrust phase will conclude and the coast phase will begin.

3. Step 3

The coast phase begins once there is no more thrust causing acceleration of the rocket. Coast will begin immediately after the thrust phase and will continue until apogee is reached.

4. Step 4

When apogee is met, the rocket will have a vertical velocity of 0 FPS. Throughout thrust and coast phase, avionics logs and monitors data across the IMU, altimeter, and GPS. While in the inflight state, the flight status decision system internal to the flight computer looks for median changes in altitude across the previous seconds in order to determine that the apogee, or apex of the flight graph has been reached. Avionics uses the middle point of the three generated points to determine apogee in real time by looking for a global maxima, but defaults to consistent drops across time to reliably determine apogee.

5. Step 5

Once apogee is detected, the avionics will send a signal to the Eagles and black powder charges to separate the motor and avionics body tubes. The pressure difference caused by the CO_2 and/or black powder explosion will break the 2-56 shear pins. As the two tubes separate, the 30 inch diameter drogue parachute will be pulled out and will deploy. The descent under the drogue parachute will be 130 FPS.

6. Step 6

After drogue parachute deployment, a signal will be sent to the payload motor. This will move the nose cone away from the payload body tube, and all the CRICKET to deploy from its housing unit. 10 seconds after this initial signal is sent, the motor will be sent a signal to reverse its direction. This will cause the nose cone to retract back into the payload body tube.

7. Step 7

At 1,000 feet, the tender descender will receive a signal to release the 120 inch diameter main parachute. Once deployed, the rocket will descend at 28 FPS until touchdown with the ground has occurred.

8. Step 8

Once the rocket and parachutes have made touchdown with the ground, they will await recovery. The Featherweight GPS will provide the location of the touchdown to a team member's mobile devices and this will be used during recovery.

9. Step A

After the nose cone moves out of the payload body tube, the CRICKET will deploy from the rocket. As the CRICKET deploys, it will pull a parachute out with it.

10. Step B

The CRICKET will descend at 20 FPS. While it descends, it will collect information on temperature, pressure, humidity, and GPS, and send these signals to the ground station via live telemetry. Once touchdown has occurred, this phase is over.

11. Step C

Once touchdown has occurred, the CRICKET will await recovery. In addition to the GPS on the PCB, an additional Featherweight GPS will transmit the location of the touchdown to a team member's mobile device.

IV. Conclusion and Lessons Learned

A. Conclusion

With CU Later, the CRE team has focused on building upon their 2022 Spaceport America Cup competition rocket. To achieve this, more advanced aspects, such as redesigning the motor, avionics and payload retention, SRAD avionics, and new payload efforts were made. As part of the payload redesign, the CRE works with the NASA Langley Research Center to provide their engineers with usable data on their Close-In Covert Autonomous Disposable Aircrafts, CICADAs, by dropping drones from the rocket around apogee. Along with the redesign, the CRE team wanted to diversify the data being collected, so the team designed and created test aircraft to collect weather data known as the Clemson Rocket Innovative Cruising Kit for Environmental Testing, CRICKET. The avionics subteam has redesigned the avionics bay to include two student research and designed raspberry pi boards along with the general COTS components to track live telemetry of the rocket with a newly designed user interface that presents many data points of the rocket: velocity, acceleration, position, etc. CU Later will show that the Clemson Rocket Engineering team can succeed with simple designs and innovate, diversify, and explore unique and advanced features while flourishing. The success that the CRE team has had in the past and will continue to have is due to the plethora of ingenious minds at Clemson University that want to pursue Aerospace Engineering, and with a growing new member population, the team has its sights on even more success and innovations within the team in the future.

B. Lessons Learned

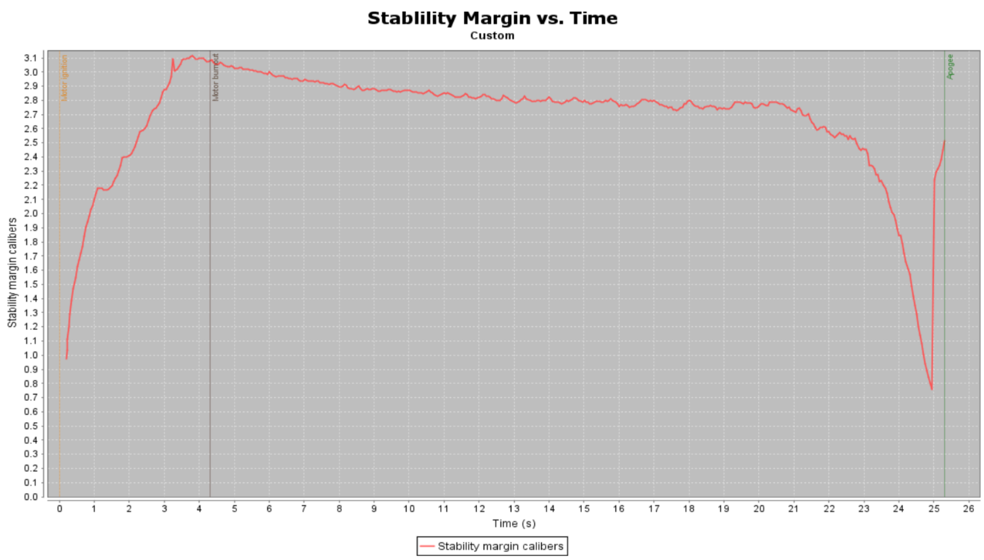
Creating a competition rocket came with many learning opportunities for individuals and the team as a whole this year. A large takeaway from this year is the importance of communication with an emphasis on understanding. Many times leads would give directions on what needed to be done with the rocket, however every now and then there was not a clear understanding on why it needed to happen. This sometimes caused questions throughout subteams, where a member may have an idea to improve what was being done, however this improvement was not useful, because there was no understanding on why something was actually being changed. This made members quickly realize that they did not just need to know what they were doing within their rocket system, but also the reasoning behind it as well which prompted for the opportunity for more improvements as well.

Throughout the rocket build process, timelines became increasingly important. Determining the amount of time that a project would take, as well as when projects needed to be completed for testing was an important lesson to take away this year. Going into the next year with a clear timeline on when rocket systems need to be completed, as well as how the schedule for completion should be organized would help avoid inconsistent long hours working on the rocket because systems were not ready.

Learning this year also involved understanding what the team was doing very well in order to continue it for years to come. This year, the team did an incredible job with engagement within the subteams. Any member that had the desire to contribute to the rocket was immediately plugged in to an area where they could help. The ability for upper leadership to teach and help those who just joined the team was an incredible feat, and should be recognized to attain throughout the future. These lessons among many others will allow the Clemson Rocket Engineering team to improve and continue to grow for years to come.

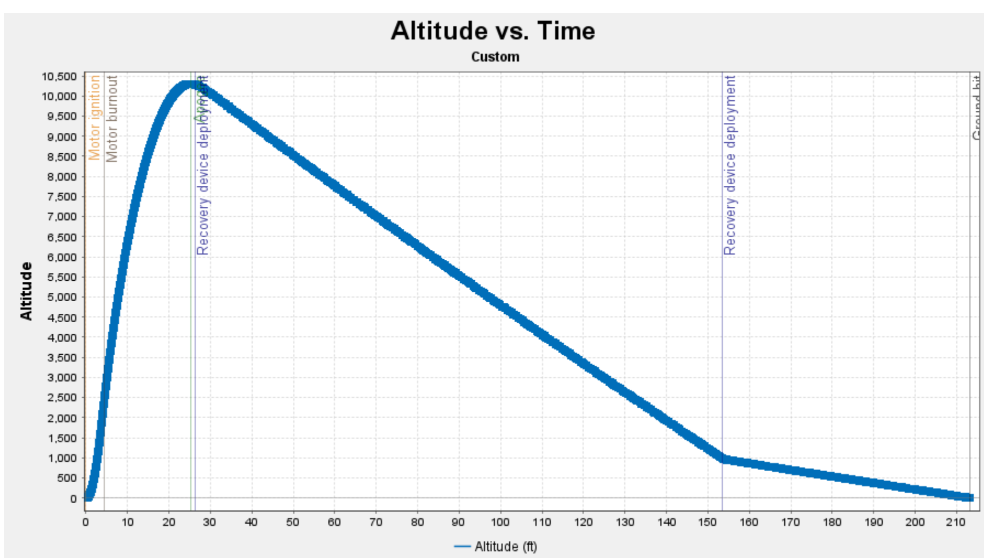
Appendix

A.1 System Weights, Measures and Performance Data



A.1.1 - Stability Margin vs. Time

As shown above in A.1.1, the stability of the rocket over time is graphed for evaluation. Starting at a stability margin of one, the rocket quickly increases to 2.2 in the second following ignition. This upward trend continues until right before motor burnout, reaching a stability margin of 3.1. This is a result of the motor ejecting its fuel from the rocket, making the center of gravity travel farther up the rocket, and away from the center of pressure. As the rocket coasts upwards, the stability drops very little until three seconds to apogee. However, the drogue chute deploys before the stability can drop below 1.0. A.1.2 suggests that the rocket is stable and will be stable for the duration of the flight.



A.1.2 - Altitude vs. Time

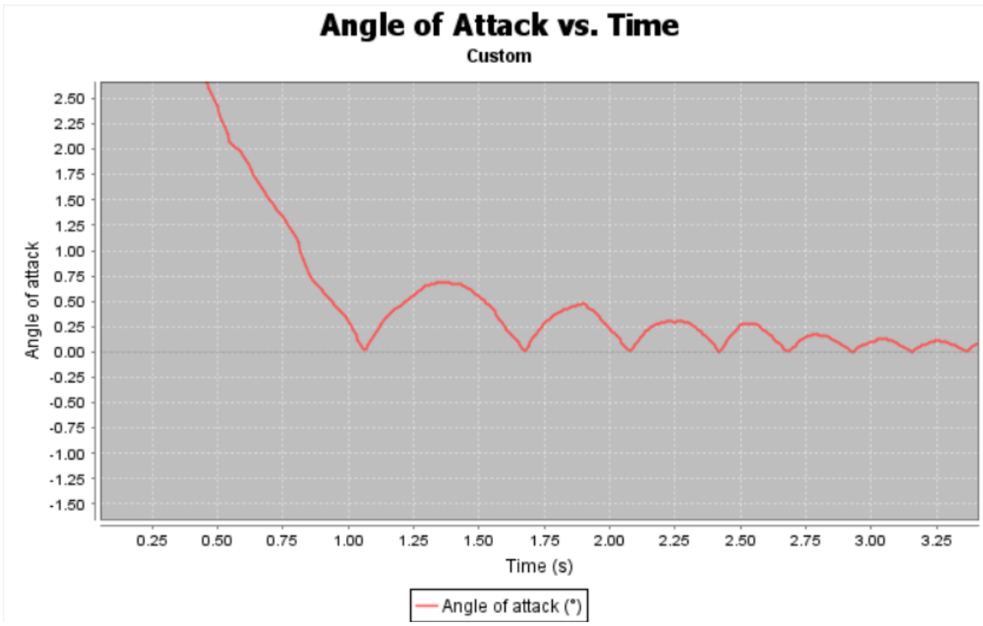
A.1.2 displays the altitude of the rocket over the course of its flight. As can be seen, the rocket deploys a drogue chute at apogee, and then its main chute at 1000 ft above the ground, slowing its descent further. This graph, along with A.1.2 suggest that the rocket will maintain its stability through its flight.

