IIT Madras' Team Abhyuday Rocket Chetak-1

Team 36 Project Technical Report to the 2023 Spaceport America Cup

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This document is the project technical report of IIT Madras Team Abhyuday's rocket, *Chetak-1*, contending for the 10,000 ft COTS Motor Category in IREC, Spaceport America Cup 2023. Chetak-1 is an iteratively improved successor to MockingJay with which the team participated in Spaceport America 2022. Chetak-1 features improved lighter and shorter aero-structures with the use of carbon fiber for our first time, a dual-deployment recovery system, and student-researched and developed components.

I. Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
C_x	=	force coefficient in the x direction
C_y	=	force coefficient in the y direction
CP	=	Coefficient of Pressure
c	=	chord length
dt	=	time step
F_x	=	X component of the resultant pressure force acting on the vehicle
F_y	=	Y component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate
P	=	Pressure
λ	=	Chord tip to root ratio
G	=	Shear Modulus
AR	=	Aspect Ratio

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II. Introduction

Spaceport America Cup'23 IREC is Team Abhyuday's second participation in the competition. Started in 2020, our team has gained experience substantially, with increased interest towards rocketry and space exploration. With a team of over 30 students from various engineering streams, our motto Burn Build Blastoff suggests the goal towards the project is unidirectional and more focussed towards flying the rocket as perfectly as possible.

Over the past year, we have iterated over the design of our rocket numerous times, analyzed the simulated flight results and also have done stress analysis of individual rocket components, both simulated and tested. The manufacturing of the rocket has been challenging this year both on work and as well as funding basis, but it was made sure that the components have been made conscientiously.

Avionics and recovery subsystem have meticulously constructed an avionics bay consisting of electronics such as telemetry components, GPS tracker and flight computers. For deployment of parachutes, precise calculation for blackpowder mass and also the ejection testing has also been covered.

The Payload subsystem of the team following the standard cubesat dimensions, is a presentation for generation of electricity caused by the initial transience of the rocket, for which the prototyping has been executed.

Fig. 1 Chetak-1

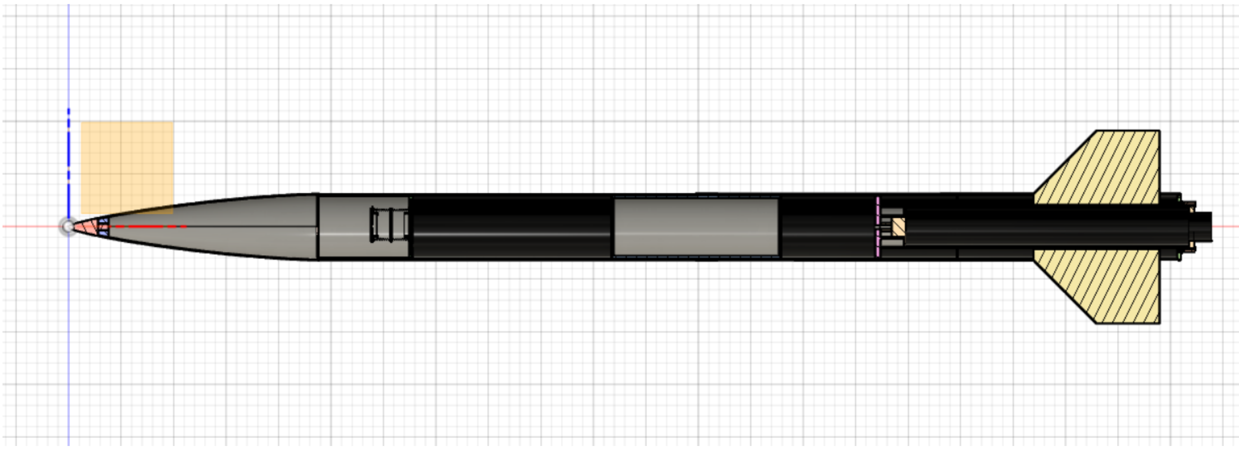

Fig. 2 Sectional view of Chetak-1

III. System Architecture Overview

Team Abhyuday's Project **Chetak-1** is divided into three sub-systems **Aero-Structures and Propulsion**, **Payload** and **Avionics and Recovery**. Aero-Structures subsystem attributes to designing and manufacturing of the external and internal framework of the vehicle that houses the propulsion system, recovery, and avionics system, and the payload. It supervises the aerodynamics of the rocket. The Propulsion subsystem accounts for the integration of the propulsion power plant into the airframe of the vehicle. Chetak-1 uses the Cesaroni Pro98 M-class motor (M1890-0) which produces a maximum thrust of 2401.60 N (539,.90 lbf).

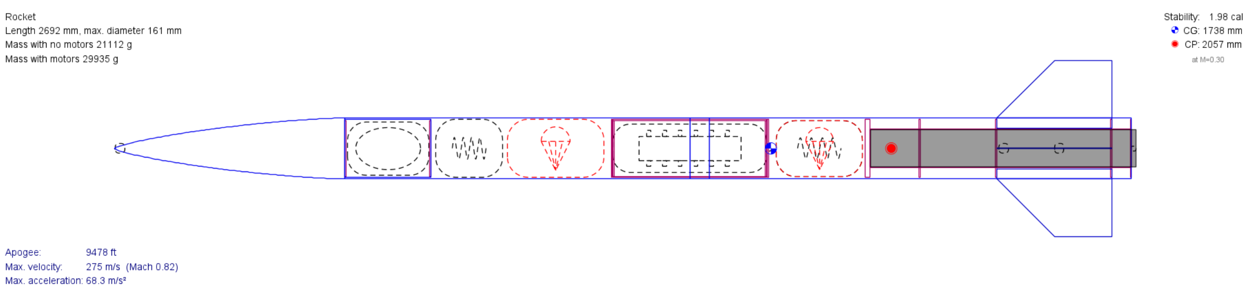

Fig. 3 Chetak-1's Internal configuration

Table 1 Technical Specifications

Specification	Value	Target	Units
Airframe length	106	-	inches
Airframe Diameter	6.354	-	inches
Motor	Cesaroni M1890RL	-	-
Max thrust	2158.60	-	N
Liftoff Mass	29870	<30000	grams
Thrust/Weight ratio	6.450	>5	-
Max Mach number	0.84	<0.85	-
Off-Rail velocity	80.4	>100	feet/s
Minimum Static Margin	1.94	1.5-2.5	-

A. Propulsion subsystem

1) **Motor specifications**

Chetak-1 employs a Cesaroni Pro98 M1890, with a total impulse of 9875.60 Ns (2222.01 lb/s) with a total burn time of 5.52 seconds. This motor provides sufficient force to reach the off-the-rod velocity of **24.5 m/s**, and a specific impulse of **190.70 s** to reach the target altitude of 10,000 ft.

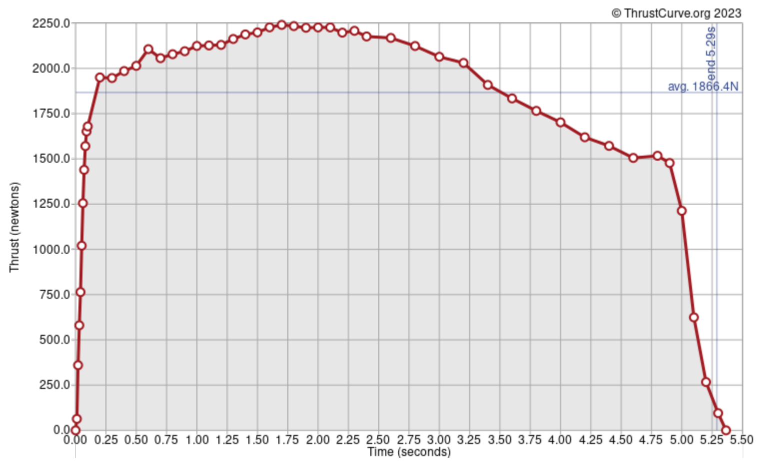

Fig. 4 Thrust curve of M1890-0 Red Lightening

During the iterative process to select the motor with various configurations, we decided to go for M1890, when integrated with our configurations M1890 kept our vehicle well below Mach one (as shown in the simulations section), and we were able to achieve 10,000 ft of altitude with our 4-Kg payload. The motor was easily available which was one of the main reasons to got for Cesaroni Pro98 M1890, we had no issues with procuring it. The Mach number (M) of a moving object is the ratio of its speed (v) to the speed of sound (a) in that surrounding atmosphere.

$$M = \frac{v}{a}$$

$$a = \sqrt{\gamma RT}$$

For Spaceport America, the environmental conditions we found the average temperature over 2 weeks at Truth or Consequences from May 12 - May 26, 2023 which turned out to be $84°F$. Hence, the speed of sound is

$$a = \sqrt{\gamma \times 287 \times 302}$$

$$a = \sqrt{1.4 \times 287 \times 302}$$

Therefore,

$$a = 348.34 m/s$$

The maximum velocity (which we got from simulations) is 276 m/s for the given parameters. Therefore, the maximum mach number of the rocket is:

$$M = \frac{276}{348.34}$$

$$M = 0.80$$

Our maximum Mach number is at 0.80, preventing the rocket from going into the transonic region (0.85 - 1.20). Fig. 5 is a graph of the Mach number vs time along the flight path.

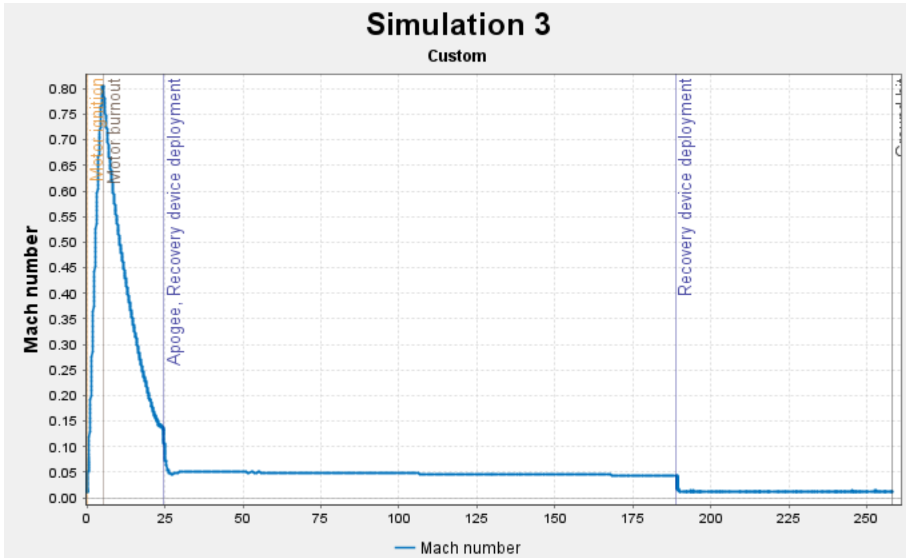

Fig. 5 Mach number vs time graph

The maximum apogee of our rocket is 9,765 ft simulated on OpenRocket. The altitude of our rocket with time is shown in Fig. 6.

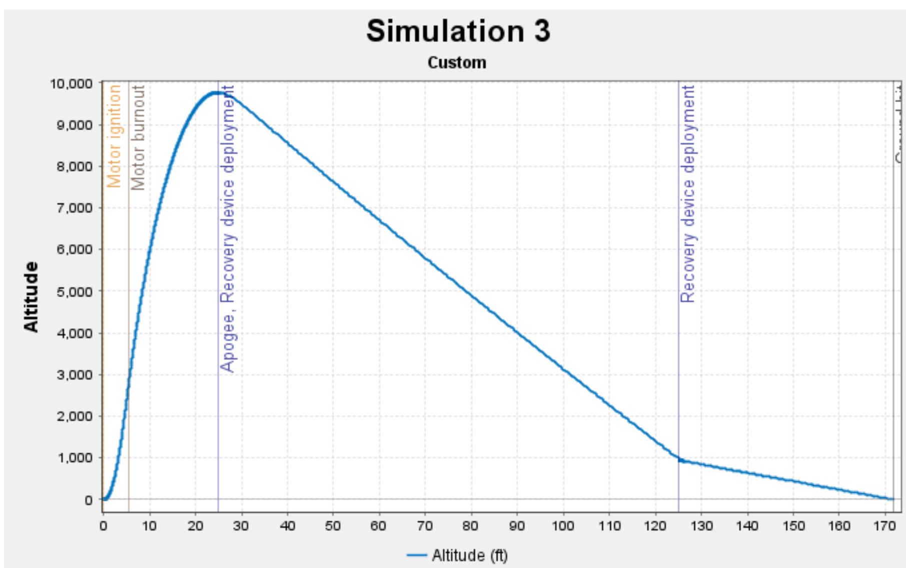

Fig. 6 Altitude vs time

*1. **Aluminium Motor bulkhead***

The large force applied to the airframe from the motor called for the use of an SRAD motor bulkhead. It prevents the motor from ripping through the rocket during peak thrust. This engine block system consists of an aluminum bulkhead machined to be placed inside the 6mm ID body tube, a section protruding out to hold the forward closure of the M-class motor. A **3-8" 16 UNC eye bolt with a shank length of 40 mm**. The bulkhead also has a circular groove for the inner tube to fit ensuring a sturdier fit of the entire motor mounting assembly. As the bulkhead is supposed to handle the loading due to the motor, it needs to be strong and lightweight. Therefore, we chose T6 Aluminium 6061 as the material for the bulkhead.

