Team 116 Project Technical Report for the 2019 IREC

Design and Construction of Solid Experimental Sounding Rocket, HELEN

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The following document consists of the summary of the functionality and operations of HELEN, a sounding rocket competing in Spaceport America Cup 2019 from the University of Sheffield. Team 116 will be competing in the 30,000 ft. category, for a 30,000 ft. apogee target with a COTS Solid motor. The components of the rocket such as body tubes, nosecone, fins and the interior mechanical systems was manufactured in-house. The use of unique bio-resin in the place of epoxy resin displayed the team's aim to reduce environmental impact in manufacturing processes. The rocket will also carry a scientific payload on-board to conduct vibrational analysis on interior components, which will aid with future vibrational studies for sounding rockets in the university. Each subsystem will validate the requirements outlined by the SAC's rules and requirements documentation.

Nomenclature

ρ	=	Air density at 30,000 ft. (9144 m) = 0.4671 kg/m3
μ	=	Dynamic viscosity of fluid
γ	=	Ratio of Specific Heats
M	=	Mach Number
T	=	Static Temperature (Ambient)
R	=	Specific Ideal Gas Constant
A	=	Inner cross-sectional area of the airframe/compartment (in^2)
C_D	=	Estimated drag coefficient of an elliptical parachute = 1.50
F	=	Force needed to eject the compartment (N)
g	=	The gravitational acceleration = 9.81 m/s^2
l	=	Characteristics length, chord width of aerofoil
m	=	Zero fuel rocket mass = 23 kg
m_b	=	Mass of black powder in grams.
R	=	Ideal Gas constant = 266 in*lbf/lbm
T_b	=	Combustion temperature of the 4F black powder.
S	=	Parachute area
T	=	3307 degrees R / 2840 Fahrenheit (combustion temperature)
V_D	=	Rocket descent speed (dependent on the stage of descent) = 30 m/s
V	=	Volume of the parachute compartment (in^3)
v	=	Velocity of fluid

I. Introduction

The SunrIde (Sheffield University Nova Rocket Innovative Design Experiment) team is a student-led rocketry team at the University of Sheffield founded with the purpose of competing in the 2018 Spaceport America Cup. SunrIde was founded in October 2017 and began with the objective of bringing engineering skills and innovation for rocketry design for our university. In the second installation of this project, SunrIde is competing in the 30,000 ft. COTS Solid category and will be carrying a scientific payload onboard. The SunrIde team consists of 15 students from 1st year undergraduates to Master students, from five Engineering departments (Automatic Control and Systems Engineering, Mechanical Engineering, Materials Science, Aerospace Engineering, Civil Engineering) and the Maths and Statistics department at the University of Sheffield. The SunrIde project is supported by the Automatic Control and Systems Engineering department and the Mathematics and Statistics department of University of Sheffield. The team is further funded by ANSYS for fluid flow simulation packages, SHD Composites for the sponsor of CFRP and GFRP composites, Additive Manufacturing Research Centre (AMRC) for machining for epoxy tooling block. Additive manufacturing of the fins was facilitated by the Department of Engineering & Mathematics at Sheffield Hallam University and the Alumni Foundation grant, a funding committee of the University of Sheffield partially contributed to monetary means. All the modelling and simulations of the rocket were conducted using the OpenRocket, ANSYS CFD, RASAero, Solidworks, and Fusion 360 softwares.

II. Mission Concept of Operations (CONOPS)

The Mission Concept of Operations (CONOPS) for our rocket consists of several mission phases:

A. Ignition and Lift-off

The launch phase primarily constitutes of checking through the pre-flight checklists to ensure safe and secure launch of the rocket. At this phase, all of the components are armed and the rocket is launched. A signal is sent to the igniters, which lights the motor.

B. Powered ascent

This phase consists of the rocket accelerating due to the Cesaroni Pro98 M3400 solid burn. Motor burnout occurs at 3.5s in the flight (*phase transition*).

C. Coasting flight

This phase starts the moment the rocket motor burns out. The rocket continues gaining altitude but it decelerates until it reaches apogee. The electronic systems will measure the altitude and the acceleration forces continually to determine the progression of the rocket.

D. Drogue parachute ejection charge (*phase transition*)

The electronics will signal at the correct altitude to ignite the charges of black powder placed in the drogue section. The electronics' system has a complete backup in case the primary system does not fire the charges. Additionally, a redundant system is placed and fired in case of malfunction of the primary system.

E. Slow Decent

The drogue parachute size has been calculated to guarantee a fast but controlled descent reducing the drift of the rocket. The structural components have been tested to withstand the forces occurring from the drag generated by the parachute.

F. Main parachute ejection charge (*phase transition*)

At 115 seconds from launch, the electronics are set to eject the main parachute for landing of the rocket. As for the drogue parachute, backup electronics and ejection charges have been implemented.

G. Landing descent

The main parachute size has been calculated to considerably decelerate the rocket for safe landing. The structural components have likewise been tested to withstand the forces occurring from the drag generated by the parachute.

H. Landing

The rocket lands intact and safely to the ground. A GPS module will signal the position of the rocket to the team to be picked up when deemed safe by officials.