The most likely times that the team expects to launch include 5 am, 11 am, 2 pm, and 5 pm. Each of which and each of these corresponds to different launch conditions that need to be accounted for. If launch is available at sunrise, this would be the optimal choice for launch due to wind speeds being the lowest at this time. To account for the possibility of this option not being available, wind speed data is also collected for the times throughout the day. Launch conditions are most likely to be the least optimal in the afternoon due to surface wind speeds naturally increasing as the day progresses until evening. To account for this, wind speed data was also gathered for the time of 5 pm. This data is collected and organized as seen in A.1.3.

June _18_ 2022		
Altitude [m]	Speed [mph]	Direction (deg)
10	9	225
100	13	180
250	14	180
500	9	150
750	13	200
1000	13	200
1500	14	180
2000	15	225
2500	6	235
3000	16	335
3600	11	335
AVG	12.09090909	222.2727273
Standard Dev	3.015113446	

A.1.3 - Collected Wind data for June 18th, 2022 at 5am

The data is put into OpenRocket's multi-level wind plugin and the information is plotted in an angle of attack vs. time graph as seen in A.1.4.



A.1.4 - Angle of Attack vs. Time

Using the data from the graph. Logarithmic decrement can be used to determine the damping ratio of the rocket for given wind and temperature conditions. The equation below is the expression for the logarithmic decrement.

$$\delta = \frac{1}{n} ln(\frac{x(t)}{x(t+nT)})$$

Where n is the number of the last peak analyzed, which in this case is the third peak, x(t) is the overshoot of the first peak, and x(t+nT) is the overshoot of the last peak analyzed. After obtaining the value of the peaks, the damping ratio can then be found.The equation below is the expression for the damping ratio.

$$\xi = \frac{1}{\sqrt{1+(\frac{2\pi}{\delta})^2}}$$

Evaluating the results, for every case the rocket is stable. As long as the value is below .3 and above .05 there should be no issue with the damping ratio. Referencing the data below, all the data is within an acceptable range despite any wind conditions.

Damping Ratio 5 am		
Year	Max	Min
2018	0.144	0.166
2019	0.151	0.108
2020	0.188	0.150
2021	0.154	0.140
2022	0.172	0.109

A.1.5 - Damping Ratio of Variable Wind Speed at 5am for 2018-2022

Damping Ratio 11 am		
Year	Max	Min
2018	0.157	0.124
2019	0.153	0.134
2020	0.159	0.144
2021	0.144	0.155
2022	0.187	0.092

A.1.6 - Damping Ratio of Variable Wind Speed at 11am for 2018-2022

Damping Ratio 2 pm		
Year	Max	Min
2018	0.162	0.138
2019	0.153	0.138
2020	0.155	0.144
2021	0.161	0.143
2022	0.225	0.093

A.1.7 - Damping Ratio of Variable Wind Speed at 2pm for 2018-2022

Damping Ratio 5 pm		
Year	Max	Min
2018	0.160	0.138
2019	0.154	0.140
2020	0.157	0.144
2021	0.162	0.140
2022	0.157	0.111

A.1.8 - Damping Ratio of Variable Wind Speed at 5pm for 2018-2022

A.2 Project Test Reports

1. *Structures*

The first improvement made to the design and in-house manufacturing of the composite body tubes was the change from 7 layers of fiberglass to 4 layers of fiberglass. This change represents a significant decrease in weight of the airframe, which was critical to reallocate weight to other areas of the rocket and to improve apogee. This change was first developed through estimation on strength based on the extreme strength of the tubes made last year, and a hypothesis that this change would represent a worthwhile weight reduction while maintaining sufficient strength. In order to confirm feasibility, test specimens of 3, 4, and 5 wraps of carbon fiber were manufactured, and underwent axial compression testing up to 600 pounds, approximating the forces during launch, and the four layer tube was easily able to withstand this force, and was a great proof of concept.

This test was a success, providing a strong proof of concept and supported the decision, along with advice from our mentor, that our manufacturing process was capable of producing sufficiently strong composite tubes much thinner and lighter than previously used.

A new step in our tube manufacturing process of composite body tubes was the inclusion of an inner wrap of peel-ply between the initial mylar wrap and the fiber. This addition made the finish on the inside of the tube much rougher when compared to the smooth finish left by the mylar. This was advantageous because it allowed for bulkheads to be permanently epoxied in place which was previously impossible due to the smooth finish. Permanently installed bulkheads were done whenever possible to aid in a significantly quicker assembly of the rocket and for added strength compared to screws. Not all bulkheads were able to be attached this way due to layout of the internal components and needing to take certain components in and out of the rocket, in which case these bulkheads were installed with screws as before.

This addition was tested with carbon fiber bulkheads like those used on the rocket, and the process proved to be easier, more consistent, and more structurally sound than was previously possible. The test was deemed a success, confirming the use of the additional layer of peel ply.

Other improvements made to the manufacturing process of the composite tubes, learned after the manufacture of the 2022 rockets, allowed for much more consistent and higher quality body tubes to be constructed. The majority of the tubes constructed for the 2022 rocket were out of round, some by over 1/16 in, which made it extremely difficult to integrate machined aluminum bulkheads, and after some experimentation and consultation with our mentor, a new process was developed. Previously, body tubes, while curing on the blue tube mandrels, were suspended horizontally between two stands. This allowed the mandrels to slightly deform out of round, resulting in the inconsistent roundness of the tubes. Additionally, this deformation, along with improper wrapping of the mandrel with mylar, meant that occasionally it would be impossible to remove the cured body tube from the mandrel. To fix these issues, a new process where the tightness of the mylar was first closely checked, then the the tightness of the composite fabric was closely monitored during the wrapping, ensuring the epoxy was not brushed on with too much force. Finally, the most important improvement was allowing the mandrel to stand vertically, in a warm area of the shop. This not only eliminated the horizontal deformation issue, but also ensured the epoxy was able to cure relatively quickly, disallowing the epoxy or composite to slide down the mandrel.

This process greatly improved the consistency and quality of the body tubes produced by the club. Every tube constructed had consistent epoxy coverage, easily came off of the mandrel, and cured much rounder, allowing for smooth integration of round bulkheads and couplers. These tests were extremely successful, and vastly improved the manufacturing capabilities of the club.

As a part of the testing scheme of the rocket, multiple ejection tests were performed, both with full size ejection charges and with igniters to confirm correct sequencing with avionics flight data. The first tests were completed with 33g CO2 cartridges and 4 6-32 shear pins, and were deployed using the avionics system with flight data to confirm correct timing and successful deployment. The CO2 cartridges were initiated by an Eagle obtained from Tinder Rocketry.

During the first two ejection test avionics successfully and correctly deployed the ejection charges, however the shear pins were not sheared. It was determined that the failure for the first attempt was due to a shortage of black powder to ignite the mechanism within the Eagle to puncture the CO2 cartridge. The second attempt's failure was due to a shortage of lubrication within the Eagle to allow smooth puncturing and then depressurizing of the CO2 cartridge. Learning from the mistakes made in the first two tests, corrections and additional parameters were added to ensure the tube was properly sealed. All gaps were further sealed with putty, and the puncture charge was adjusted according to the manufacturer's recommendations, as well as additional lubrication. The next tests were performed with these improvements, and though the charges were successfully ignited, the shear pins were still able to resist the force of the deployment. A reexamination of our calculation was made and it was determined that the best plan of action was to test the ejection system with a 33g CO2 cartridge without any shear pins to ensure there was enough force to overcome the friction. This test with the same set up as the third experiment was deemed a success. The next step taken was to test the system with smaller shear pins. The fifth test that took place included four 2-56 shear pins, with no other change to the set up from the third and fourth test. This test was also deemed a success launching the tubes apart by nearly 3ft. After examination, it was determined that larger 45g CO2 cartridges could be used, with the 2-56 shear pins, allowing for a higher factor of safety for deployment of the parachute.

Once avionics completed their hardware system, a fully integrated test with the rocket was completed using igniters instead of full size ejection charges. This test showed that the system was able to ignite both the drogue and main charges, however, they were ignited at the same time without regard for simulated altitude. This problem was determined to be an error in the hardware, and was subsequently fixed. The system was tested once again with igniters and the system performed correctly. Unfortunately, this issue was not discovered and resolved until it was too late in the day to complete an ejection test with the full rocket assembly, but this test will be completed in the coming weeks.

These tests allow us to finalize the use of the primary charge of 45g of CO2 with a redundant charge of 7g of black powder, with a tender descender with a 0.5g black powder charge for the deployment of main.

2. *Avionics*

In order to give the conditions of a flight without needing to launch a rocket, the avionics team performed a vacuum test of the avionics SRAD 1 and SRAD 2 systems on February 10th, 2023. Each system was placed within the vacuum chamber and used an LED output to indicate the current state of the flight computer throughout the test. Using a shop-vac, the team was able to reduce the pressure of the sealed chamber over time. During this process, each system output to a second sequence of LED's its believed altitude, and as pressure was decreased, this value increased from the normalized starting altitude. As apogee was reached, and the pressure began to increase within the chamber, both systems correctly detected apogee and changed their flight state from inflight to descent

On April 16th, 2023 the avionics team performed thermal altimeter battery drain testing of the avionics SRAD flight computer, a Raspberry Pi 4B, as well as the COTS flight computer, a Stratologger CF. Through the use of a hot plate and a bucket with sand, a consistent thermal source was created for the electronics. This created a constant environmental temperature of around 41ºC, simulating the temperature conditions of New Mexico in June, while the Pi's processor temperature hovered around 82 degrees celsius. Beginning at approximately 3PM in the afternoon, the test began and lasted for 5 hours. This test was a success. Although the SRAD battery was tested and found to be still within operating voltage, the test could not be continued overnight due to safety concerns in the case of an issue/hazard. Due to the nature of the test, the flight computer ran an abridged version of the flight software, contributing to the power savings. By deriving a linear equation from the battery voltages, the system could have lasted over 10 hours, or twice the expected run time. From our calculations of current draw by the SRAD system through testing, experience, and datasheets, it was determined that even under the full computational load of the flight computer, the system would last beyond the 5 hours in this test. From this test, the team concludes that the avionics system can maintain accurate altitude measurements even when on and experiencing flight conditions.

Over the course of the year, the avionics team has performed multiple tests using flight simulation data. This data was generated during a launch in October on which a system collected data for a rocket with an apogee of approximately 1800 feet. Throughout the year, the team has used this data set in order to test and experiment with new features of the avionics system. Using the flight data the team has been able to test the onboard camera system with remote startup. As data is being processed by the flight computer pre-simulated flight, the ground station user is able to send commands to the flight computer to ready SRAD 2, start each GoPro camera, and disarm the system if needed.