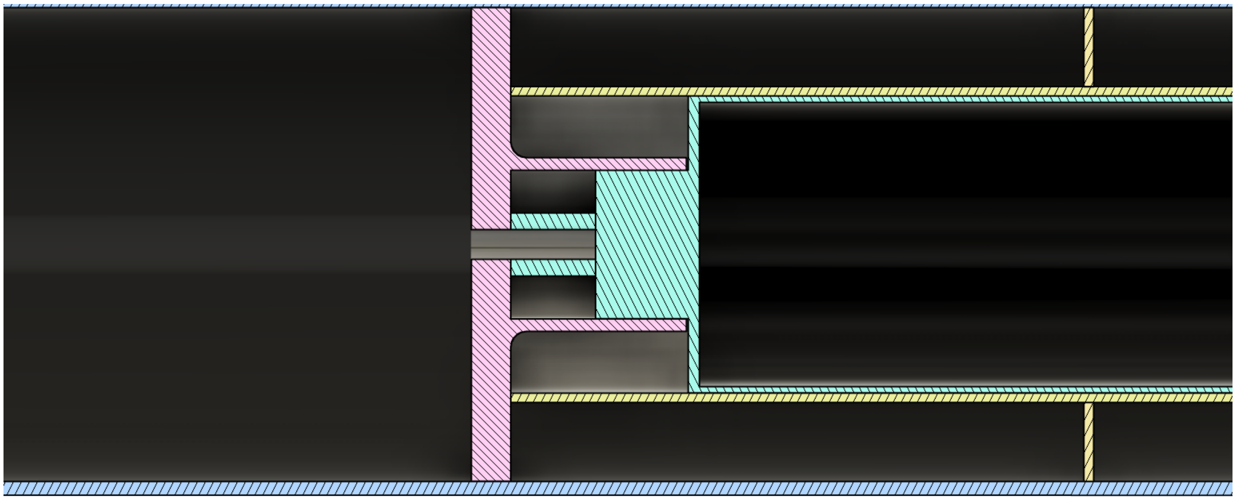

Fig. 7   Motor Bulkhead (Pink) and Motor Forward Closure (Blue)

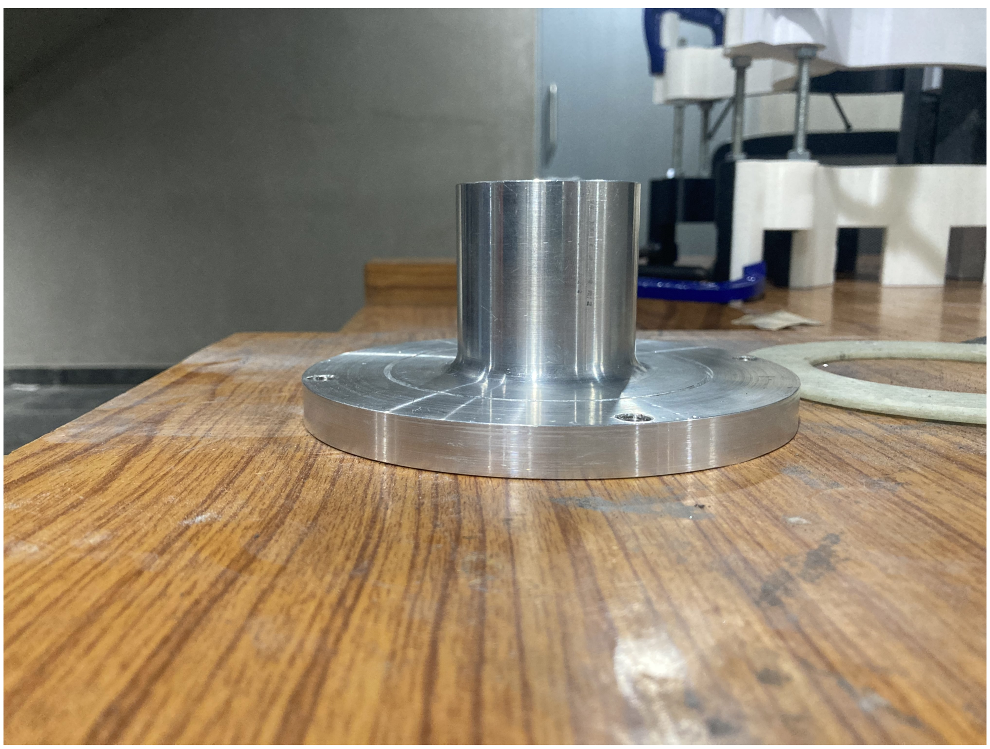

Fig. 8   Motor Bulkhead (Side View)

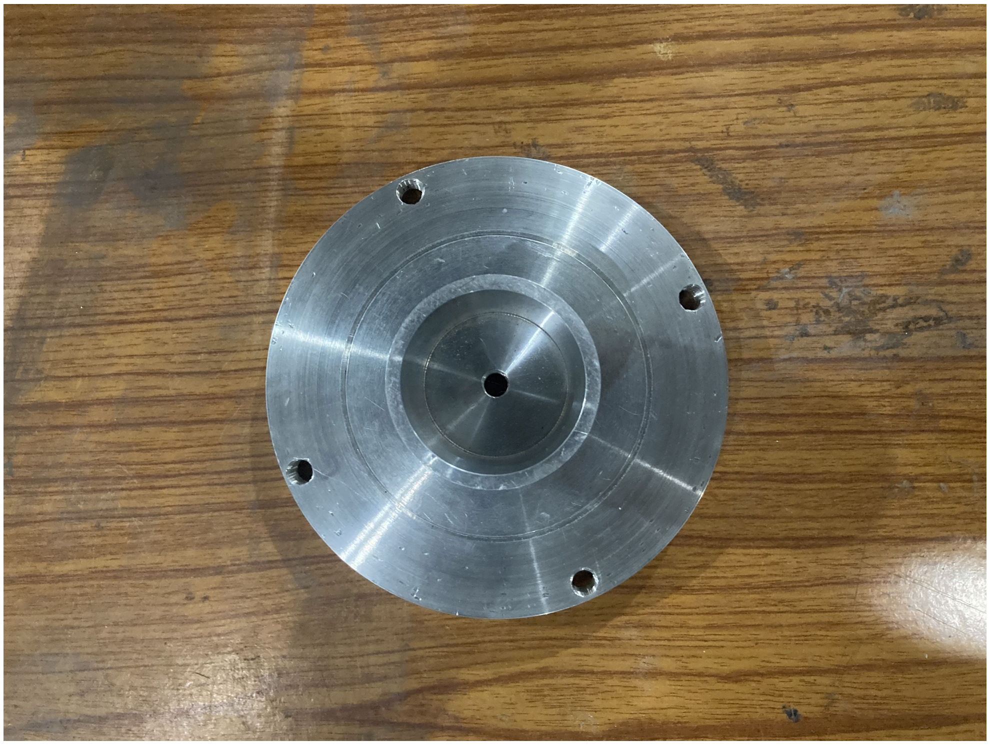

Fig. 9 Motor Bulkhead (Top View)

The static structural simulation was performed on ANSYS® and results of our motor mount static simulation have shown successful results with a high safety factor. The Fig. 10 displays the results of total principal stress on the motor bulkhead.

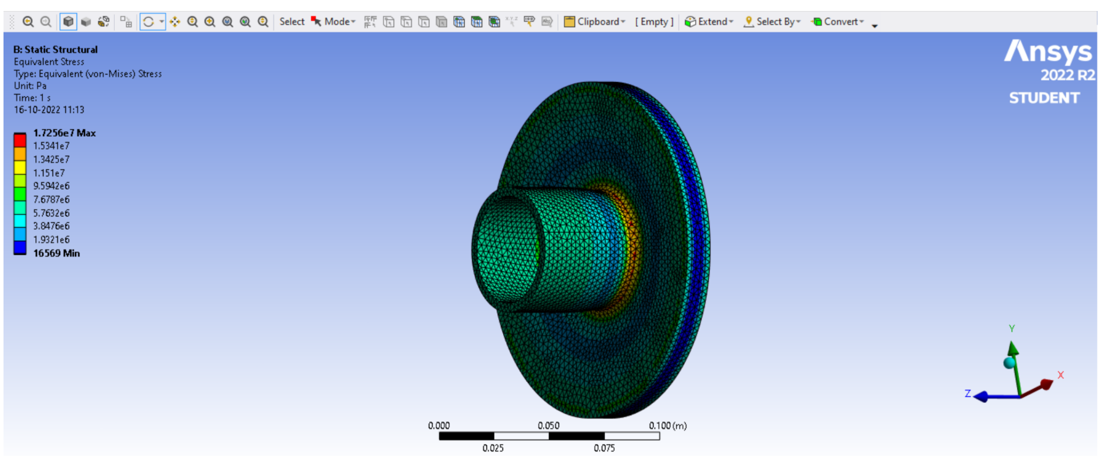

Fig. 10 Motor mount stress simulation

2. *Aluminium Thrust Plate*

A SRAD thrust plate was developed, the commercially available thrust plate has an OD of 6" but since the body tubes have an ID of 6" and OD of 6.354" a bigger thrust plate was made from aluminum T6-6061 to integrate it with the AeroPack® 98mm Thrust Retainer. The thrust retainer is connected to the aft closure of the motor and transfers the thrust from the motor to the thrust plate and the thrust plate will transfer it to the airframe through the lower body tube.

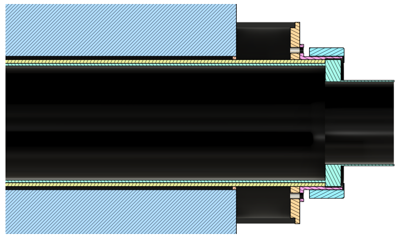

Fig. 11 Thrust Retainer with the Thrust Plate cross-sectional view

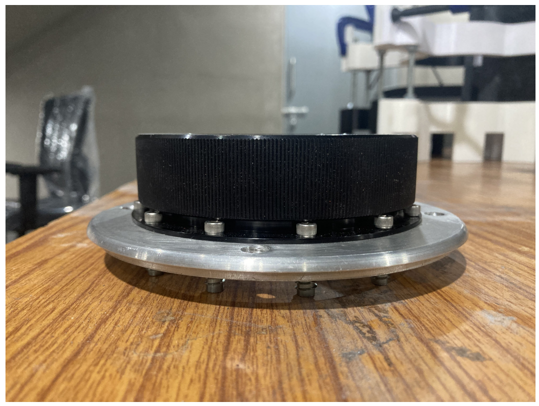

Fig. 12 Thrust Retainer with the Thrust Plate

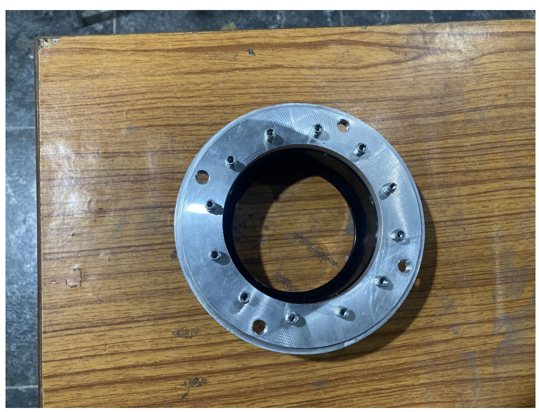

Fig. 13 Thrust Retainer with the thrust plate aligning perfectly

The static structural was performed on ANSYS® and results of our thrust plate static simulation have shown successful results with a high safety factor. The Fig. 12 displays the results of total principal stress on the thrust plate against the motor thrust. The face that is in contact with the lower body tube was kept fixed and load was applied on the face of the thrust plate.

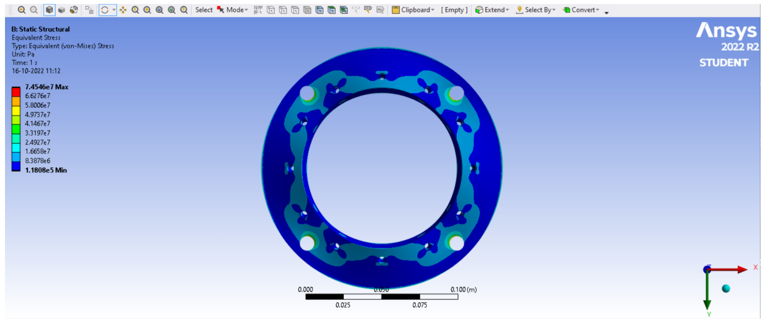

Fig. 14 Thrust plate static structural analysis

The manufacturing of all the bulkheads and the thrust plate was done using CNC Milling and CNC turning.

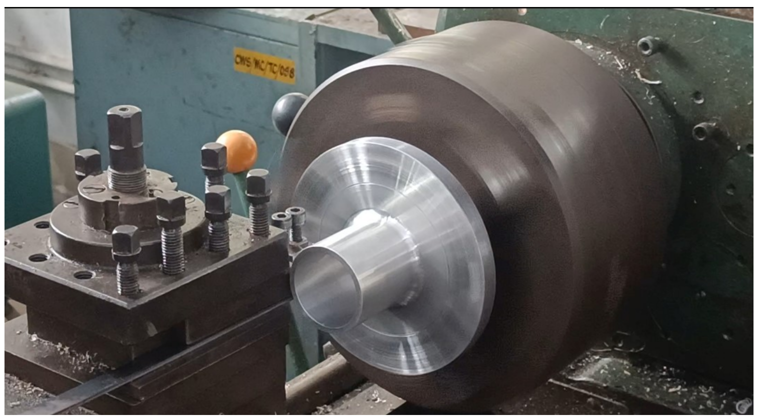

Fig. 15 CNC Turning

CNC Turning:

CNC turning is a manufacturing process that involves holding bars of material in a chuck and rotating them while feeding a tool to the piece to remove material until the desired shape is achieved. As the desired shape is achieved through the removal of material, it is also known as subtraction machining. Stock cylinders of Aluminium blocks were taken and cut using the machine in the desired shape. It was then sent to CNC Milling machine to create desired holes and engravings.

CNC Milling:

CNC Milling is a machining process which employs computerized controls and rotating multi-point cutting tools to progressively remove material from the work-piece and produce a custom-designed part or product. This was used to create precision holes in already turned aluminium components.

B. Aero-Structures

Chetak-1 features an airframe made primarily of **glass-fiber reinforced plastics GFRP**, with some crucial components constructed from **carbon-fiber reinforced plastics (CFRP)**. This design is a significant upgrade over the previous iteration, Mockingjay in numerous aspects. All the specific details of the aerostructure were decided based on rigorous testing through structural and aerodynamic simulations and analysis. The switch from fiberglass to has enhanced the airframe. It has led to lower weight and higher strength-to-weight ratio. This combination of factors leads to our projected apogee reaching the desired 10,000 feet while simultaneously keeping the maximum velocity achieved at around 0.8 Mach. By going subsonic we are able to avoid the unpredictability and risks of flying a rocket in the transonic region.

*1. **Nose-Cone:***

The Chetak-1's nose cone is made of CFRP, and designed using the LD-Haack equation with parameter 0. This is the Von-Karman nosecone profile, this design was chosen due to its ability to minimize drag for a given nosecone length and diameter. The fineness ratio of the nosecone is kept around 3.77 to minimize drag.

Dimensions :

1) Nosecone length: 24 inches
2) Nosecone outer diameter: 6.354 inches
3) Fineness ratio (Length/Diameter): 3.78
4) Wall thickness: 0.079 inches
5) Shoulder length: 9 inches

These dimensions were chosen after a string of OpenRocket simulations as well as fluid flow simulations in Ansys Fluent®. The purpose of these simulations was to ensure the rocket would produce the desired apogee of 10,000 feet and also experience as little drag as possible. The nosecone of the previous rocket MockingJay was manufactured in-house using the hand layup process and was made of fiberglass. For Chetak-1 this time,the nosecone was made from compression molding and a two-piece mold process.

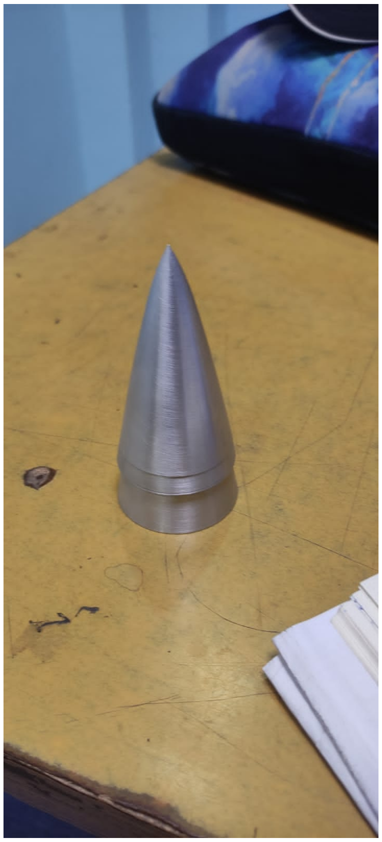

Fig. 16 Nosecone Aluminium Tip

Fig. 17 CFRP Nosecone with Aluminium Tip

Hand-Layup process:
This is the simplest and most commonly used process in the manufacturing of fiberglass components. It involves manually putting fabrics woven from the required fibers onto the mold and enforcing the shape by applying an epoxy or resin matrix.
With the newly manufactured nosecones in Chetak-1, we look to perfect any imperfections in the nosecone of Mockingjay. Replacing fiberglass with carbon fiber leads to higher structural stability and simultaneously a drop in weight. The higher fineness ratio leads to a significant drop in the coefficient of drag during the flight of the rocket. The nosecone of Chetak-1 was manufactured with the help of one of the team sponsors, ST Advanced Composites®.
The nosecone of the rocket suffers the worst conditions during the flight. It experiences the highest pressure and the highest temperatures. This calls for an update in the design which allows it to handle these conditions.
Chetak-1's nosecone has an aluminum tip to help overcome these challenges. The aluminium tip has a length of 0.984 inches as well as a diameter of 0.984 inches.

*2. **Body tubes and coupler:***

The body tubes and the coupler are made of GFRP.
The dimensions of the body are -

1) Upper Body tube length: 36 inches
2) Lower Body tube length: 44 inches
3) Outer diameter of body tubes: 6.354 inches
4) Wall thickness: 0.177 inches

Fig. 18 Body Tubes

The tube coupler houses all the electronics of the rocket in the avionics bay. It is enclosed on either side with a fiberglass bulkhead. The dimensions of the tube coupler are-

1) Length: 16 inches
2) Outer diameter: 6 inches
3) Thickness: 0.079 inches.

Fig. 19 Coupler with switch band

The rocket additionally includes an inner body tube to house the propulsion system. The inner body tube uses 3 centering rings across its length to keep in contact with the outer body tube. This tube will be fixed in place using epoxy. The centering rings are also held in place on the tube using epoxy. One of the ends of the tube will be in contact with the motor bulkhead. The motor bulkhead is designed to have a groove such that the inner tube slides into the groove when assembled. The dimensions of the inner tube are -

1) **Length**: 27.2 inches

2) **Outer diameter**: 4 inches
3) **Wall thickness**: 0.062 inches

The gap between the lower and upper outer body tubes is filled by a small tube 2 inches in length, called the switch band which will be used to turn on the altimeters.
The body tubes as well as the tube coupler in the rocket are constructed entirely from G10 fibreglass.
The body tubes were constructed using the filament winding process, with help from one of the sponsors of our team, ST Advanced Composites®.

Filament Winding:
Filament winding is the most commonly used process for manufacturing body tubes for sounding rockets. It involves weaving fibers (carbon or glass) around a spinning mandrel in a specific pattern.
The mandrel is the cylindrical mount around which the fibers are wound. It is designed such that the diameter of the mandrel matches the required inner tube of the body tubes. The body tubes for MockingJay were manufactured in-house using the machines present in our institute's workshops.
The body tubes for Chetak-1 are manufactured using filament winding as well, but a large improvement was made in using carbon fiber instead of fiberglass.

C. Simulations

1. Fins and Fin Alignment

The fins for our rocket are made of the same CFRP as the Nosecone. The composite is a layup with **fiber orientation 0/90/+45/-45/0/90**. The resin used is LY556 epoxy resin. The **sheer modulus of this CFRP is 638000 Psi**. The main consideration when choosing the material for fins was the failure of the fins due to flutter. The fin flutter velocity was calculated using a formula found in Apogee Rockets' newsletter [1].

$$V_f = \sqrt{\frac{G}{\frac{1.37AR^3P(\lambda+1)}{2(AR+2)\left(\frac{t}{c}\right)^3}}} \tag{1}$$

The final fin thickness which was chosen is 3mm. A simple rectangular cross-section was chosen as the max velocity of our rocket is 0.80 Mach. Airfoil fins are only significant in the upper-velocity regimes of 1.7 Mach. Surface finishing tolerances will largely affect the performance of airfoil fins, which would mean that opting for airfoil fins makes manufacturing harder, making it an unnecessary complexity.
Fin Attachment: Our first idea for fin attachment was to use fin clamps to hold the fins in place. Clamps are L-brackets that keep the fins in place, there's dampener material in between the fins and clamps. The clamps themselves are riveted onto the lower body tube. The preliminary design looks like the photo below:

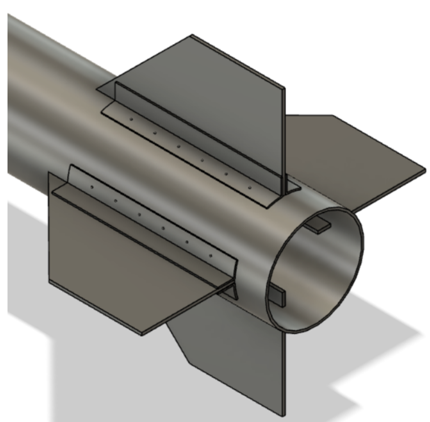

Fig. 20 Final Fin

Although this mechanism works very well in securing the fins and dampening their vibrations, it's a heavy module,

which reduces the rocket's stability by bringing its C_g closer to C_p(down towards the aft). When we simulated the drag forces acting on the fins, the total drag force came out to be around 115N, so each fin takes about 28.75N. The above clamp mechanism is capable of handling more than 150N, which makes it an overengineered solution.
Considering the forces on the fins, we decided to go with a simple but tried and tested method which is to epoxy the fins. Fin attachment to the lower body tube is by epoxying them into a slot (on the lower tube), and then aligning them meticulously so the fins are as close to 90° as possible using an alignment tool we developed called **"OctaClamps"**. The root chord is then given a fillet for structural stability, along with the intersection region of the lower tube and fins.

Fig. 21 OctaClamps

Fig. 22 OctaClamps used for fixing fins on Chetak-1

2. Flight Simulation

Chetak-1's flight behavior was simulated using OpenRocket as the main simulation software. The simulation parameters were set to match the Spaceport America weather conditions with varying launch angles to understand the behavior of the rocket. Our latest simulation had the following launch conditions: Simulation wind speed of $4.44 \pm 0.8 m/s$ which was found after getting the average of wind speeds over the last 14 days of May 2023 measured in Truth or Consequences, NM. Ground level altitude was set to 1400 ft, the atmospheric temperature was also taken over 14 days in May 2023 and pressure was 1013 mbar, and the launch rail was set to a length of 17 ft at an angle of 7° from vertical.

Other flight metrics of interest were three dimensionless coefficients: the stability margin, Mach number, and thrust-to-weight ratio, which are plotted. The position of the center of pressure on the rocket varies during due to the variations in the orientations of the rocket and the pressure fields around the rocket. The stability of a rocket is its ability to keep flying through the air pointing in the right direction without wobbling or tumbling. The stability of Chetak-1 is 1.98 cal. The stability margin calibers reach a maximum of 2.9 at the motor burnout. The Mach number of a moving object is the ratio between the speed of the vehicle and the speed of sound in the surrounding atmosphere.

The Thrust to weight ratio for the instantaneous thrust of the rocket and the weight of the rocket:

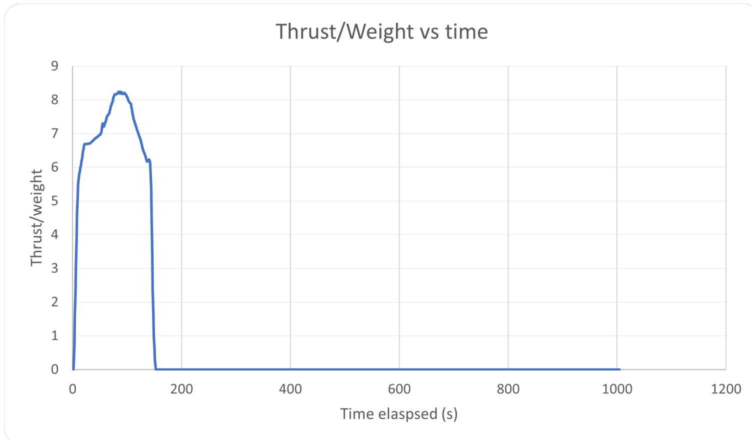

Fig. 23 Thrust to weight ratio vs time

The thrust-to-weight ratio was calculated for every 0.01 seconds of the flight and then a Fig. 23 was made. From the above graph, we can infer that the highest thrust-to-weight ratio occurs at 2.121 seconds which is 8.243. Then, at 5.401 seconds into the flight time, the thrust becomes zero hence thrust to weight ratio becomes zero.

There is also a change in the center of pressure of the rocket.

The center of pressure of a body: In fluid mechanics, the center of pressure is the point where the total sum of a pressure field acts on a body, causing a force to act through that point.

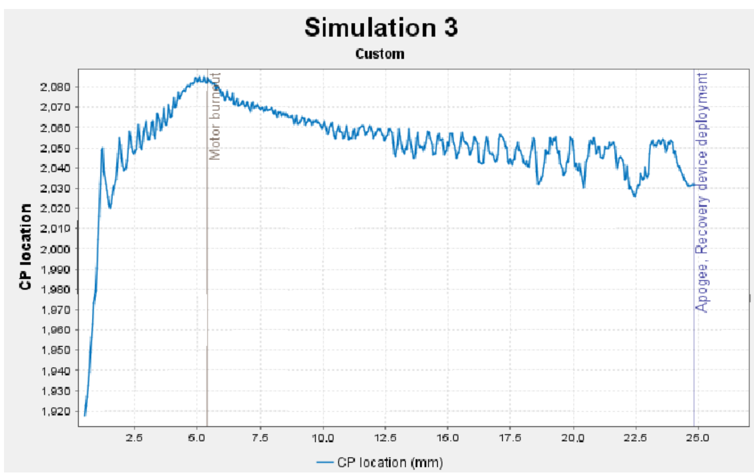

Fig. 24 Centre of pressure location in mm vs time

The CP is measured from the tip of the nose cone. The CP increases from 1920 mm from the tip of the nose cone to 2085 mm at the motor burnout. From there, the CP decreases and then oscillates - averaging at 2057 mm from the tip of the nose cone finally. The maximum acceleration of the rocket is 68.4 m/s^2. Fig shows the acceleration trend for the Chetak-1.

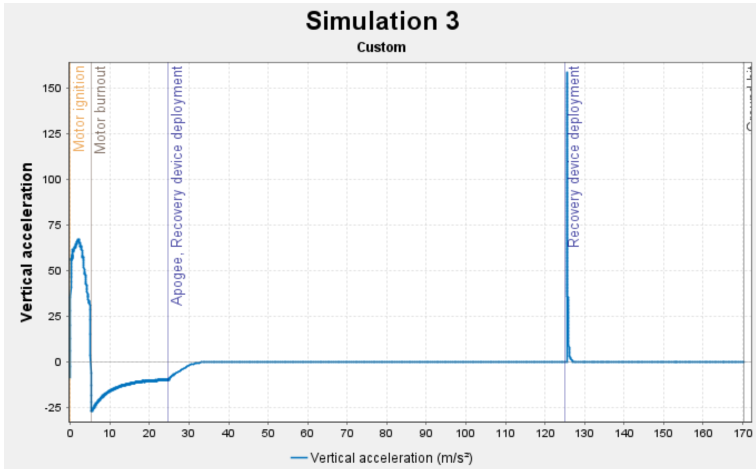

Fig. 25 Vertical acceleration in m/s^2 vs flight time

3. Coupler Bulkhead

The tube coupler houses the avionics bay, which has all the electronics present in the rocket. This makes it a critical component in the airframe. Any failure or deformation in the coupler bulkhead can cause damage to the electronics.