The team has used this flight data over the course of the year to test the drogue deployment system. The team has successfully found through multiple iterations of both software and hardware that the drogue deployment system is able to correctly detect and deploy the drogue parachute at apogee, as well as SRAD 1 properly informing SRAD 2 through BuddyComm that it has detected apogee.

Over the months of February and March, the avionics team performed multiple tests involving the avionics SRAD telemetry system in order to verify its accuracy and reliability. This culminated in a test of the telemetry system at approximately 1000 feet in distance between sets of buildings. While the distance is only part of the expected distance between the rocket and the team at the Spaceport America Cup, the team believes that the number and proximity of large buildings, which will not be present at the competition, and their effects of RF transmission of signals is a proxy for the distances expected before during and after the launch. While a longer distance telemetry test of approximately three miles was planned, this was unable to be completed due to logistical issues during the semester.

On March 14th, 2023, the avionics team conducted a telemetry transmission test at approximately 1000 feet across Clemson's campus. At one location, a team was positioned with the flight computer as well as all required components for the system. At the other location, a team sat with the ground station telemetry software, ready to receive data from the flight computer team. The teams were in a partial line of sight, and transmitted data in real time for over fifteen minutes with zero long term dropouts in overall connection. The team recorded a 99.87% message percentage rate throughout the test. As the flight computer team moved throughout their location, the ground station team saw correct/expected changes in measurements reflected on the ground station software, this included changes in altitude, acceleration and gyroscope data on all three axes, as well as GPS location, for example. The only dropouts in data that the ground station team encountered were due to a few loose wires associated with the flight computer due to its position on a breadboard, and the wiring not being secure. This test was a success, as the avionics telemetry system demonstrated its ability to transmit data consistently over large distances and be received, processed, and displayed correctly by the ground station in real time.

3. *Payload*

On February 9th, 2023, the payload team conducted two tests on a pneumatic system being considered for being the payload system's actuation mechanism. The first of these tests included starting at 30 PSI, and through intervals of 10 PSI, counting how many complete actuations (i.e. how many times the pistons would expand and retract) before the tank was fully depleted of air. This data, as seen in A.2.1 below, led the team to conduct testing with #4-40 lead screws starting at 100 PSI

PSI Being Tested	Number of Actuations Completed	Comments
30	0	30 psi was not enough pressure to complete one actuation
40	1	One complete actuation was completed slowly
50	1	One complete actuation was completed slowly
60	3	The first complete actuation was quick, and the second and third complete actuations were slow
70	3	The first and second complete actuations were quick, and the third complete actuation was slower
80	3	Three complete actuations were completed at full speed
90	4	Four complete actuations were completed, the first two were quick, and the last two were slow but complete

100	5	The first two complete actuations were at full speed, getting slower with the last three actuations
110	5	The first three complete actuations were at full speed, getting slower with the last two actuations

A.2.1 - Pneumatic Testing Results at Varying PSI Values

The second test involving the pneumatic system was conducted also on February 9th, 2023. This test consisted of one nylon #4-40 shear pin being secured through a composite tube into a threaded bulkhead. This test was completed three times, once at 100 PSI, once at 110 PSI, and once at 120 PSI. The results of this test are shown in A.2.2 below. Out of the three tests conducted, none of them were capable of breaking a singular shear pin.

PSI Being Tested	Number of Shear Pins in the Tube During Testing	Results
100	1	The bulkhead wanted to move up, however, the shear pin did not break.
110	1	The bulkhead wanted to move up, however, the shear pin did not break.
120	1	The bulkhead wanted to move up, however, the shear pin did not break.

A.2.2 - Pneumatic Testing Results with Shear Pins

On March 7th, the payload team also conducted testing with the DC motor and lead screw system to determine how much added weight the motor was capable of moving. The motor used for this test was a GoBilda 12VDC Motor with 8mm REX Pinion Shaft. Weight was added to the system two different ways. When weight was added "on one side" this means all of the weight was added to one CRICKET bay. When weight was added "on two sides", this refers to the added weight being evenly distributed between two of the CRICKET bays. Excess weight of 1000 grams was initially added and tested to determine a max threshold. From here, weight was added in 100 gram increments starting at 200 grams up to failure to determine the added weight's range. It was determined that between 400-500 grams was the max amount of weight the motor could handle. Both 440 grams and 460 grams were added to the system to test until failure. This data is shown, in order, below in A.3.3. Because of this data, it was determined that a motor with higher torque would be required to complete the payload's required tasks. This conclusion led the payload team to the INJORA RC Motor 550 21T Brushed Motor which has a stall torque of 310 g.cm.

Amount of Weight Added (grams)	Did it Work?
1000 (on one side)	No
1000 (on two sides)	No
200 (on one side)	Yes
400 (on one side)	No
400 (on two sides)	Yes
500 (on two sides)	No *but very close
600 (on two sides)	No
440 (on two sides)	Yes

460 (on two sides)	No

A.2.3 - Motor Load Testing Data

Following the selection of the INJORA 550 Motor, the payload team tested motor control and throttle signal format. When the HobbyWing QUICRUN 1060 Brushed ESC motor driver was selected to work with the motor, it was uncertain what the Pulse Width Modulation (PWM) signal was and its relation to the motor's speed and direction. To determine these data points, an Arduino Uno and a Raspberry Pi code was created to send control signals to the driver. The lowest pulse width was determined to be 500 microseconds and the largest pulse width was determined to be 2500 microseconds. Using these numbers, it was determined that 1500 microseconds was the point at which the motor did not rotate. Values below 1500 microseconds rotates the motor counterclockwise and values above 1500 microseconds rotates the motor clockwise. These values allow the team to code the flight code for motor deployment.

A.3 Hazard Analysis

Hazard	Management	Mitigation
COTS motor	Handling	Delicately hold and move, avoiding any excessive force and harsh contact with other objects.
	Storage	Store inside of a labeled container in a temperature-controlled environment, away from any sources of ignition.
	Transportation	Store inside of a labeled container which is secured in mode of transportation to minimize movement and interaction with other materials or sources of ignition.
Black powder	Handling	Delicately hold and move, avoiding any excessive force and harsh contact with other objects.
	Storage	Store in a sealed, labeled container in a temperature-controlled environment, away from any sources of ignition.
	Transportation	Store inside of a sealed, labeled container which is secured in mode of transportation to minimize movement and interaction with other materials or sources of ignition.
Carbon dioxide cartridges	Handling	Delicately hold and move, avoiding any excessive force and harsh contact with other objects.
	Storage	Store inside of a labeled container in a temperature-controlled environment. Ensure the cartridge itself is sealed.
	Transportation	Store inside of a labeled container which is secured in mode of transportation to minimize movement and interaction with other materials.
E-matches	Handling	Delicately hold and move, avoiding any excessive force and harsh contact with other objects. Avoid accidental power connection.
	Storage	Store inside of a labeled container away from other electronics and potential power sources
	Transportation	Store inside of a labeled container which is secured in mode of transportation to minimize contact with electronics and potential power sources.

A.3.1 - Hazard Analysis

A.4 Risk Assessment

The risk assessment matrix shown in A.4.2 details risks associated with each stage of CONOPS, with the stage of CONOPS defined with a number in parenthesis preceding the risk. The risk is defined, along with possible causes, the pre-mitigation risk, the mitigation, and the post-mitigation risk. The level of risk is determined by how likely the possible cause is, and how the possible cause could interfere with mission operations or harm personnel on or offsite. The pre-mitigation and post-mitigation risks are assigned a number on a scale from 1-10 , with 1 being of very little to no risk and 10 being the highest risk. This number ranking was defined to easily quantify the assessed risk for easy reference during design, manufacturing, testing, and operation. The risk assessment number ranking is summarized in A.4.1 below.

1-3	Extensive testing to validate and verify heavily mitigates the risk.
4-6	COTS solution on the rocket is already empirically verified by manufactures and work under a given set of conditions from the manufacturer. Integration with the rocket systems still needs testing.
7-9	Operation is purely theoretical from good engineering research and design but has not yet been verified through testing or fabrication.
10	Operation is purely theoretical and cannot be verified in any manner

A.4.1 - Risk Assessment Ranking

Risk	Possible Causes	Pre-Mitigation Risk	Mitigation	Post-Mitigation Risk
(Prior to Launch Rail Integration) Rocket falls from the launch rail during prelaunch operations	Rail button tear out	3	Set up rocket in test launch rail to verify rail button security.	2
	Improper rocket to rail alignment	2	Set up rocket in test launch rail to verify how the rocket should be placed on the rail safely.	1
(Prior to Launch Rail Integration) Recovery system deploys during prelaunch operations	Accelerometer failure	5	Test the accelerometer readings prior to loading the recovery system into the rocket to ensure accurate data collection	2
	Barometer failure	5	Test the barometer readings prior to loading the recovery system into the rocket to ensure accurate data collection	2
	Software Bug	5	Test the recovery system software with simulated and actual accelerometer and barometer readings	2
(0) Solid propellant explodes when ignited	Propellant grain deforming/cracking	7	Pressure testing on the motor airframe section	2
	Propellant separating from propellant grain	4	Visually inspect the propellant for any breaching from the propellant grain during motor assembly	2
	Clogged Nozzle	3	Visually inspect the nozzle prior to loading the rocket on the pad	2

Risk	Possible Causes	Pre-Mitigation Risk	Mitigation	Post-Mitigation Risk
(1 & 2) Rocket strays from projected flight path	Low launch rail departure velocity	3	Verify optimal weight and motor for desired launch rail departure velocity using launch simulations.	1
	Winds and wind gusts	6	Use stability analysis with launch simulations to determine maximum wind allowable for launch.	2
	Excessive rocket roll	5	During fabrication, minimize openings to the inside of the rocket and optimize center of gravity location using symmetrical parts & distributed weight.	2
	Fin misalignment	8	During fabrication, use a precise 3D printed fin jig to ensure fin alignment for attachment to the motor airframe section.	2
	Fin tear out	8	During fabrication, attach fin shoulders to the inner motor airframe and attach fin to the outer motor airframe. Verify by performing fin deflection testing.	2
(5) Drogue parachute fails to deploy successfully shortly after apogee	Accelerometer failure	5	Test the accelerometer readings prior to loading the recovery system into the rocket to ensure accurate data collection.	2
	Barometer failure	5	Test the barometer readings prior to loading the recovery system into the rocket to ensure accurate data collection.	2
	Software Bug	5	Test the recovery system software ignites e-matches at appropriate time.	2
	Shear pins fail to shear	8	Determine sufficient quantity of carbon dioxide for pneumatic separation with shear stress calculations. Verify with ejection testing.	3
	Battery Depletion	5	Select a battery with sufficient capacity and verify with extended testing in a thermal chamber.	1