Analysis using Ansys Static Structural was performed on the coupler bulkhead.
The goal of these analyses was to simulate the first few seconds of the rocket's flight, i.e. the burnout time of the rocket motor.
The outer surface of the bulkhead is considered as a fixed support. The full thrust of the rocket is made to act on the entire flat surface of the bulkhead. To establish a safety factor in our results, the thrusts we considered are over twice that of the actual motor. This ensures that any faults are minimal even in unexpectedly extreme conditions.

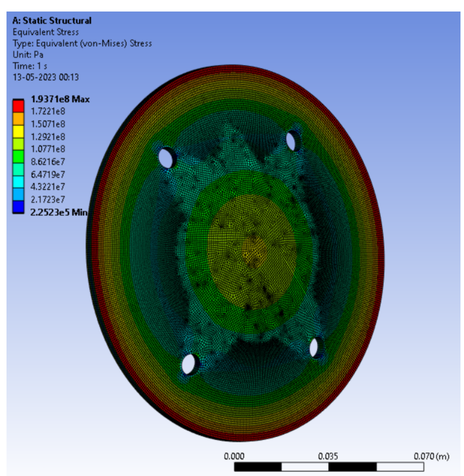

Fig. 26 Equivalent (von-Mises) Stress

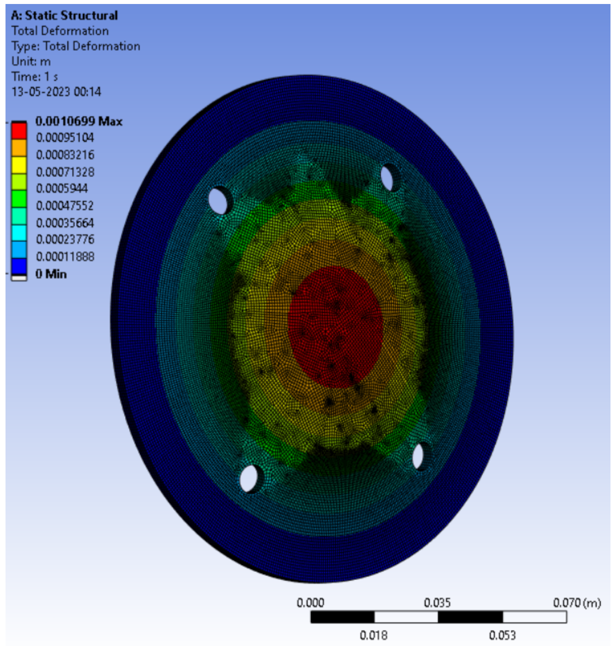

Fig. 27 Total Deformation

The coupler bulkhead has a diameter of 5.84 inches and a thickness of 0.125 inches .
The maximum total deformation obtained in the simulation is 1.069 mm. This is within the acceptable region for our requirements.
The maximum equivalent stress is found to be 193 MPa which is also acceptable.

4. Fluid Simulations

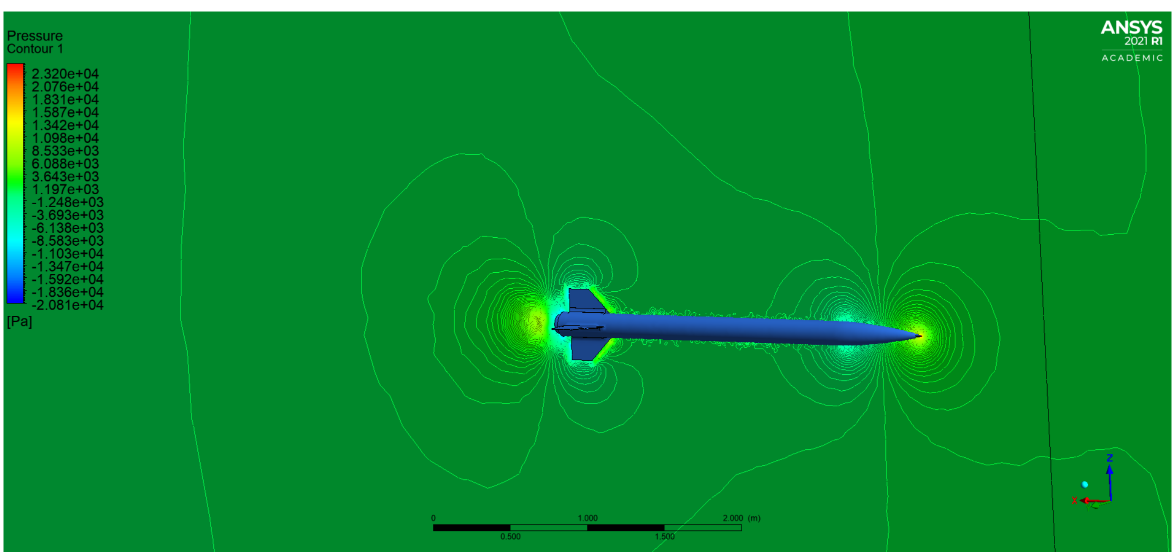

Fig. 28 Pressure Contour for Fluid Simulation

ANSYS FLUENT simulations were performed on the CAD model of the rocket under an enclosure. These were done to validate the OpenRocket designs and simulate the MaxQ condition on the rocket. Fine mesh was made for the rocket + enclosure, Simulation was setup with the necessary conditions. Turbulence was accounted for using K-Omega SST Turbulence Model. Ideal compressible gas was chosen as the cell zone conditions. This accounts for the compressibility of air at higher velocities (M>0.3). Energy equation was also enabled to model accurate results. The boundary conditions were set as follows:

Boundary Conditions:
1. Velocity Inlet set at 328 m/s.
2. Outlet was set as a Pressure outlet.
3. Enclosure boundary and rocket's body was set as walls with no slip conditions.

The results obtained for the drag force and the drag coefficient were under acceptable error margin of the results obtained from OpenRocket. Hence, proving that the simulations for the model were accurate and acceptable.
Pressure and Velocity contours were plotted to observe the shock waves obtained.

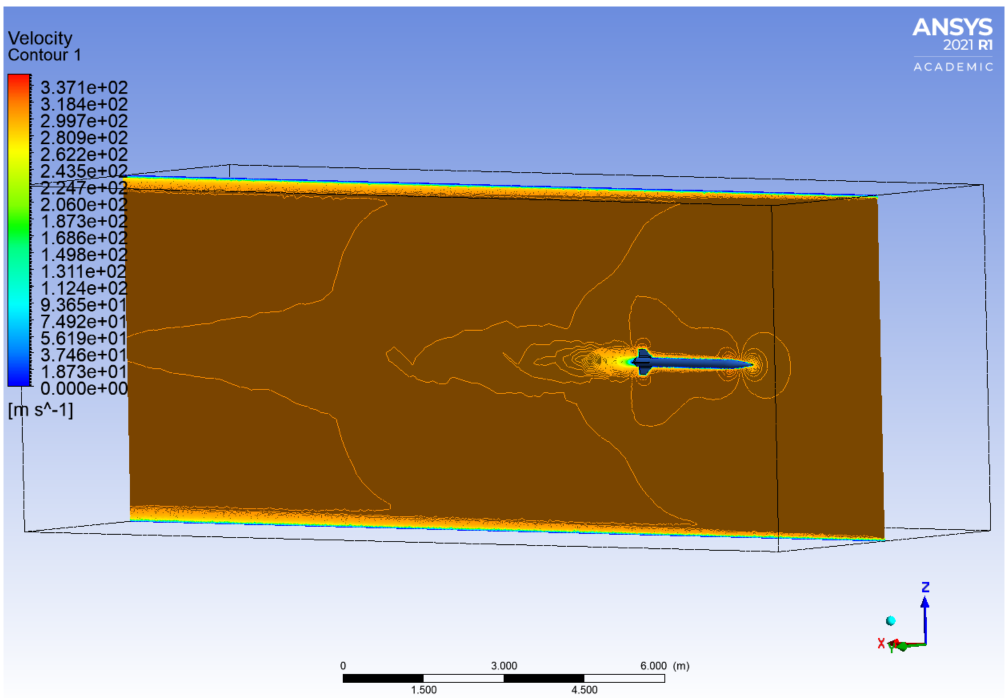

Fig. 29 Velocity Contour for Fluid Simulation

D. Avionics & Recovery subsystem

1. Avionics

The Avionics subsystem deals with the development of the electronic components required for the safe operation of the rocket. The developed electronic component should be able to measure the important parameters of the rocket, like altitude, velocity, etc., and ensure that the recovery systems are deployed correctly. The different components under the Avionics subsystems are given below.

a. *Altimeters*

Altimeters are electronic components that measure the rocket's instantaneous altitude and store this information for later use. It is measured using the fact that the air pressure of the atmosphere decreases by approximately 1 millibar for every 10 meters increase in height. The pressure measured is static pressure and so is independent of the airspeed of the rocket. There are two COTS altimeters that are used in the project. The second one is to ensure redundancy. The components are detailed below.

- *Featherweight Raven4 Altimeter[2]*

  The primary altimeter in the project. It can measure pressure data using the onboard barometer at a rate of 20 Hz, with an accuracy of 0.3%. It also incorporates an accelerometer which is used to get the velocity data as well. It can be used to operate four different sets of e-matches at a time using the four different outputs. The first two outputs are for drogue parachute (released at the apogee) and the main parachute (released at the lower altitude). The other two outputs can be used for redundancy.

  It is operated using a standard 9V battery. It can store data in its onboard memory at a high rate for 8 minutes and an additional 45 minutes of flight data at a lower rate. The altimeter can be programmed for certain configurations which we require using the Featherweight Interface Program (FIP). Once the rocket is successfully recovered, the altimeter beeps out the maximum altitude. The flight data onboard can also be read using the FIP and can be analyzed to study the flight parameters.

  The circuit diagram for the Raven4 altimeter is given below in Fig. 30.

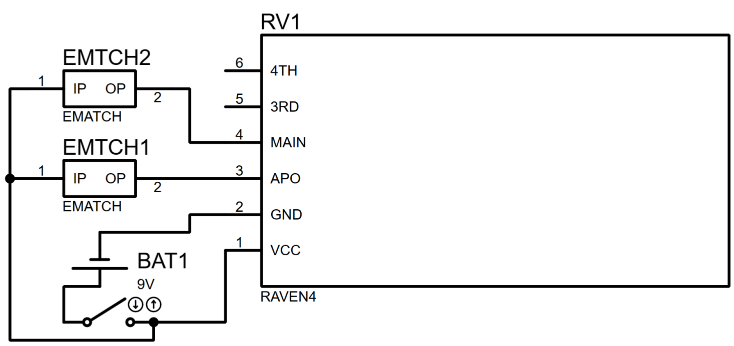

Fig. 30 Circuit diagram for the Raven4 altimeter

- *AltusMetrum EasyMini[3]*

  The secondary altimeter in the project. It can measure the pressure data accurately till an altitude of 100k ft above mean sea level (MSL). It can measure the altitude and store this information in the onboard memory. It can be used to operate two separates sets of e-matches. One of them is used for the drogue (apogee) parachute and the other for the main parachute. Thus, in total, both the drogue and main parachutes will have two separate black powder charges, each fired using a unique e-match from each altimeter. The e-matches from the EasyMini have a small time-delay of 2 s. This will ensure that both charges do not fire simultaneously and destroy the body tube due to excessive pressure.

  The altimeter is operated using a separate standard 9V battery. This will ensure that both altimeters have enough battery storage to survive the entire flight. The EasyMini altimeter records data at a rate of 100 samples per second during the ascent phase and at 10 samples per second during the descent phase. It has enough storage to store 10 minutes worth of data at the maximum rate. The altimeter can be configured according to our requirements using the AltOS firmware. This firmware also allows to do recover the saved flight data once the rocket is successfully recovered.

  The circuit diagram for the EasyMini altimeter is given below in Fig. 31.

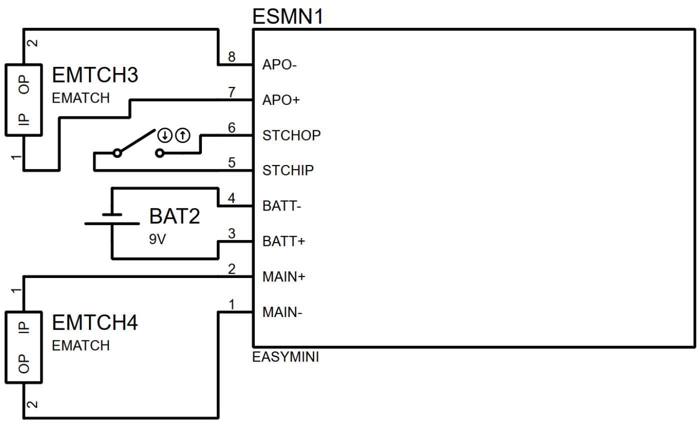

Fig. 31 Circuit diagram for the EasyMini altimeter

b. *GPS Tracker[4]*

The GPS Tracker is an electronic components which combines a GPS receiver and a transmitter. The receiver connects to different satellites in the Global Positioning System (GPS) and uses the signals given out by them to locate itself on the Earth. We can thus get the exact longitude, latitude and the height of the receiver on the Earth to a very good accuracy.

We use the Featherweight GPS Tracker and Ground Station for tracking our rocket. The tracker can provide 10 GPS solutions per second. It can be used to measure the position till an altitude of 50 km. The tracker transmits data to the ground station using an antenna according to the LoRa (Long Range) protocol in the 915 MHz band. This has a line of sight range of almost 300,000 feet.

It is operated using a 3.7V LiPo Battery with a capacity of 400 mAh. With this battery, we were able to get almost 6.5 hours of continuous transmission from the tracker during our battery test. The ground station has an in-built LiPo battery of 2000 mAh capacity. This can run continuously for almost 50 hours.

The circuit diagram for the GPS Tracker is given below in Fig. 32.