Risk	Possible Causes	Pre-Mitigation Risk	Mitigation	Post-Mitigation Risk
(6) Payload fails to deploy successfully following apogee	Nose cone does not separate from upper airframe	2	Through extensive testing, actuate the coupler to drive the nose cone up and hold it in place.	1
	CRICKETs are stuck in the airframe	2	During fabrication, thorough clearance is allotted allowing the CRICKET to fall.	1
	Nose cone separates but does not retract	2	Through extensive testing, actuate the coupler to drive the nose cone down and back into the upper airframe. Determine correct time to retract nose cone and verify through flight simulation	1
(7) Main parachute fails to deploy successfully at target altitude	Accelerometer failure	5	Test the accelerometer readings prior to loading the recovery system into the rocket to ensure accurate data collection.	2
	Barometer failure	5	Test the barometer readings prior to loading the recovery system into the rocket to ensure accurate data collection.	2
	Software Bug	5	Test the recovery system software ignites e-matches at appropriate time.	2
	Shear pins fail to shear	8	Determine sufficient quantity of carbon dioxide for pneumatic separation with shear stress calculations. Verify with ejection testing.	3
	Battery Depletion	5	Select battery with sufficient capacity and verify with extended testing in a thermal chamber	1
	Shock cord separates from rocket body	8	Calculate maximum parachute deployment speed and verify speed is not exceeded in flight simulations	3

A.4.2 - Risk Assessment Matrix

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A.5 Assembly, Preflight, Launch, and Recovery Checklists

1. **Assembly:**
    a. Pre-Assembly:
        i. Confirm correct COTS deployment settings
        ii. Confirm correct SRAD deployment settings
    b. Assembly Eagle [1]
        i. Putty Pyro Charges
        ii. Load Black Powder
        iii. Lube spring
        iv. Screw in CO_2 Cartridge
    c. Bolt in Eagle to bottom bulkhead (Insert from bottom)
    d. Properly seal the bottom bulkhead
        i. Putty the Connection between the DB9 outbreak and the DB9 connector
        ii. Putty the Eagles rim
    e. Backup method for drogue deployment
        i. Load 7 grams of black powder into a baggie with a pyro charge in the middle
        ii. Tape to the bottom bulkhead
    f. Tinder Descendar (Deployment method for the main parachute)
        i. Load black powder
        ii. Connect one link to the permanent eyebolt and the other to the flap holding the main parachute in
    g. Connect pyro charges to DB9 outbreak
        i. Eagle: ports 1 and 4
        ii. Backup black powder: ports 2 and 4
        iii. Tinder Descendar: ports 5 and 3
        iv. Ensure no wires are touching and that they are tightly screwed into ports
    h. Begin to insert the Avionics bay into the top of the tube
        i. Ensure the cutout of the mount lines up with eagle
        ii. Connect the DB9 connector to the DB9 terminal on the bay, ensuring a proper and tight connection
    i. Secure Avionics Bay
        i. Ensure the eyebolt mount is all the way into the hole on the bottom bulkhead
        ii. Screw in the four bolts connecting the upper-bulkhead to the upper-ring
    j. Screw in the main eyebolt to the eyebolt mount
    k. Tie the shock cord to the main eye bolt
    l. Connect the motor tube to the avionics tube
        i. Slide the coupler (already epoxied to the motor tube) into the bottom of the avionics tube
        ii. Insert the four 2-56 shear pins into the holes connecting the avionics tube to the coupler
    m. Connect Payload and avionics tubes together
        i. Payload is already assembled including a proper connection between the nose cone and the coupler
        ii. Place the payload coupler into the top of the avionics tube
        iii. Screw in four bolts successfully connecting the avionics tube to the payload coupler

2. **Preflight:**
    a. Rocket entering final safety check
    b. Rocket is not vertical, pad team at pad
    c. Rocket is vertical, pad team at pad
        i. Verify accurate Featherweight GPS readings from pad team members with Featherweight ground stations.
        ii. Pull COTS power on switch using magnetic pole
            1. Verify power on through Stratologger startup beeps
        iii. Open ground station telemetry link from base camp
        iv. Pull SRAD 1 power on switch using magnetic pole

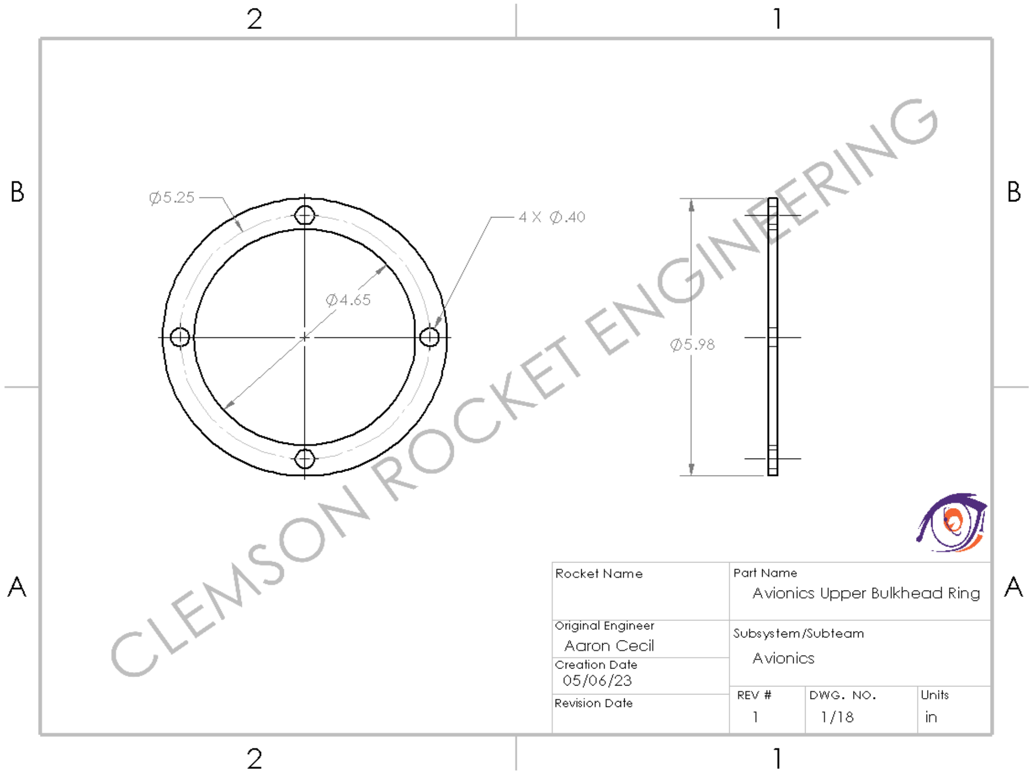
            1. Verify power on and accurate main deployment altitude through startup beeping output
        v. Repeat process for SRAD 2 power on switch
        vi. Verify telemetry connection to ground station, verify preflight state, and report valid message rate
    d. Rocket is vertical, pad team at base camp
        i. Reverify preflight state of flight computer
        ii. Send ready command from ground station to rocket to verify system integrity and buddy comm connection to SRAD 2
            1. Note: Ready command is <u>NOT</u> an arming command and has no relation to any flight events, only used as indicator that system is functioning
        iii. Send camera 1 activation command from ground station to activate first camera
        iv. Repeat for cameras 2 and 3. Wait for each status indication light to be set green before proceeding to the next camera.
        v. Monitor state of flight computer before launch through telemetry readouts

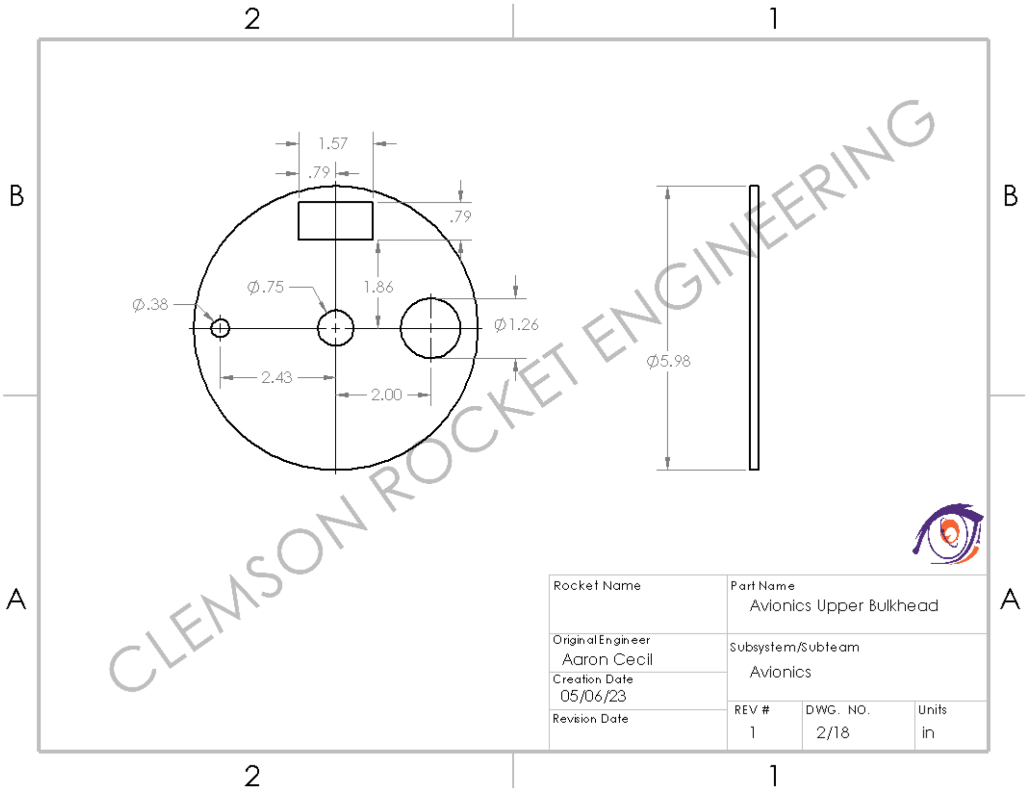
3. **Launch:**
    a. Ascension
        i. Confirm that SRAD 1 has entered flight mode
        ii. Monitor live telemetry data for rocket state
        iii. Monitor Featherweight ground station readouts
    b. Apogee and drogue descent
        i. Confirm deployment of drogue chute at apogee
        ii. Compare expected drogue descent rate to live descent rate and data from Featherweight GPS tracker
        iii. Look for payload deployment indicator on GUI and begin tracking CRICKETs via software defined radio
    c. Main deployment and main descent
        i. Visually confirm main deployment at 1000’ AGL
        ii. Confirm flight computer recognition of main deployment
    d. Touchdown:
        i. Record touchdown GPS location from ground station and Featherweight
        ii. Record CRICKET final GPS locations
4. **Recovery:**
    a. Flight completed, recovery team not deployed
        i. Determine rocket location from GPS coordinates from telemetry system, as well as Featherweight GPS
            1. Plot course to rocket using mapping tool, such as Google Earth
            2. Make note if backup drogue charge was used or is unfired
        ii. Determine location of all CRICKET drones, and graph on map alongside rocket
            1. Determine plan for drone recovery order
        iii. Fill extra water jugs and discuss plan with upper leadership
            1. Bring pins for arming switches
        iv. Pick up GPS radio bag from recovery tent and wait for confirmation
    b. Flight completed, recovery team deployed
        i. Follow course to the rocket, covering as much distance as possible by car
        ii. Leave car only when team can not reasonably go further
            1. Record GPS coordinates of car and relay to each team member
            2. Record time of leaving car
            3. Confirm lock on GPS bag reestablished and begin walking towards rocket
    c. Recovery team deployed, rocket not located
        i. Walk towards rocket