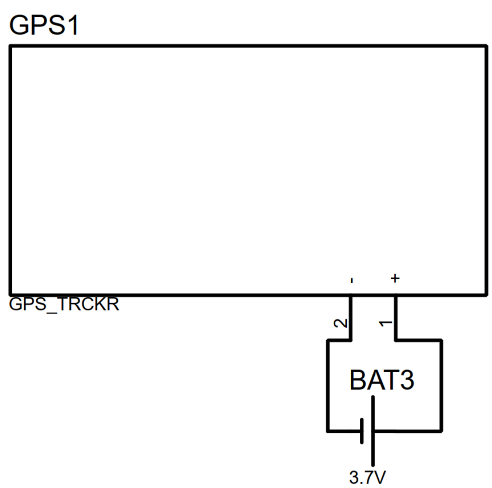

Fig. 32 Circuit diagram for the GPS Tracker

c. *Avionics Bay*

The avionics bay is made out of polypropylene (PP) sheet. It has two cylindrical PP bulkheads of diameter 5.3 inches (approximately 13.4 cm), which are joined together with a cubical PP sheet. All of these have a thickness of 0.315 inches (approximately 8 mm). To ensure that the entire avionics bay is strong enough to withstand the high loads endured during the entire flight, we have added two threaded metal rods made of galvanised iron and having a diameter of 20 mm and a length of 453 mm. The threads are of dimension M20×2.5 (in metric units). The avionics components are screwed onto the avionics bay.

2. Recovery

A dual deployment recovery system is employed here with 2 parachutes - the drogue and the main parachute. The drogue parachute will be deployed at apogee (the maximum altitude achieved by the rocket), and the main parachute will be deployed when the rocket reaches 1000 feet above ground level (AGL) during the descent phase. The parachutes will be protected with chute protectors to protect their cloth from getting tangled within the cords and also being damaged from the black powder ejection method of recovery that will be employed. We are using an e-match that will ignite a black powder ejection charge that pushes the parachute out of a rocket. Dual deployment ensures that the rocket's drift is reduced and it is recovered safely.

a. *Parachute[5]*

As mentioned, there are two parachutes in our system. Their properties are given below.

- Drogue Parachute

  The drogue parachute is deployed at the apogee. This ensures that the unfolding loads on the parachute and rocket are very less. The chosen parachute is **Rocketman 3ft Standard Parachute**. It is a Toroidal/Annular/Iris type parachute and has a $C_D = 0.97$. It gives a descent rate of 81 feet per second (approximately 25 m/s). It is made out of nylon, has a weight of 42 g.
- Main Parachute

  The main parachute is deployed at an altitude of 1000 feet. This ensures that the unfolding loads on the parachute and rocket are very less. The chosen parachute is **Rocketman 8ft High Performance Parachute**. It is a Toroidal/Annular/Iris type parachute and has a $C_D = 2.2$. It gives a descent rate of 19 feet per second (approximately 6 m/s). It is made out of nylon, has a weight of 524 g.

b. *Shock Cords[6]*

Shock cords are used to endure the high shock load experienced during the parachute deployment event. The shock cord must endure two forces: 1) The force as the nose or electronics bay reaches the full length of the shock cord following ejection, and 2) then immediately after, the force of the parachute opening while the rocket wants to fall much faster than the parachute will allow.

The shock cords are recommended to be 3-5 times the length of the corresponding body. The shock cord lengths for the main and drogue parachutes are 30 ft for each. The shock cord chosen is **Rocketman 5/8th Inch 30 ft Tubular Nylon Shock Cord**. It has a width of 5/8th inch and can withstand a force upto 2250 lbs.

c. *Black Powder & Canisters[7]*

Black powder is used to release the parachute. When the e-match is lit, the black powder are ignited and this causes a sudden release of gas, which builds up pressure. This cause the shear pins connecting the two parts of the body tube to shear off and separate. The generated force also pushes the parachute out, while the incoming flow unfurls it. We can calculate the amount of black powder required as follows.

From the ideal gas equation, we can find the mass of the black required as

$$m = \frac{PV}{R_c T g}$$

where,
P is the pressure required to break the shear pins
V is the volume of the chamber to be pressurized
$R_c = 12.1579$ m/K is the combustion gas constant for FFFFg black powder
$T = 1739$ K is the combustion temperature for FFFFg black powder
$g = 9.807$ m/s^2 is the acceleration due to gravity

We require a 5 psi pressure to break the shear pins. Thus, the black amounts required are:

- Drogue (Primary) - 0.88 g
- Drogue (Backup) - 1.10 g

- Main (Primary) - 1.52 g
- Main (Backup) - 1.90 g

The backup charges are the ones ignited by the secondary altimeter (EasyMini). They have a higher amount (25 % more) to ensure that the parachute is expelled out at the second charge if not by the first charge.

Canisters are the containers in which the black powder is stored. We know the packing density of the black powder to be 0.581 g/cc. From this, we find that a cylinder with inner diameter 14 mm and length 10mm is enough for the all the canisters. We use PVC (polyvinyl chloride) as the material of the canisters.

d. *U-Bolts & Swivel links*

U-Bolt is used to attach the shock cord to the bulkhead. It allows the load on the shock cord to be easily transmitted to the bulkhead. The final dimensions of the U-Bolts are:

- Inside Height - 2 1/2 inches
- Diameter - 5/16 inches
- Inside Width - 1 1/8 inches
- Thread length - 1 1/8 inches

A swivel link is used to reduce the amount of twisting in the lines of parachutes. This ensures that these lines will stay straight, and the parachute canopy will be fully inflated during the entire descent of the rocket. Because of that, the rocket will land slower and softly on the ground, reducing the chances of it getting dinged up on landing. The chosen swivel links are **Rocketman 1500 lb Stainless Steel Swivel**.[8]

e. *Nomex Blankets & Shock Cord Protectors*

Nomex Blankets are used to protect the parachute from the heat of the ejection charges. They are made of a Nomex/Kevlar blend that is a tough, soft, fire and heat-resistant fabric. These blankets won't melt, drip, burn or support fire combustion in the air and are affordable and lightweight.

The shock protectors are used to protect the shock cords from the heat of ejection charges. This sheath of fire-resistant fabric gives it extra protection and prevents fatal cord damage that can occur, allowing the rocket to separate at deployment.

E. Testing

1. Compression testing of Body tube

An important phase of our rocketeer journey is to perform all kinds of testing for assurance and also as a safety measure, parallelly to check if the manufactured components have turned out to be "strong" or not.

Since we went with similar properties for the body tube, both material wise and dimension wise, we have conducted a compression testing on the body tube which was manufactured last year. The testing has been carried out in a structures lab in the department of Aerospace Engineering by using a Universal Testing Machine (UTM). We found out that the tube had around a 45° crack at the center and at a peak compression load of 59.34 GPa which resulted in a maximum displacement of 13mm.

Fig. 33 Compression test conducted on old body tube

2. GPS Battery Testing

To ensure that the rocket is safely recovered, we need to confirm that the GPS Tracker onboard survives for enough time. This can be done by performing a battery test, where a GPS tracker is made to continuously transmit its location to the ground station module, using a fully charged battery. A planned 400 mAh battery was used and the GPS tracker successfully transmitted for around 6 hours and 20 minutes. Thus, we can conclude that **the GPS tracker is capable of transmitting for more than 6 hours with a fully charged 400 mAh LiPo battery.**

3. Parachute Testing

The parachutes were tested to ensure its functionality. They were inflated and tested to ensure that it will inflate properly when deployed in the real flight. Figs. 34 & 35 show the inflated main and drogue parachutes respectively.

Fig. 34 Inflation test of main parachute

Fig. 35 Inflation test of drogue parachute

F. Payload

The payload is the component of the rocket that accomplishes its scientific objective. Typical rockets are known to experience large amounts of vibrations during flight. Our payload experiment, the VibroGen, intends to test a novel mechanism of harnessing the vibrational energy of the rocket to generate electrical energy, which will be used to power onboard sensors. This method effectively combines electromagnetic induction and piezoelectric effects to generate enough voltage to power onboard devices. [9].

1. Components

The payload weighs 4kg and has 2U size specification. The components in the payload subsystem are listed below:

a. Magnet

The payload houses a Neodymium magnet of dimensions 5cm x 5cm x 2.5 cm. This magnet will be responsible to generate flux through the coil and emf correspondingly.

Fig. 36 Neodymium magnet

b. Copper coil

Copper coil will be placed at top and bottom on the upper and lower places respectively, change in magnetic flux through these coils because of magnet moment will be responsible for emf.

Fig. 37 Copper coil

c. Springs

Springs will be joining the upper, middle and lower plates and the middle plate containing the magnet oscillates about mean position through springs. Thereby altering the magnetic flux through coil and generating emf.

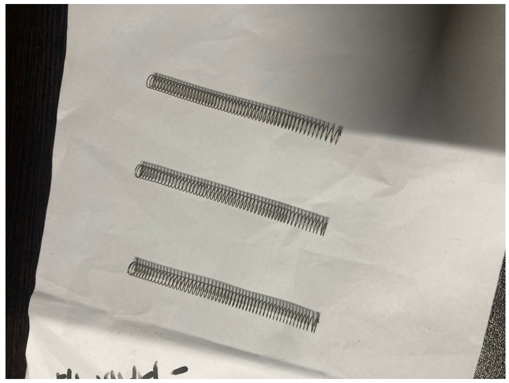

Fig. 38 Springs

2. Working Principle

The VibroGen is used to harvest electricity from vibrations and works on the principle of electromagnetism and piezoelectricity. A schematic diagram is shown in the figure below.

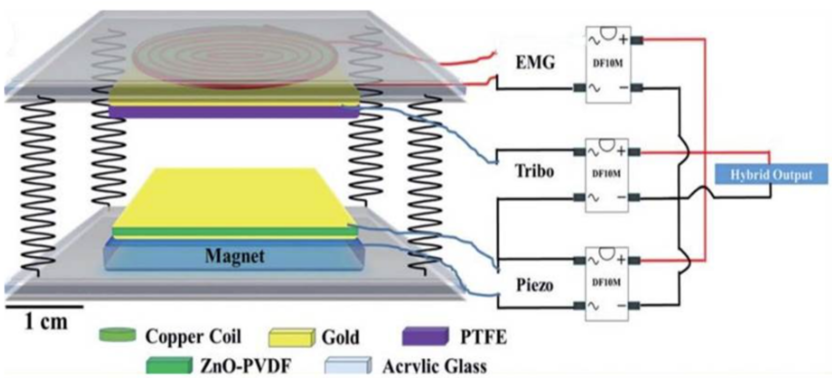

Fig. 39 Schematic diagram to illustrate working principle of payload

Vibrations cause the acrylic sheets to oscillate. The movement of the coil & magnet will produce an electromotive force inside the coil. When the two layers come in contact with each other due to vibrations, the pressure developed in piezoelectric stacks would cause a potential to develop. We are using three low-loss bridge rectifier ICs (DF10M) into which the AC output of each device will be fed. The outputs from the three bridge rectifier ICs are connected in parallel to obtain the hybrid output.

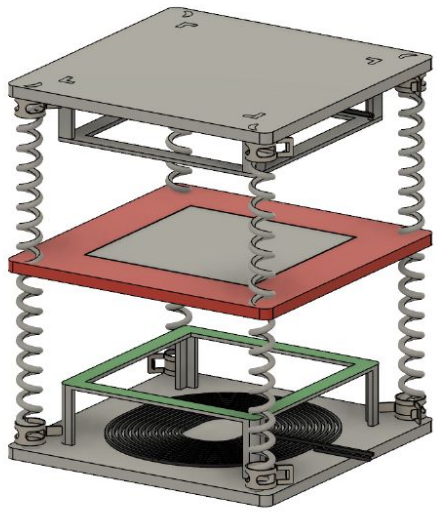

Fig. 40 Schematic diagram of payload

We have the top and bottom plate fixed to the payload bay frame and consisting of the copper coil, and piezoelectric stacks. The middle layer has the magnet sandwiched between these two layers.

From the g-force curve, we can divide the VibroGen operation into 3 phases.

The **1st phase** is the hypergravity phase when the rocket is burning. In this phase, the g-forces push the middle plate downward. The spring constants are decided such that in this phase, the magnet just touches the bottom coil. The main source of vibrations is the rocket motor. Since the middle plate is pushed down, high voltage piezoelectricity is mainly produced and a small amount of power is produced due to electromagnetic induction (which is of much lower voltage).

The **2nd phase** is right after burnout. Here, the g-forces are much lower. Since in the previous phase, vibration is about the equilibrium of that g-force level, now, we get high amplitude oscillations and vibrations from external sources would not cause much effect. The main component now is power from electromagnetic induction, while piezoelectricity is also produced on both upper and lower plates.

The **3rd phase** begins once the high amplitude oscillations have damped out due to electromagnetic induction. The vibration is from external sources. In this phase, power is mainly produced from electromagnetic induction.

We will measure altitude, temperature, pressure, humidity, battery and the VibroGen voltage throughout the flight. Acquired data will be stored in an SD card for post-flight analysis. We will also have a radio module and an antenna for transmitting data to a ground station. For plotting real-time data, we will use software like XCTU, microPython, Python libraries (pyQtGraph and PyQt6), Arduino IDE, etc. We use omni antennas on the ground and on the rocket (5dBi gain) to communicate the data.

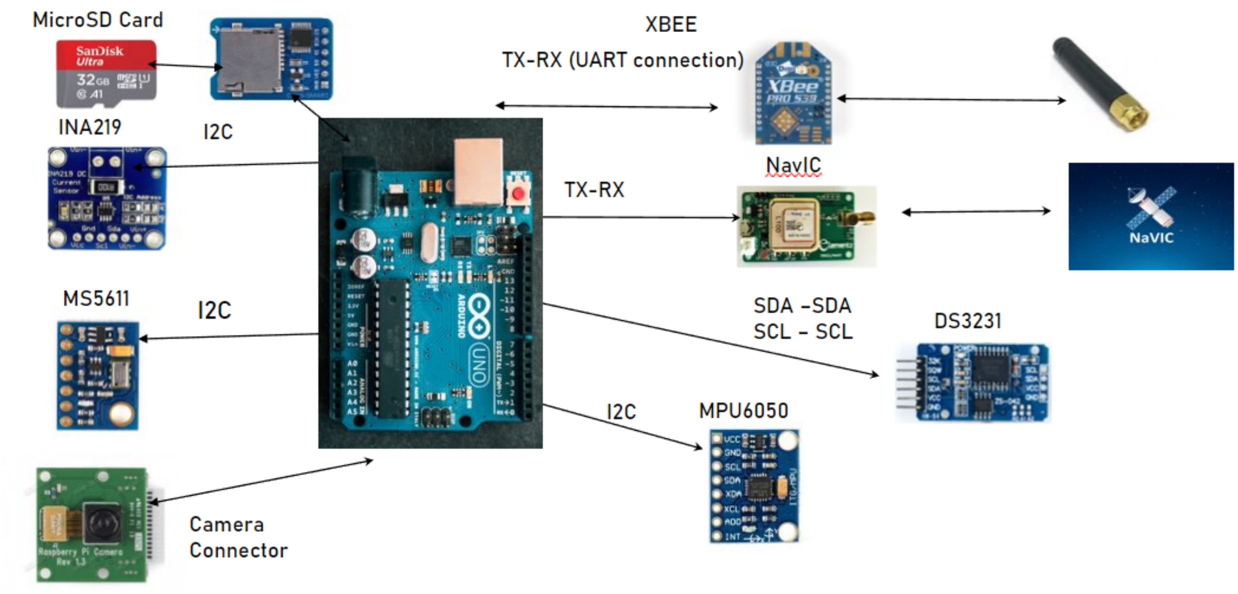

Fig. 41 Communication module

4. Payload design parameters

The payload consists of 3 acrylic plates, supported by 8 springs. The top and bottom plates have a coil and piezoelectric stacks. The spring lengths are chosen such that the middle plate remains midway between the top and bottom plates after the magnet has been placed on the middle plate. This means that the top set of springs will be shorter than the bottom set of springs. By calculating the resulting spring lengths, we get that the top set of springs must be of 33mm and bottom set of springs should be of 67mm. The spring constants are decided by ensuring the forces on the middle plate are balanced at 1.25g. This was chosen since most of the time, the g-force is close to the 0.25g. The spring constant thus calculated is 17.7N/m. The magnet is 450g weight.

5. Testing

a. *Piezoelectric*

The current produced by the piezoelectric circuit is of the order of $10\mu A$. The voltage characteristics are discussed as follows. The stacks once assembled, were loaded upon by weights starting from zero, after a threshold value, there was voltage difference observed between the two terminals connected to the stacks, this increased proportionately, with increase in load. These values are plotted against corresponding weights as below. Similarly, a potential difference is expected to be observed across the terminals of the stacks while the magnet strikes the stacks attached to the lower stack of the payload. This voltage difference would be maximum during the initial moments of flight (from start to burnout) during which the acceleration of rocket is expected to be as high as 10-12g cause Magnet would be pushed towards the stacks and considerable pressure would be applied because of pseudo force

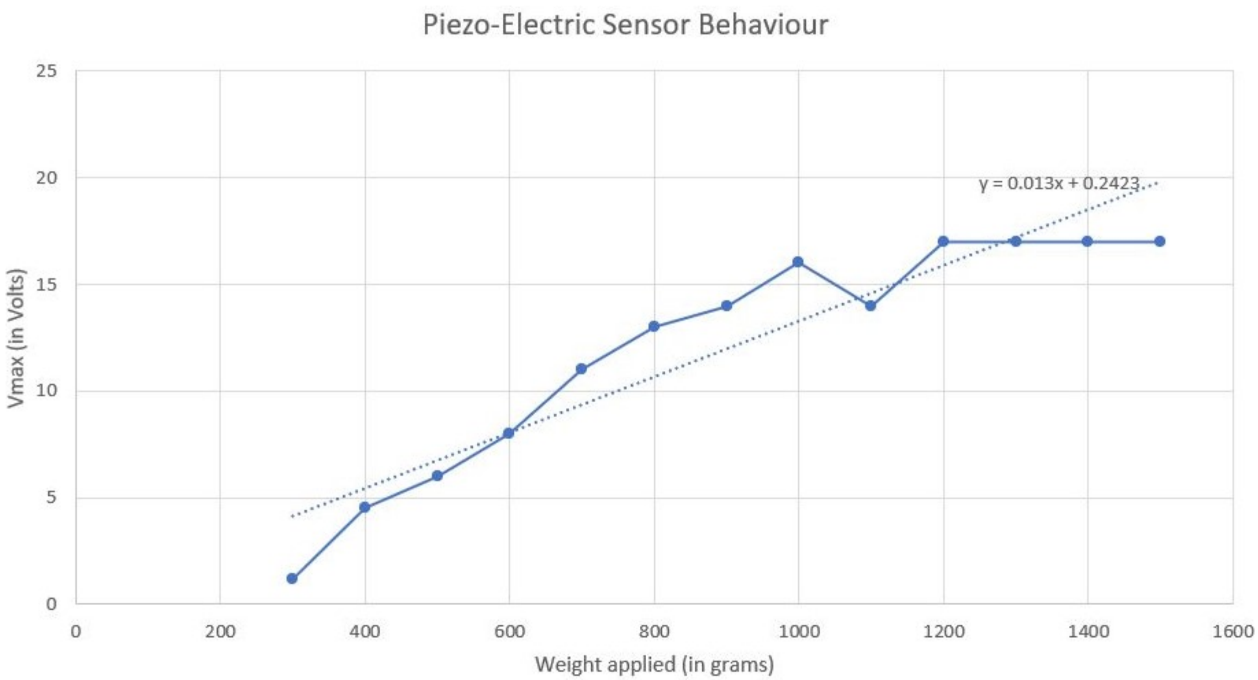

Fig. 42 Piezoelectric Characteristics: We see a linear relation and observe a plateau at a voltage 15V

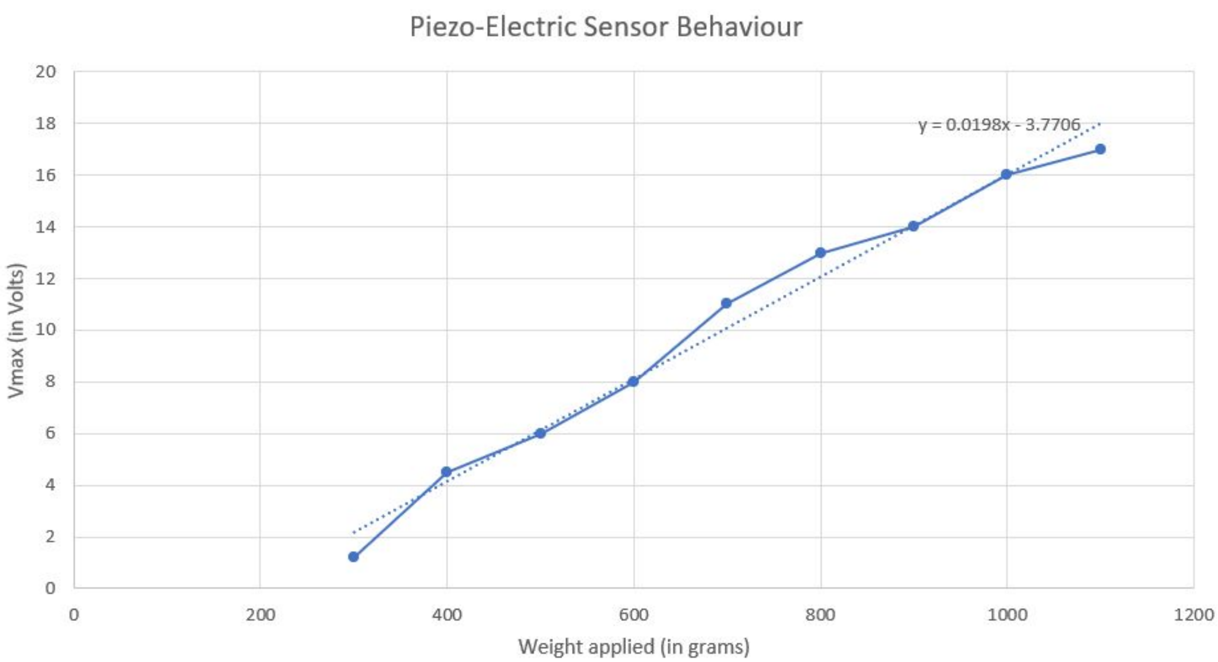

Fig. 43 Piezoelectric Characteristics linear regime

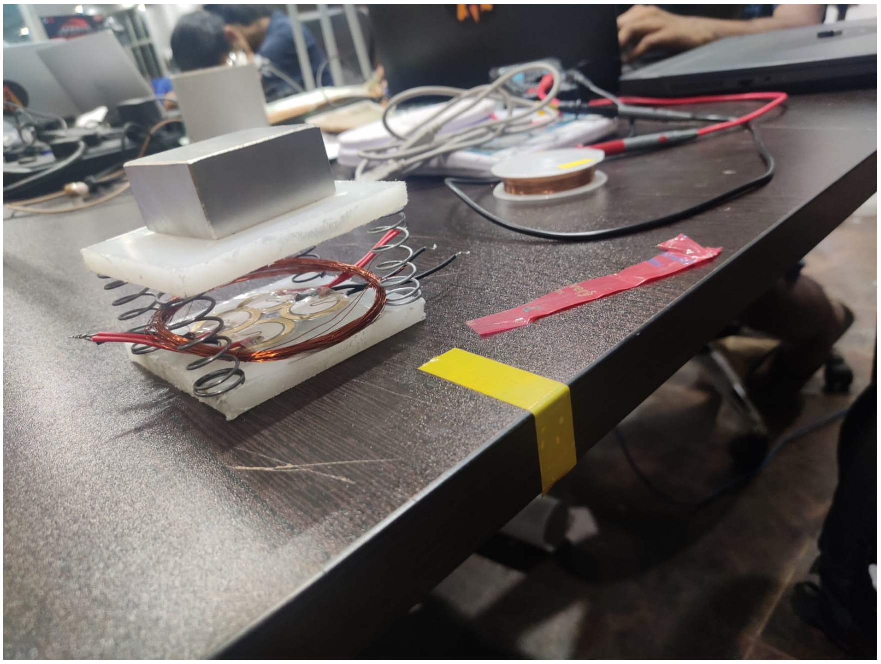

Fig. 44 Piezoelectric Characteristics linear regime

b. *Electromagnetic*

For testing the electromagnetic part of the Vibrogen we plan to induce various velocities using different forces in the vibrational test bed and measure the emf generated.

We can estimate the strength of oscillations and hence get the force on the piezo plates. Moreover the spring constants will give us typical velocities and frequencies of the magnet and hence the flux.

We estimate the power to be of the order of mW.

IV. Conclusion

In conclusion, the project was a valuable and transformative learning experience for our newly formed team. As newcomers to the field of rocketry, we faced a steep learning curve, but our dedication and enthusiasm propelled us forward. Throughout the project, we embraced the challenges and uncertainties that accompanied building a rocket for the first time. We approached each obstacle with a spirit of curiosity and a willingness to learn from our mistakes. The process of designing, prototyping, and testing our rocket provided us with invaluable hands-on experience in aerospace engineering. We encountered setbacks and had to adjust our plans along the way, these moments became valuable opportunities for growth and improvement. We learned the importance of effective communication, collaboration, and adaptability as we worked together to overcome technical hurdles and refine our designs.

Participating in the SA Cup 2023 provided us with a platform to showcase our learning journey and gain exposure to the wider rocketry community. We extend our gratitude to the organizers and sponsors for their support and for providing us with an opportunity to learn, grow, and connect with other like-minded individuals. We are proud of the progress we made and are eager to continue expanding our knowledge and skills in rocketry.

V. Acknowledgments

The team would like to acknowledge the endless support it has received from its members, family, friends, institute, donors and sponsors.

Firstly, the team would like to thank the faculty advisors Prof. Prabhu Rajagopal and Prof. Sathyan Subbiah from Mechanical Engineering department. Their expertise and constructive feedback has been instrumental in shaping the direction and quality of this work. We would also like to thank Prof. P.A. Ramakrishna from Aerospace Engineering department for his assistance and continued support.

The team would also like to thank the sponsors, ST Advanced Composites for helping us in making our aero-structure and providing material sponsorship, Ansys for sponsoring us with their fluent software licenses and Dassault Systèmes Solidworks for providing us with their licenses as well.

Finally, the team would like to thank Centre for Innovation, IIT Madras and IIT Madras alumni for supporting our innovative work here and providing us with the facilities for it.