1. Form a horizontal line to increase search radius
2. Perform mandatory radio check-ins with base camp every 15 minutes

d. Rocket located and recovered
   i. Perform mandatory radio checks as needed
   ii. Assess state of rocket
      1. Locate all sections of rocket
      2. Insert pin arming switches back into rocket, disabling power from SRAD systems
         a. Disables backup drogue charge, if not fired during flight
      3. Record apogee altitude
         a. Use Stratologger beeping output to determine apogee altitude for scoring at basecamp, and to provide chain of evidence
   iii. If in recoverable condition (per DTEG definition)
      1. Assess what sections can be carried by whom
      2. Carry sections of rocket to car
   iv. If in non-recoverable condition
      1. Assess damage and effects upon recovery
         a. Ie: Shattered piece of tube, how to properly recover all pieces
      2. Determine best way to safely recover rocket sections
         a. Depending on conditions of sections
      3. Bring sections of rocket back to car
   v. Once rocket is recovered
      1. Begin course to recover CRICKET drones
      2. Ask for update from team at base camp regarding location of drones
      3. Execute plan determined in 4.a.ii.1
      4. Recover each drone, regardless of condition, and return and place in car once all are collected
   vi. Return to base camp via car

A.6 Engineering Drawings

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Original Engineer
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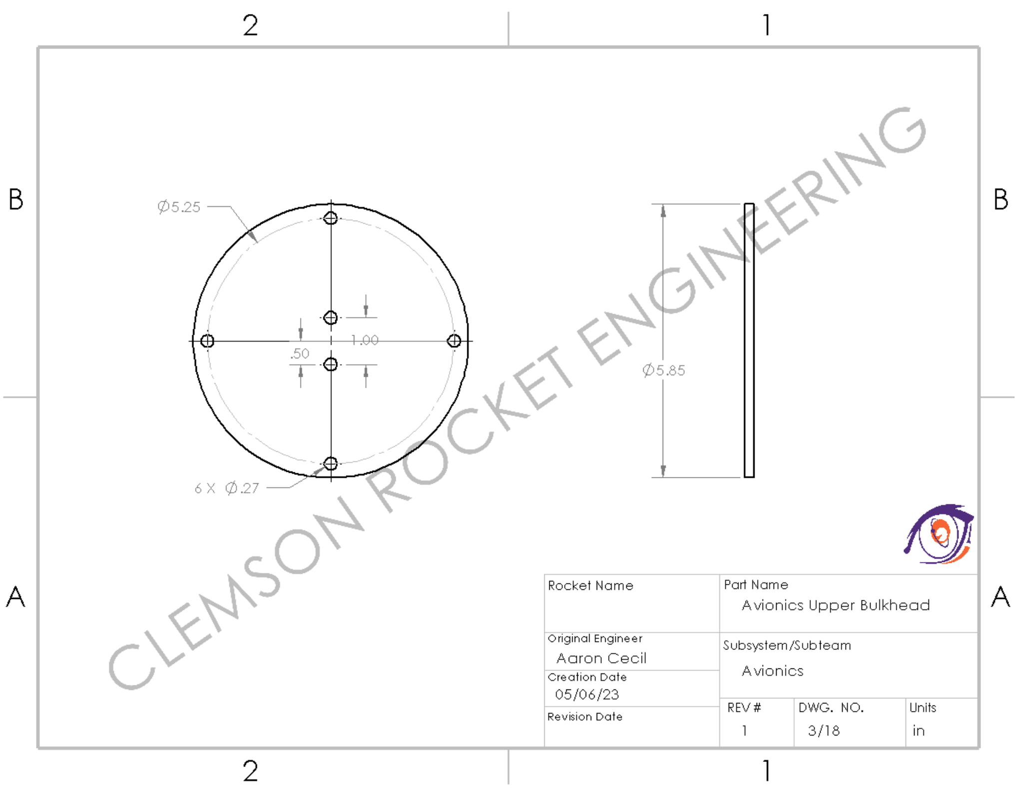
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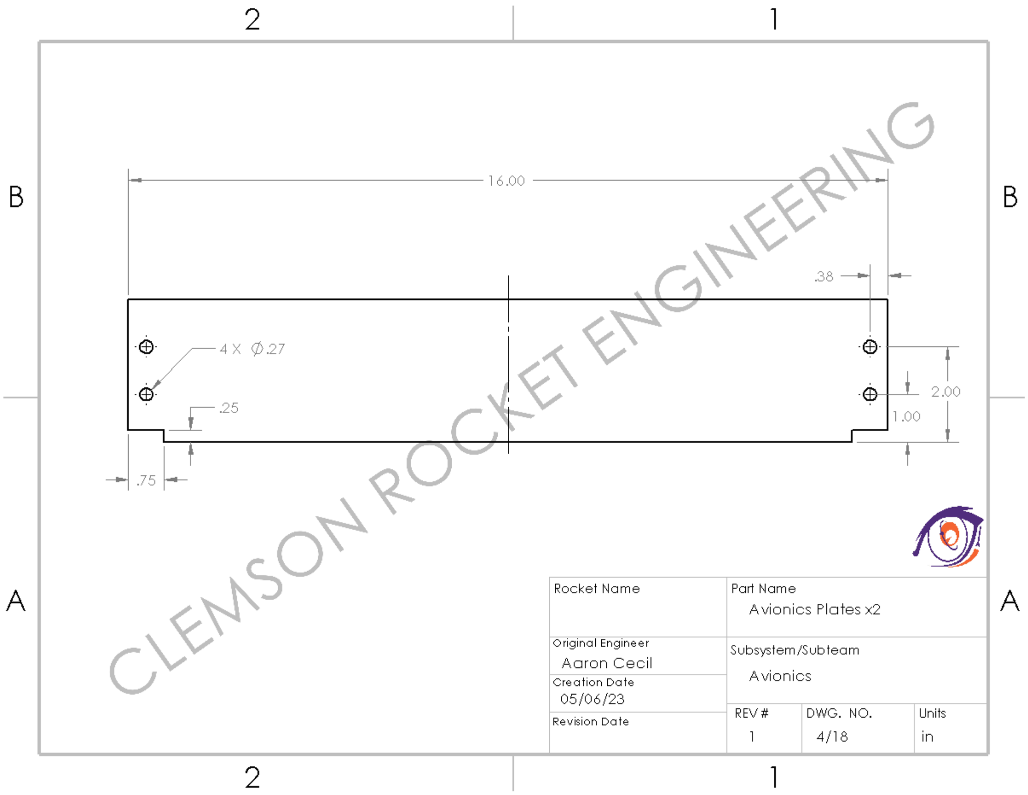
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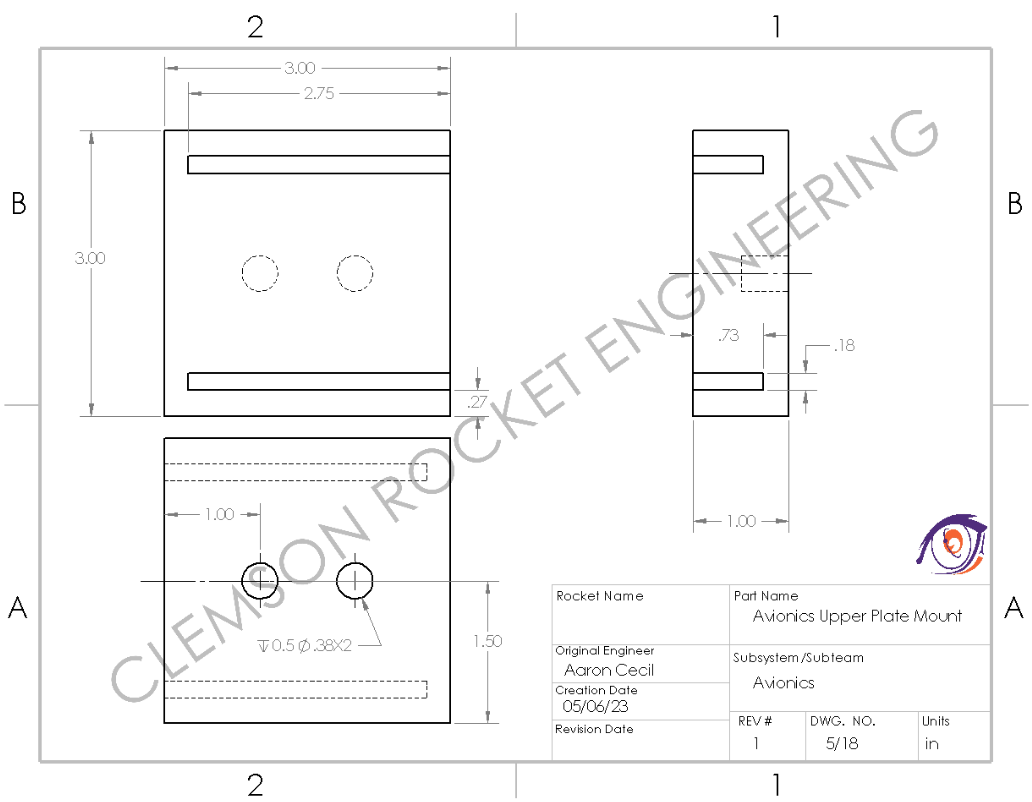
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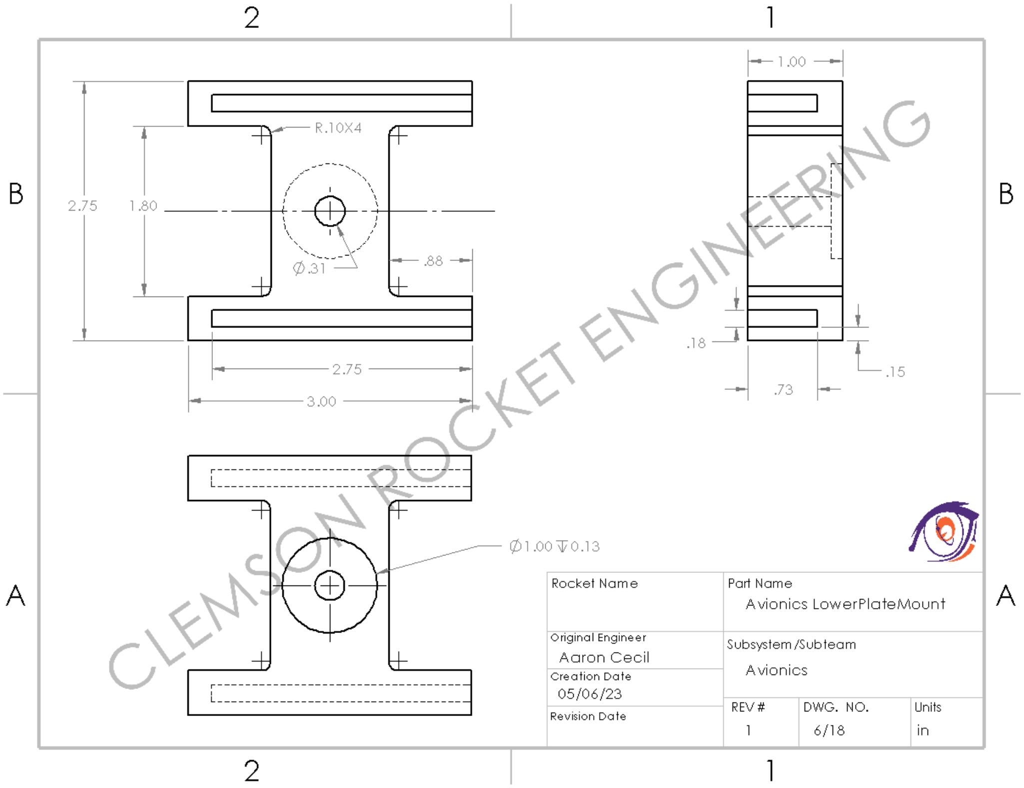
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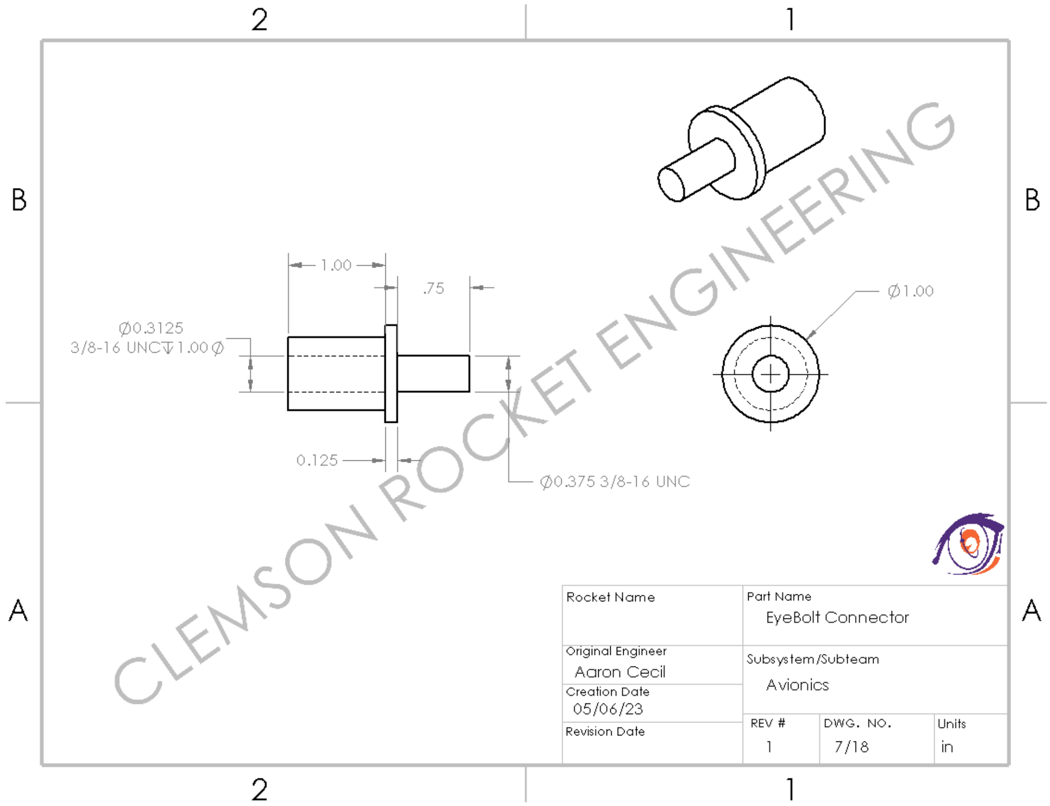
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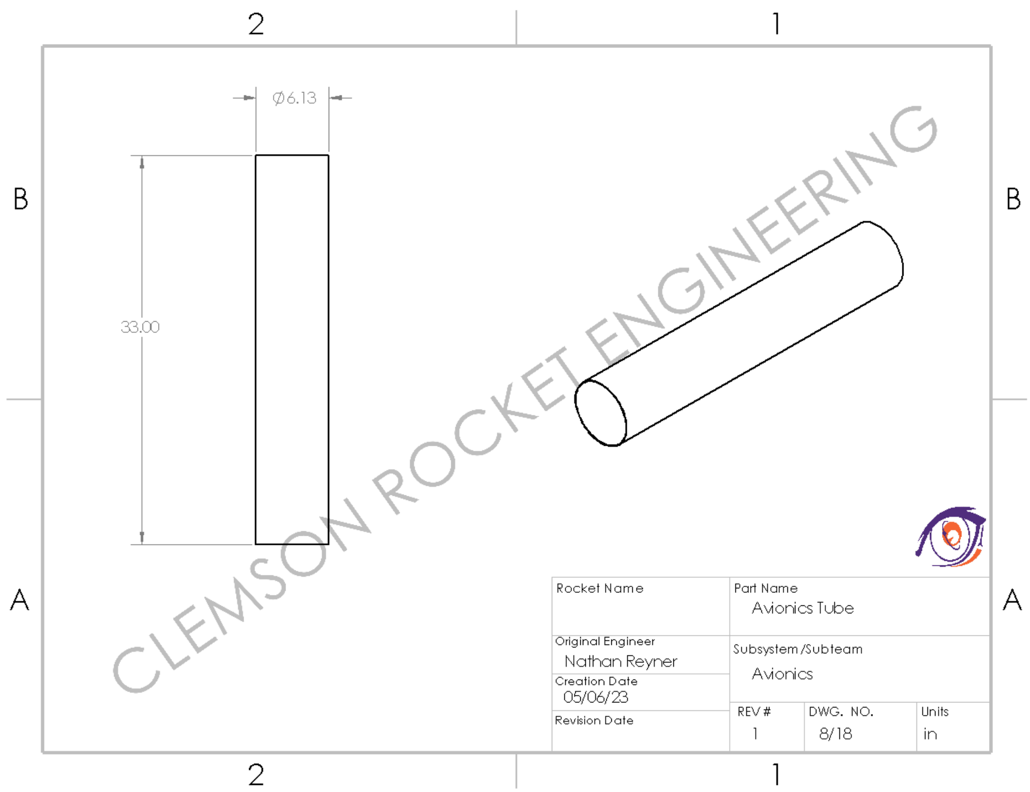
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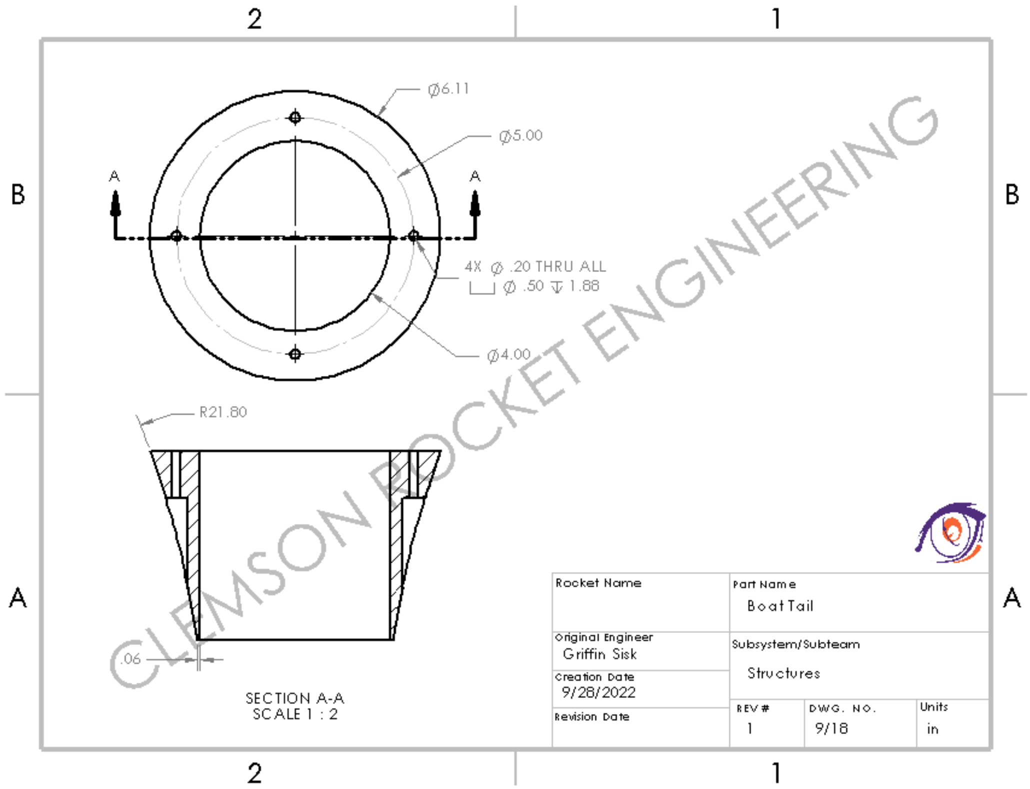