Appendix A - Hazard Analysis

Table 2 Hazard Identification and Mitigation Plans

Possible Hazards	Storage	Handling	Transportation	Risk	Mitigation	Risk after Mitigation
Solid Motor Propellant	Stored in a designated, well-ventilated area away from ignition sources.	Handled with care to avoid impact, friction, or static electricity.	Transported in a secure, non-combustible container.	High	Thoroughly trained personnel on proper storage, handling, and transportation procedures. Regular inspection of storage facilities and containers for signs of damage or leakage. Implementation of strict access control measures.	Moderate
Black powder ejection	Stored in a separate, designated area away from other materials. Kept away from heat, sparks, and open flames.	Handled with caution to avoid accidental ignition. Used appropriate protective measures.	Transported in a secure, non-combustible container. Avoided proximity to ignition sources during transportation.	Moderate	Stored black powder in fire-resistant containers. Clearly labelled containers with appropriate warning signs. Conducted regular inspections and maintenance.	Low
High-altitude flight	Ensured the rocket was designed and built to withstand the forces and stresses of high-altitude flight.	Performed thorough pre-flight checks and inspections. Followed proper assembly procedures. Verified stability and integrity of the rocket before launch.	Used appropriate transportation methods to prevent damage to the rocket. Secured the rocket during transportation to avoid vibration or impact.	Moderate	Conducted comprehensive structural analysis and testing during the design phase. Implemented redundancy and fail-safe mechanisms in critical systems. Performed rigorous testing and quality control checks before launch.	Low
Parachute deployment	Used reliable parachute systems designed for the intended altitude and payload weight.	Followed proper procedures for parachute installation and packing. Inspected parachutes for any signs of damage or wear. Handled parachutes with care to prevent tearing or tangling.	Transported parachutes in protective containers to avoid damage. Avoided exposing parachutes to excessive heat or moisture during transportation.	Low	Conducted thorough testing and evaluation of parachute systems before launch. Implemented redundancy or backup systems for parachute deployment. Trained personnel on proper parachute handling and deployment procedures.	Low
Ignition source	Avoided storing or handling the rocket near open flames, sparks, or heat sources.	Used non-sparking tools and equipment. Followed proper procedures to prevent accidental ignition.	Avoided transportation near potential ignition sources. Secured the rocket to prevent accidental contact with ignition sources.	Moderate	Implemented strict safety protocols to prevent ignition source contact. Conducted regular inspections for potential ignition sources.	Low

Appendix B - Risk Assessment

Table 3 Risk assessment of potential dangers and failures - Airframe and Propulsion

Hazard	Possible Cases	Risk of Mishap	Mitigation Approach	Risk of Injury after Mitigation	Subsystem
Structural degradation	Inadequate material or component wear over time	Moderate	Thorough material selection and testing, regular inspection and maintenance.	Low	Airframe
Structural failure	Weak or inadequate structural design or manufacturing defects.	Moderate	Thorough structural analysis and testing, quality control in production, regular inspection and maintenance.	Low	Airframe
Propellant combustion issues	Improper mixing or contamination of propellant components	High	Strict quality control during propellant manufacturing, testing and verification of propellant composition	Moderate	Propulsion
Motor ignition failure	Igniter malfunction or failure to ignite motor propellant	Moderate	Rigorous testing and inspection of igniter systems.	Low	Propulsion
Propellant over-pressurization	Over-pressurization or improper sealing of motor casing.	High	Careful propellant loading and sealing procedures, testing and verification of motor integrity.	Moderate	Propulsion
Motor ignition during ground operations	Premature ignition or accidental ignition during ground handling.	High	Enhanced safety protocols, strict ignition procedures	Low	Propulsion

Table 4 Risk assessment of potential dangers and failures - Avionic and Recovery

Hazard	Probable Causes	Risk of mishap	Mitigation Approach	Risk of Injury after Mitigation	Subsystem
The recovery system fails to deploy	Electronics failure	Low; several built-in redundancies	Testing of primary systems for reliability, in addition to redundant altimeters and independent battery sources	Low	Avionics
	Pyrotechnic segregation fails	Low	Excess black powder for a high safety factor of over 2 ensures the separation, even if 50% black powder is not ignited	Low	
Recovery systems partially deployed	Parachutes get tangled	Medium; orientation can be unpredictable in flight	Professionally packed parachutes to ensure proper deployment. Clear exit paths for the parachute to open fully	Low	Recovery
Main parachute deploys at or near apogee	Incorrect wiring, accidental electrical contacts due to acceleration and vibrations	Medium; Nature of wiring is prone to mistakes	Repeated software testing, proper cable management, labelling and repeated checks for wiring	Low	Avionics
Power Loss	Batteries are not fully charged. Severed wires due to high acceleration	Low	Batteries of excessive battery life are used and are charged the night before whilst under proper storage conditions	Low	Avionics
Failure to detonate at a decoupling event altitude	Power loss, wire severance due to high acceleration speeds, bad e-match	Medium	Redundant systems that are entirely independent of alternative apogee detection schemes	Low	Avionics
Loss of Flight Data	Loss of communication with rocket	Medium	Data is logged to the internal memory of the GPS module. Memory is independently powered	Low	Avionics

Appendix C - Checklists

- **Assemble Recovery System**
    1) Pack main parachute in deployment bag
    2) Fold drogue parachute and wrap both of them in individual Nomex blanket
    3) Weigh the black powder and make the canisters
    4) Connect all the shock cords to the parachutes and U-bolts
- **Assemble Avionics Bay**
    1) Make sure all the switches are turned off
    2) Assemble all the components on the avionics bay
    3) Verify all the connections are proper
    4) Insert the bay into the body tube and secure it
    5) Connect the e-matches to the altimeters
    6) Activate all components and arm them once the rocket its on the pad
- **Assemble Nose Cone Enclosure**
    1) Activate the payload components
    2) Insert the payload into the nose cone assembly
    3) Place the bulkhead into the nose cone
- **Assemble Upper Body Tube**
    1) Insert the assembled avionics bay into the upper body tube
    2) Secure the upper bulkhead and secure the U-bolt to it
    3) Place the canisters and the drogue parachute
    4) Attach the shock cords and attach the nose cone assembly using the shear pins
    5) Secure the lower bulkhead and secure the U-bolt to it
    6) Place the canisters and the main parachute
    7) Attach the shock cords
- **Assemble Lower Body Tube**
    1) Obtain the motor and attach it to the motor mount
    2) Attach the motor mount, the upper bulkhead, thrust plate to the lower body tube
    3) Connect the U-Bolts, shock cords
    4) Attach the two body tubes together using the shear pins

Team Abhyuday

PRE-FLIGHT CHECKLIST

Nominal procedure

- ☐ Carry rocket to launch pad
- ☐ Install rocket on rail
- ☐ Set launch angle on rail
- ☐ Arm - remote pull-pins
- ☐ Ensure proper beep sequence and active telemetry
- ☐ Install engine igniter
- ☐ Verify continuity on motor igniter

Off-nominal procedure

- ☐ Remove engine igniter
- ☐ Disarm - re-insert circuit breaker pins
- ☐ Remove rocket from launch rail

LAUNCH CHECKLIST

Nominal procedure

- ☐ Ignite motor
- ☐ Track rocket through telemetry and visual aid

Off-nominal procedure

- ☐ Remove engine igniter if still in rocket motor
- ☐ Take cover until given all clear to approach rocket or rocket wreckage
- ☐ Insert circuit breaker pins to cut power to all avionics connected to energetics

RECOVERY CHECKLIST

- ☐ If arming lock is still intact and it is possible to do so, disarm - insert circuit breaker pin and deactivate switch to disengage all electronics
- ☐ Recover all sections of rocket and any pieces that may have broken off

Appendix F - Diagrams and schematics

The following images are the CAD drawings of the SRAD components in our rocket.