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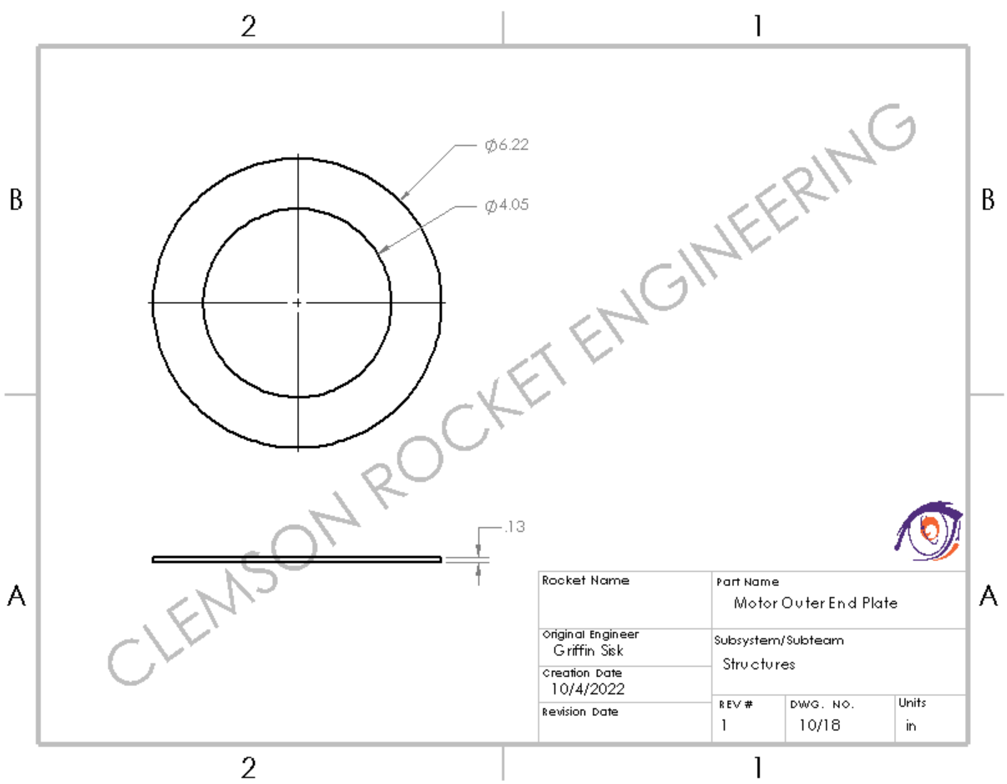

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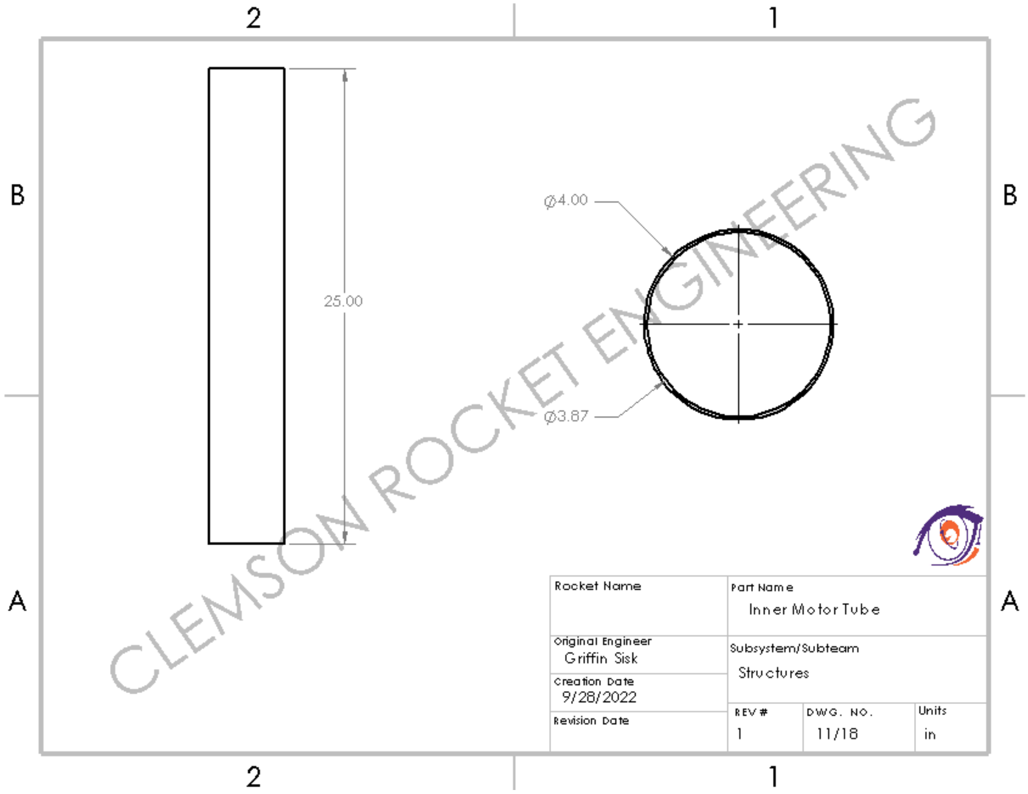
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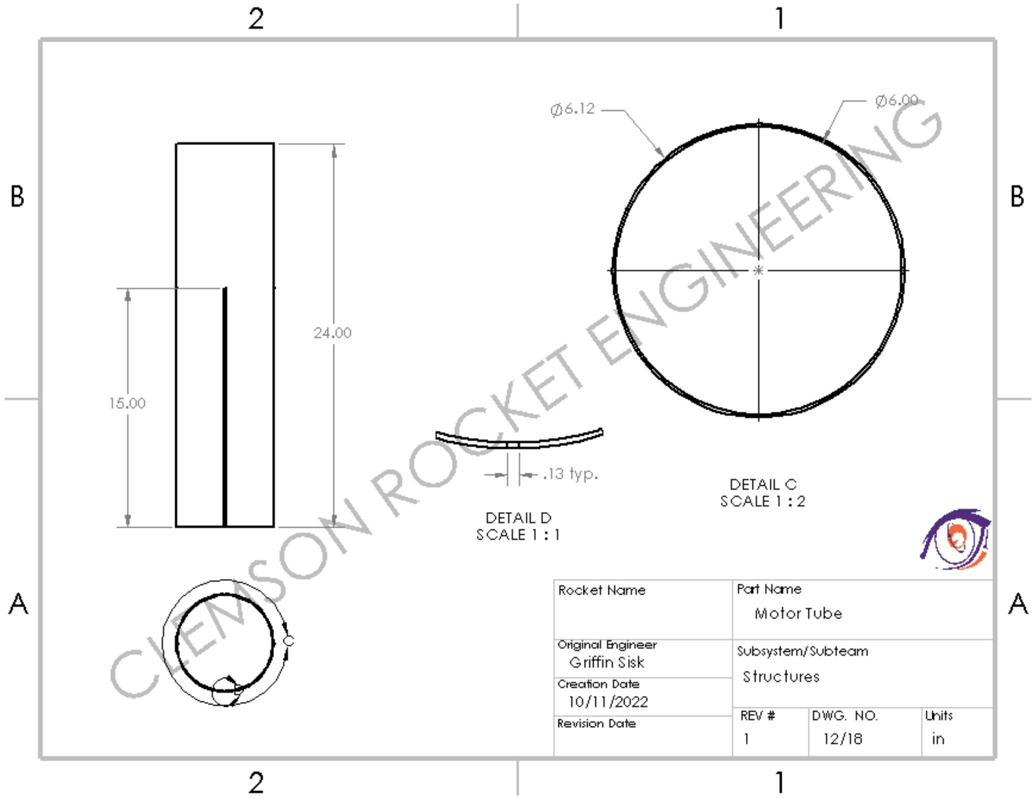
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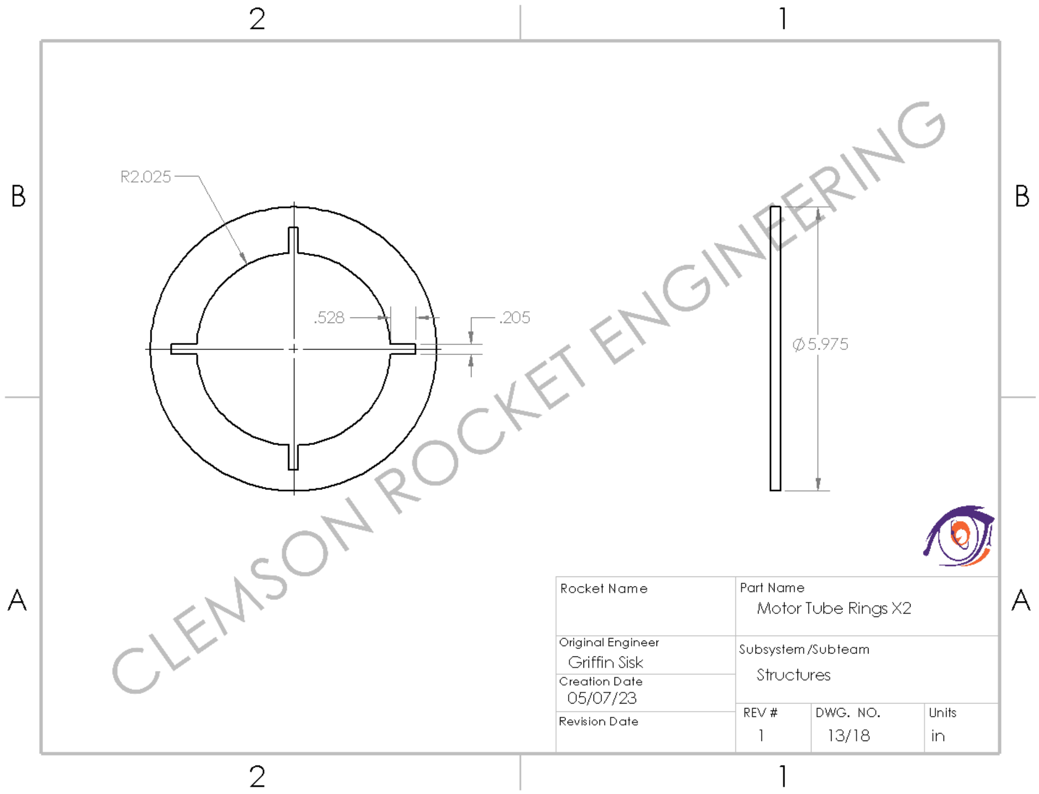
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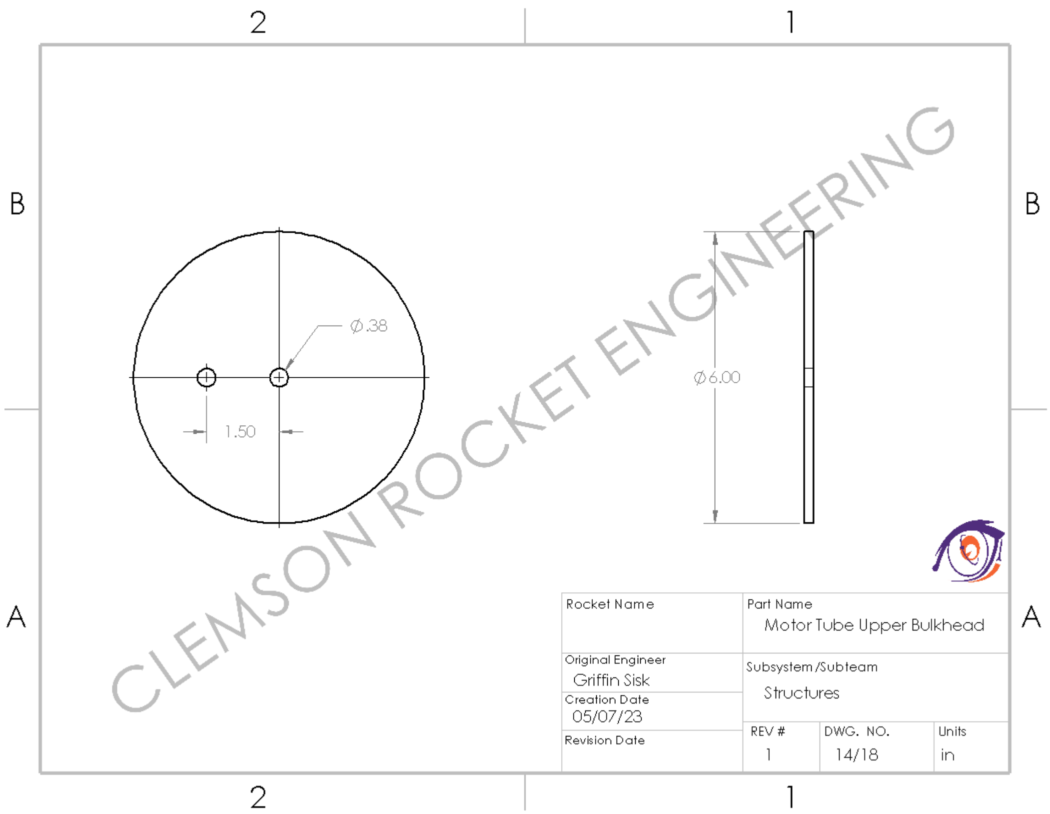
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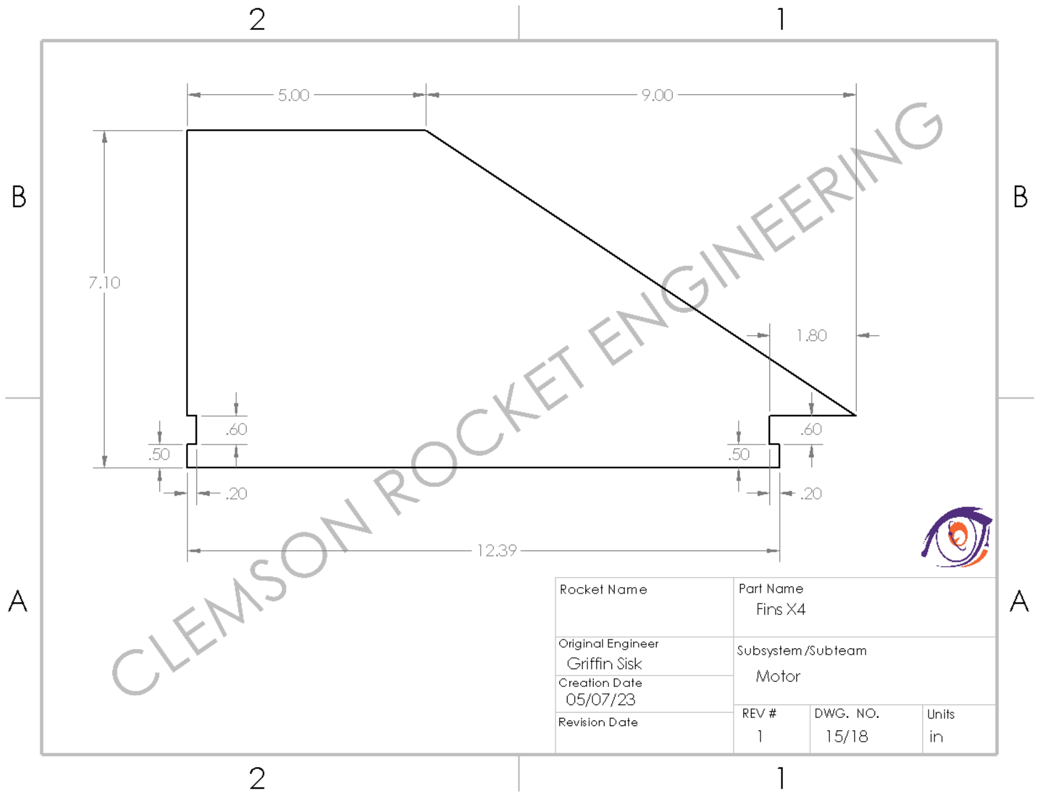