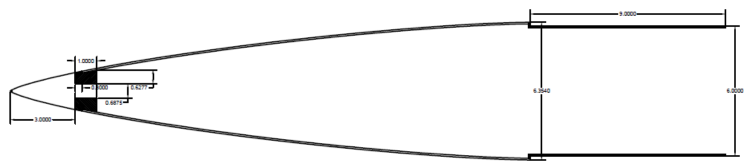

Fig. 45 Side-view of the nosecone

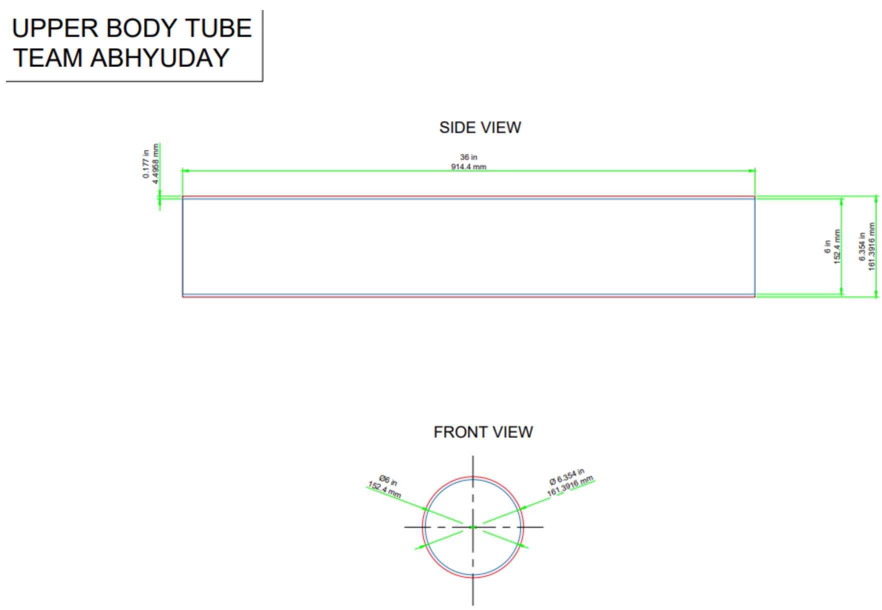

Fig. 46 Upper Body tube

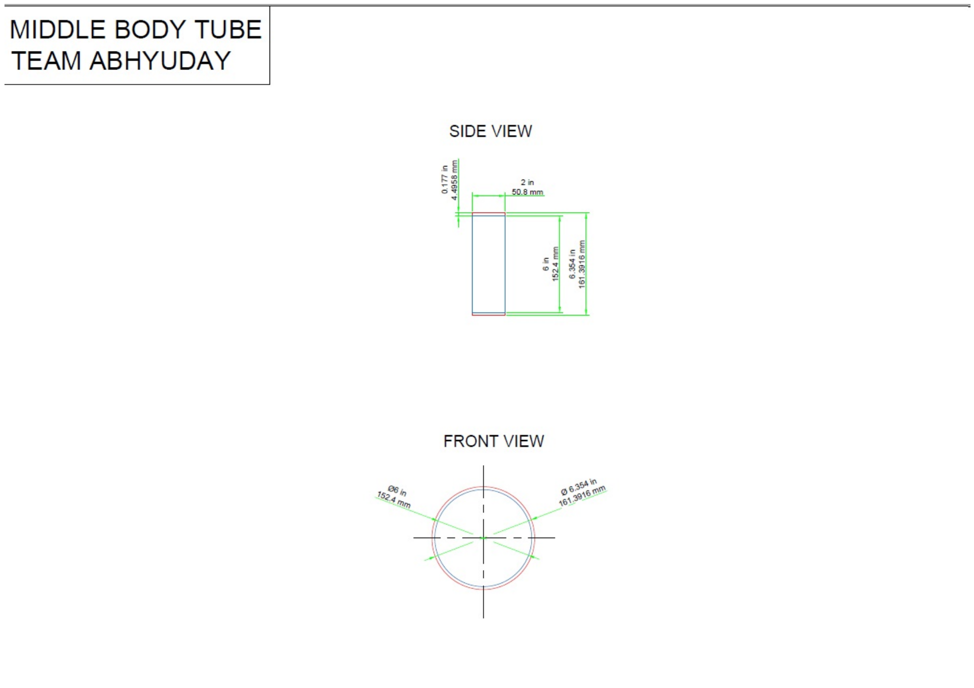

Fig. 47 Switch band

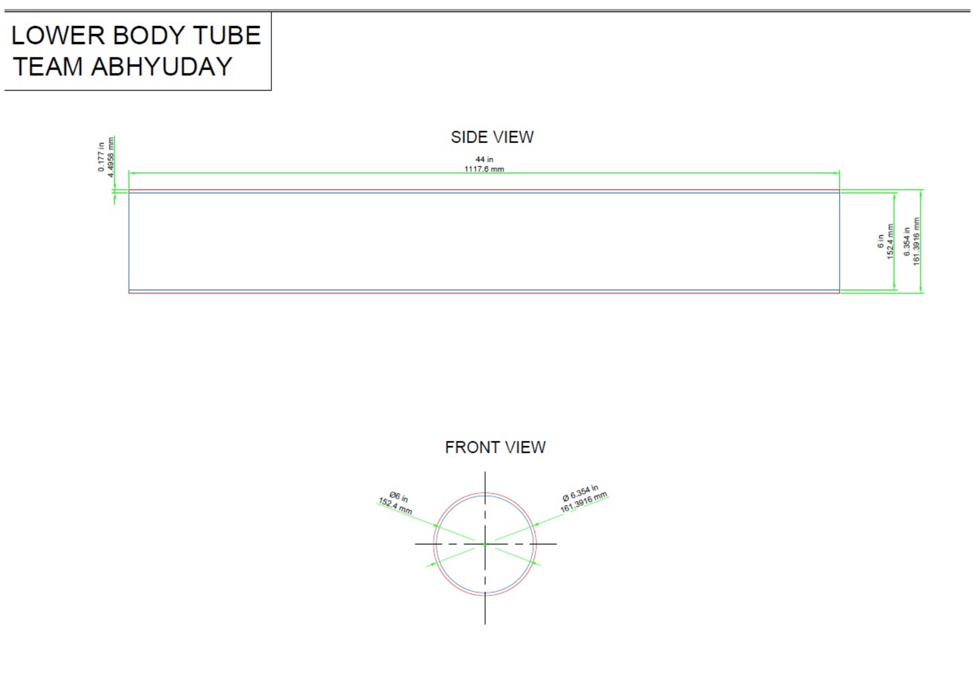

Fig. 48 Lower body tube

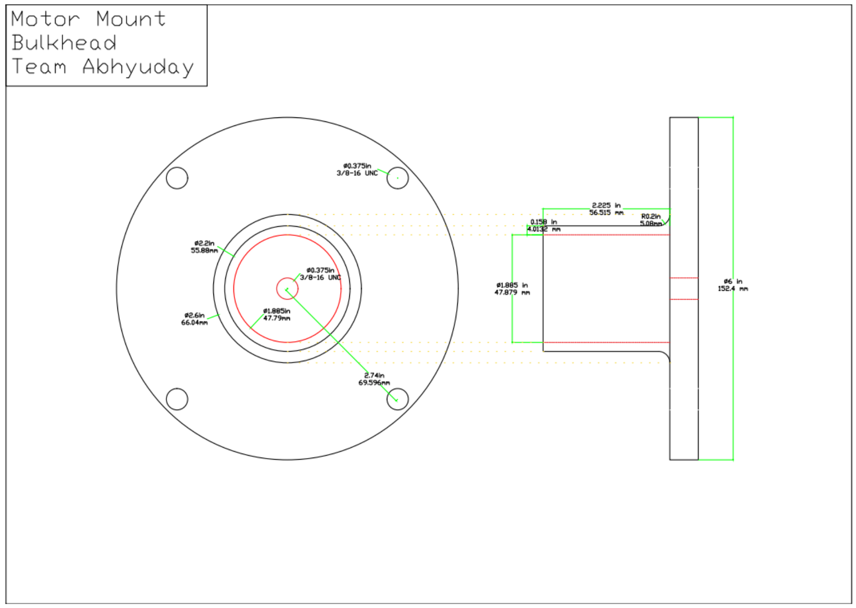

Fig. 49 Motor Mount

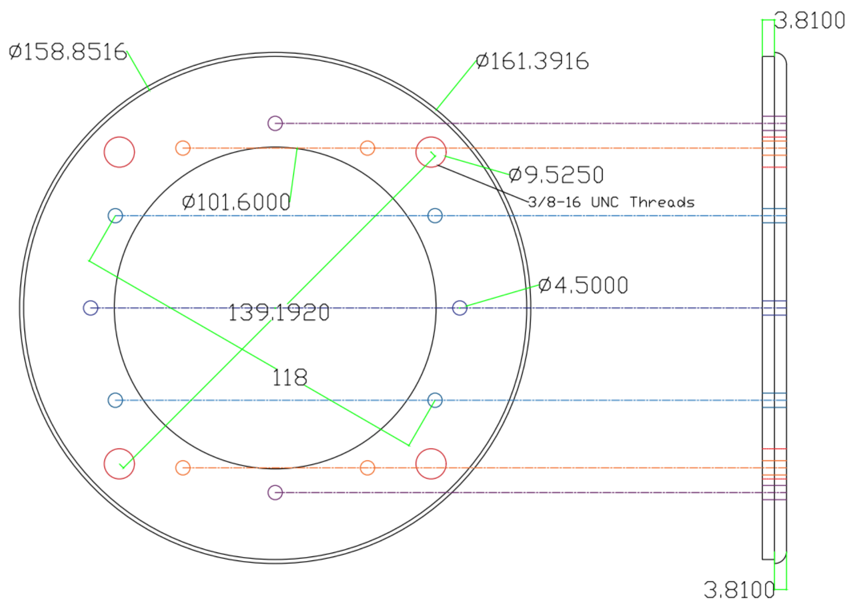

Fig. 50 Thrust plate

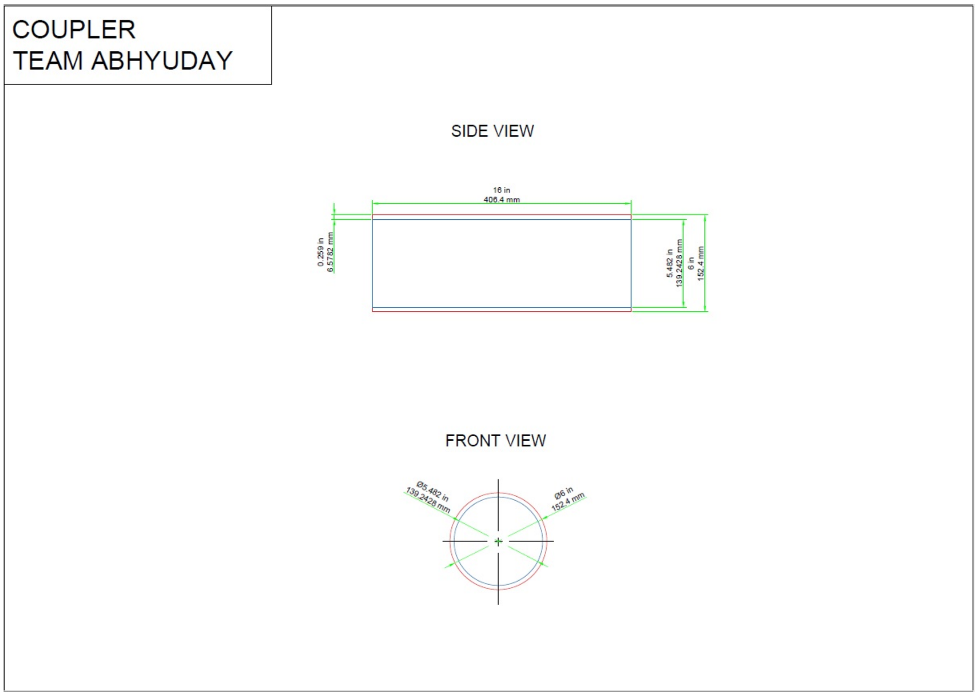

Fig. 51 Coupler

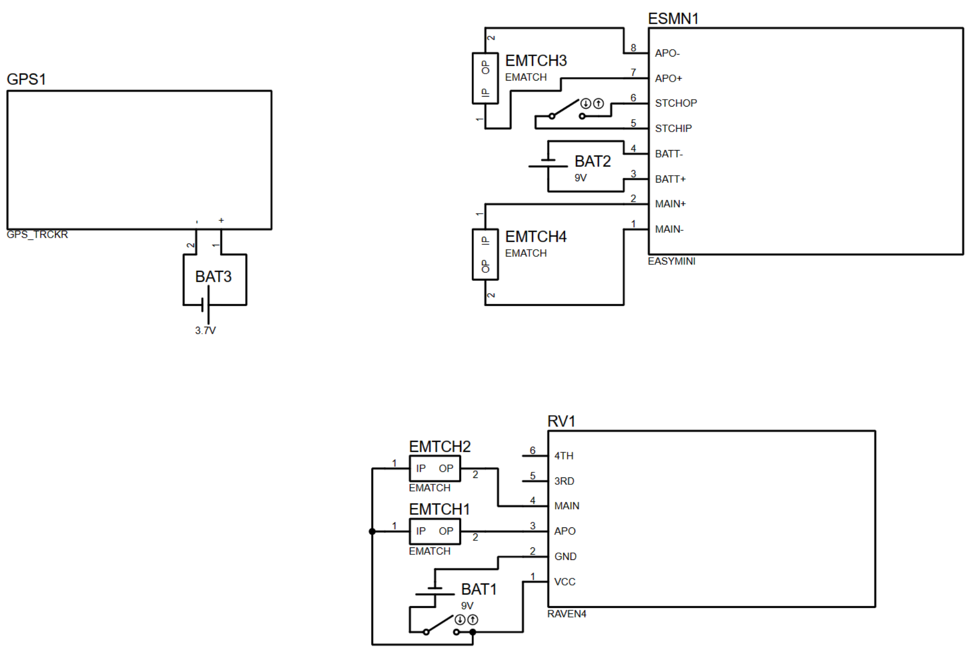

Fig. 52 Avionics Bay Circuit Diagram

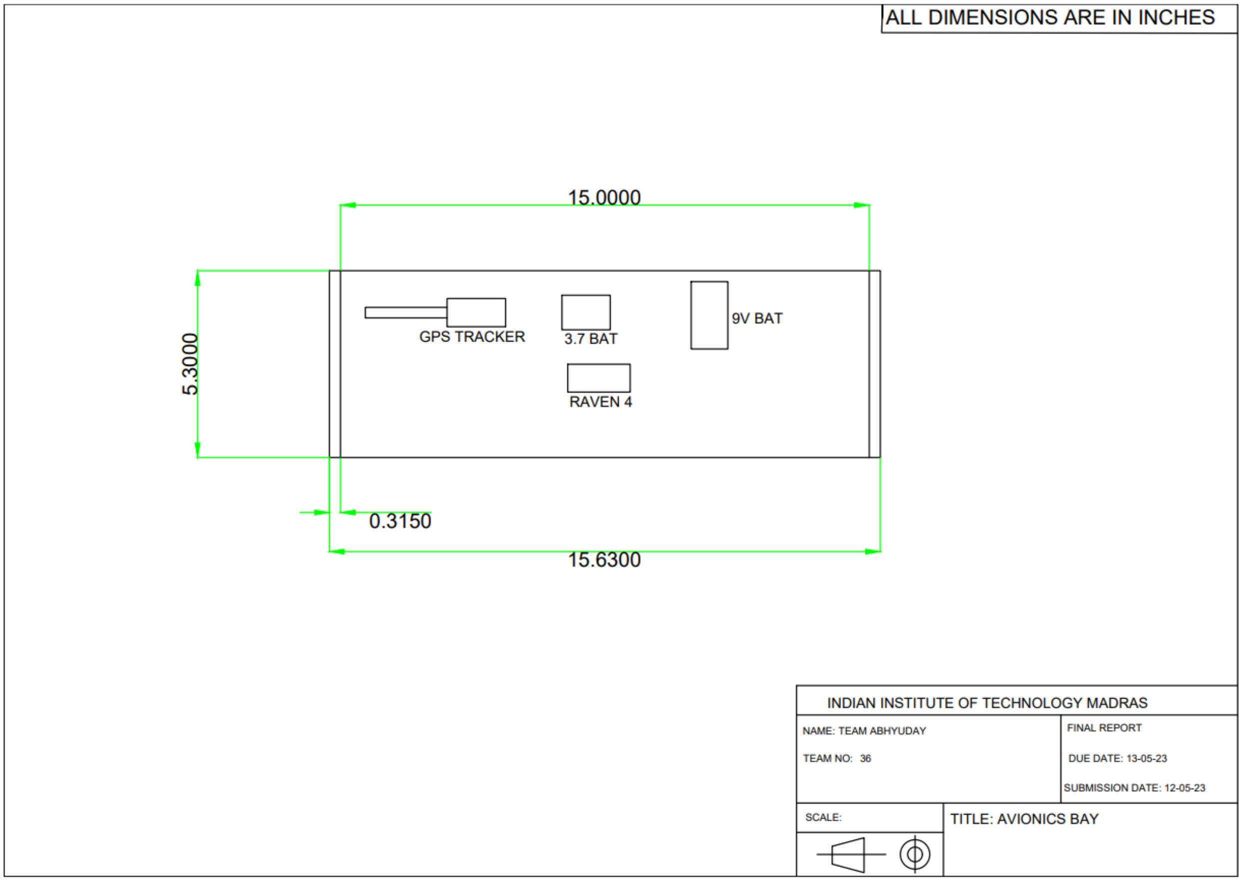

Fig. 53 Avionics Bay

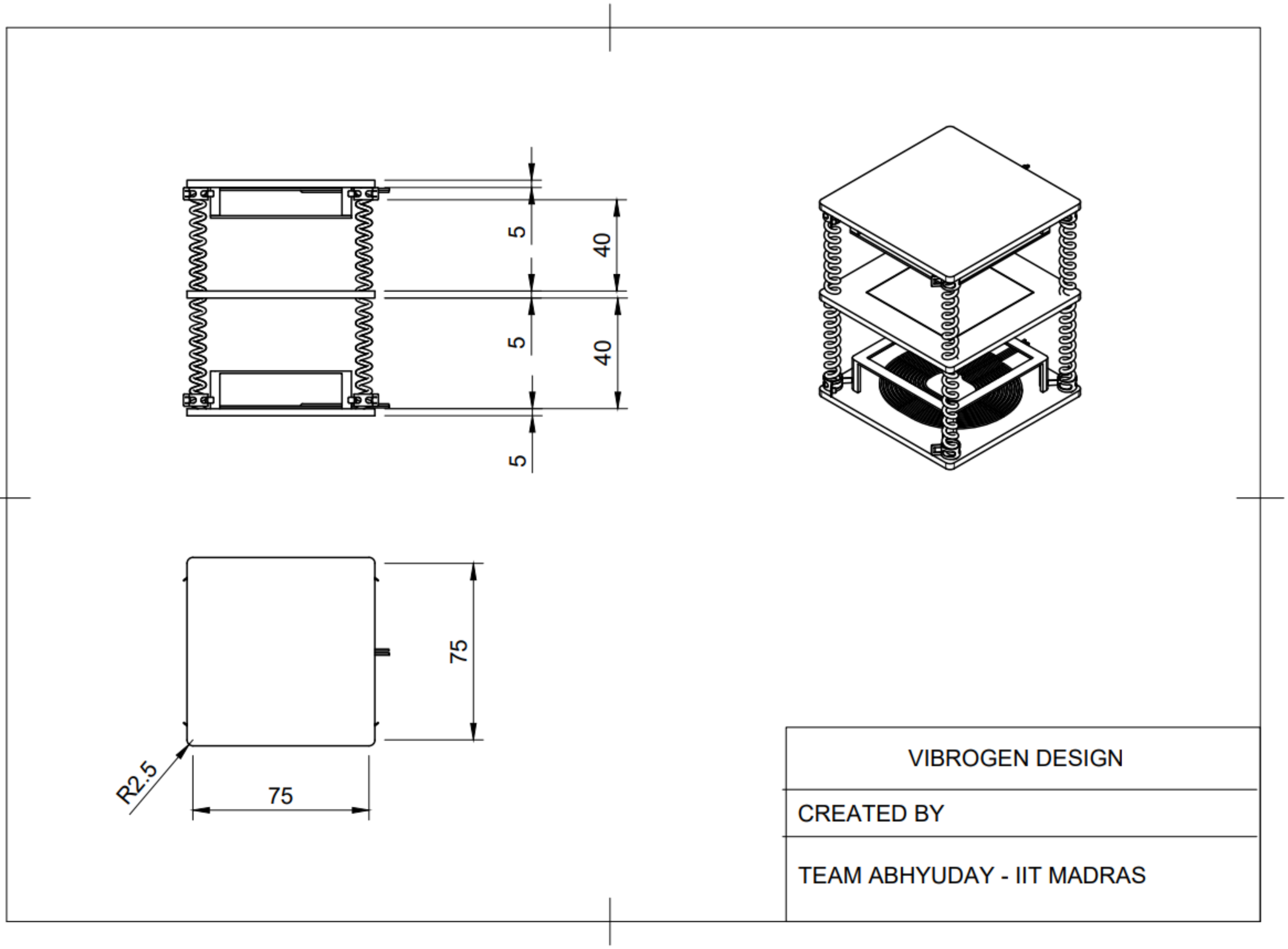

Fig. 54 VibroGen schematic

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