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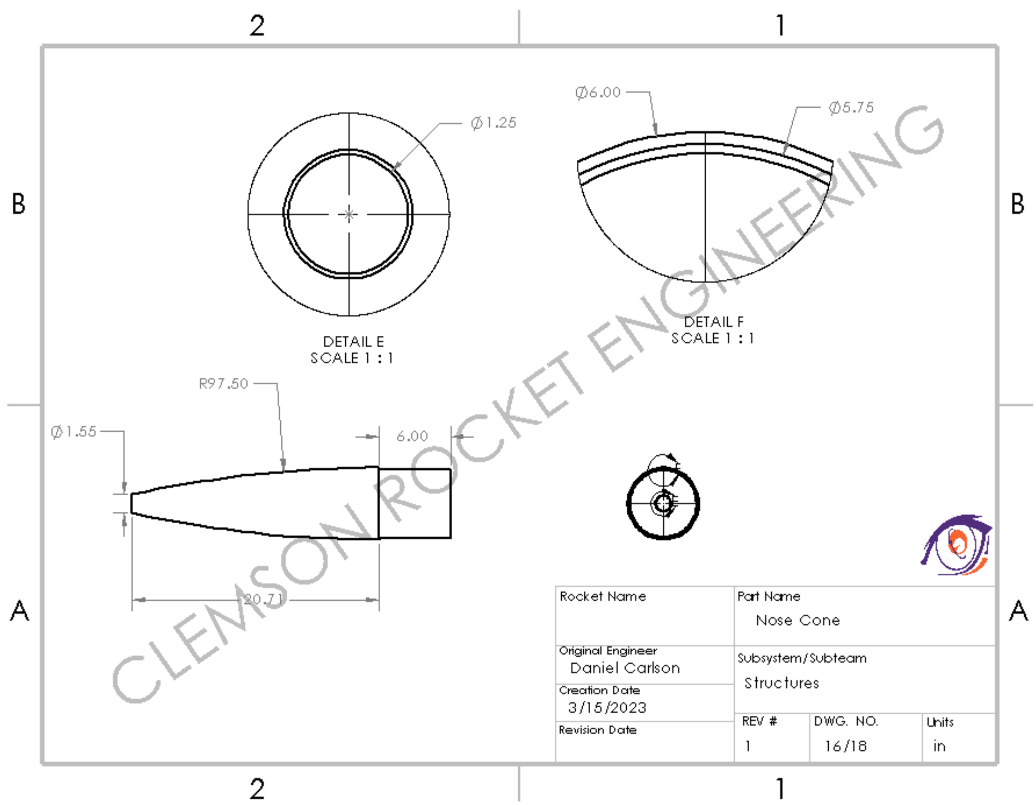

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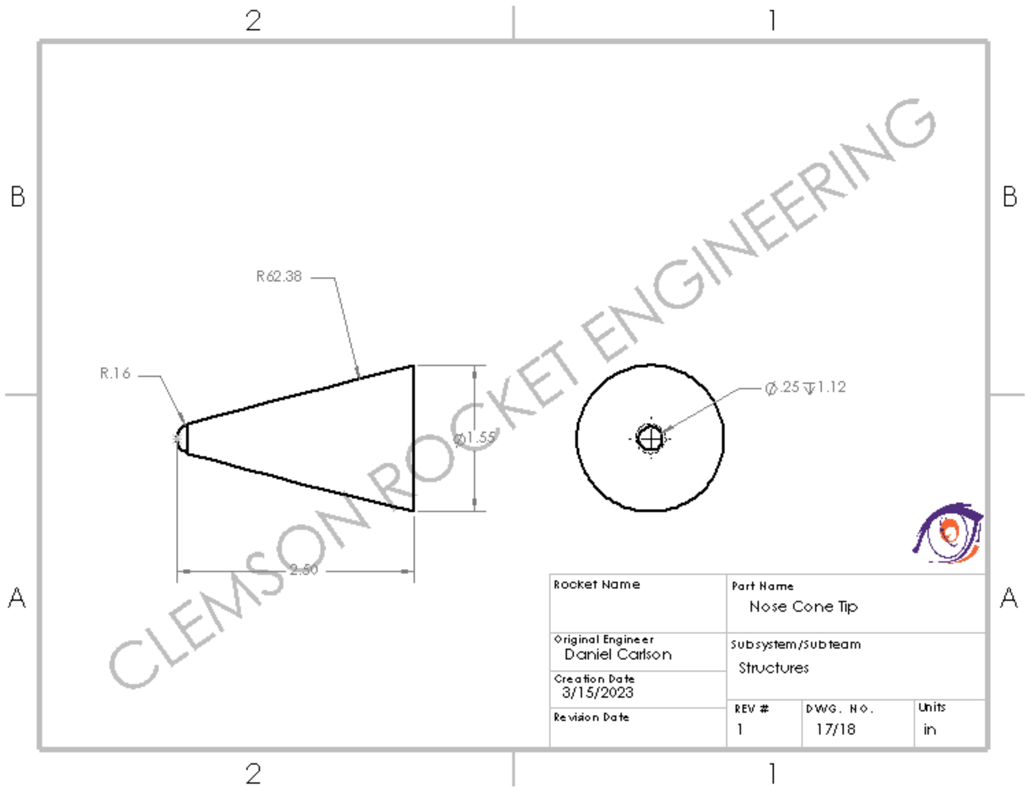
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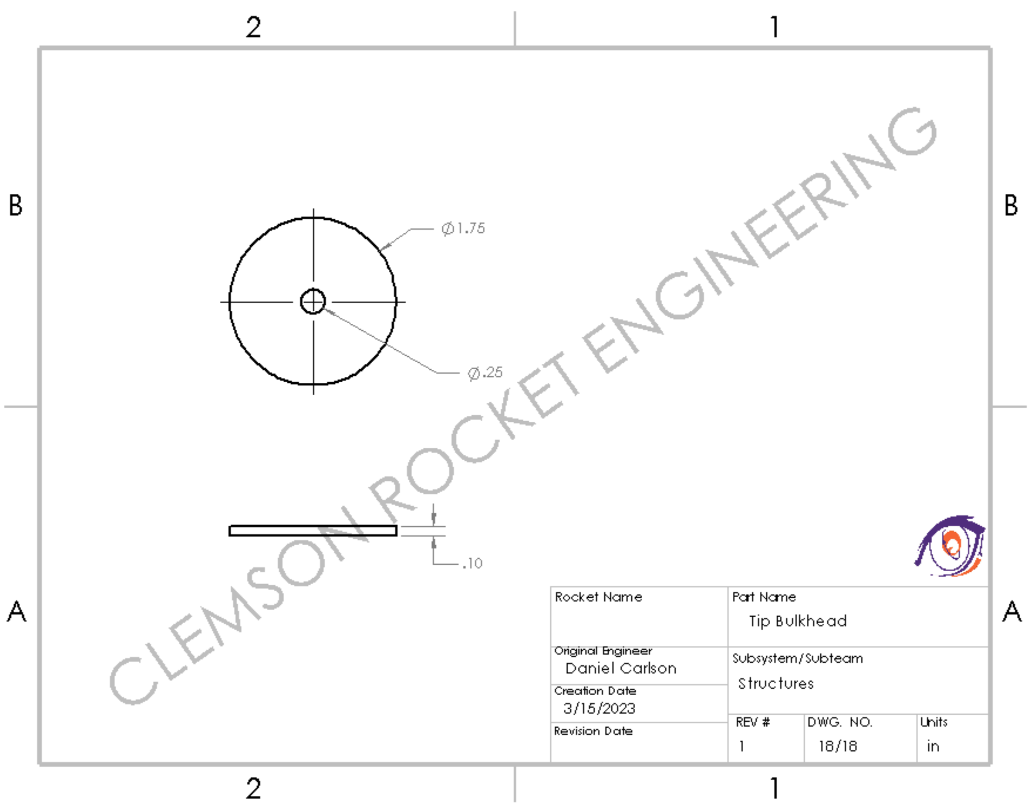
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18/18
Units
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