III. Material Selection

A. Bio-based resin

The team used a PS200, a revolutionary bio-based resin that is derived from a food waste product. This resin has been designed specifically to solve the problem of the fire risk that lithium ion batteries pose. Primarily for the manufacture of electric vehicle battery boxes, PS200 is available on a number of reinforcements and capable of autoclave, oven or press cure. This allowed for flexible production processes for any finished component. With a high service temperature and non-flammable properties meeting UL94 V0 specifications, PS200 can be used to contain fires and act as a flame and heat shield. Not only this, PS200 has been manufactured to be almost 100 per cent bio-based from a waste by-product of the food industry and is REACH compliant. This is in accordance with the aim of the team to create a sounding rocket with materials that yield only technical benefits in regards to high temperature performance. Also, it has added benefits of containing no hazardous materials providing safer environment during manufacturing process.

B. Body tubes

The body tubes of the rocket are manufactured from PS200 carbon fibre impregnated in bio-resin. This type of carbon fibre composite was chosen due to its very low combustibility, high insulation properties, shear strength, no delamination or blistering, unlike epoxy materials. The in-plane shear strength and in-plane shear modulus are 62 MPa and 3.52 MPa, respectively. The interlaminar shear strength at 0 degrees loading and interlaminar shear strength at 90 degrees loading are 38.7 MPa and 38.2 MPa, respectively. Such mechanical properties allow the material to withstand air friction and variations in atmospheric pressure over anticipated altitudes. Additionally, the service temperature of PS200 is up to 330 degrees Celcius after complete curing which makes a good head shield throughout the whole flight of the rocket. In fact, under the action of extreme heat, PS200 can turn into a ceramic-like material which maximises heat and flame shielding. The material does not contain substances that may be harmful to users and rocket.

C. Coupler and Avionics bay

The coupler and the casing of the electronic bay are manufactured from glass fibre composite impregnated in bio-resin because it is transparent to radio frequency waves and it provides rigidity to the structure.

D. Fins and Nose cone tip

The fins and nose cone tip is made from aerospace grade aluminium alloy, Al6061 T6. The fins and the nose cone tip were CNC machined that guaranteed accurate dimensions. This aluminium alloy was chosen due to its high fluttering velocity (885.5 m/s), high stiffness (68.9 GPa), high tensile strength (276 MPa), high shear strength (207 MPa) and ease of machining. The fins will be attached to the fin can by applying 3M's Scotch-Weld structural epoxy adhesive EC-9323 B/A which is a two-component epoxy paste adhesive and cures at room temperature or with mild heat to form a tough, impact resistant structural bond. It has excellent adhesion to a wide variety of substrates such as metals, glass, ceramics and plastics, incl. GFRP and CFRP. Once cured it provides extremely high shear and peel strength over a wide temperature range, with outstanding resistance to harsh environments and chemicals commonly encountered in aerospace applications.

E. Nose cone

The material for the nose cone is PS200 carbon fibre impregnated in bio-resin.

IV. Recovery system

The recovery system is a dual expulsion system based on the two-stage separation of the rocket's airframe. Each separation stage is achieved by detonating two pyrotechnic charges that use black powder, which pressurize the two parachute compartments enough for the deployment to occur. The three separate rocket sections will be held in place by structural inner tubes, each two body diameters in length, which are rigidly fixed to one airframe tube, and friction fitted, with shear pins to the other. The drogue deployment will take place at the fore section (nose cone) level when at apogee (about 30,000 ft), while the main parachute deployment will occur at the aft section (booster) level when at the lower altitude of 1477 ft. The three individual parts of the rocket will connect to the parachutes using shock cords. The shock cords differ in length as to prevent airframe collisions during the descent phase while absorbing the parachute deployment shock. The firing of the pyro charges is controlled by a programmable flight altimeter called StratologgerCF. To assure contingency, StratologgerCF will be assisted by a redundant Eggtimer system. The main altimeter controls the precise timing at which the pyro charge cups are to be fired, allowing for the main and drogue parachute deployment.

A. Parachute Material, Shock Cords and Swivel Link

The shape of the parachute is chosen to be elliptical as it provides more drag coefficient and is also cost-efficient. Parachute is made from ripstop nylon, as nylon material ensures durability and makes the parachute more resistant to tearing. Shock cords which connect the parachute to the vehicle, are made of Kevlar since it's flame resistant. A riser is knotted along with the shock cord and is connected between the parachute and the shock cord. A riser is implemented to avoid tangling of the shock cord or the parachute. Elastic materials can also be used for the shock cord, this being cheaper and more effective at absorbing the deployment impact, although they're not flame resistant. For better performance, the main shock cord can be made of elastic materials and the cord connecting the vehicle can be made of Kevlar. The length of the main parachute's and drogue's shock cord must be approximately three times the body length of the rocket, plus a 10 percent added for knotting, i.e. This, to pull the parachute away from the body and avoid zippering. A swivel link is attached between the riser and the parachute. This component will ensure the unthreading of the bolted connections during recovery.

B. Parachute Material, Coloration and Markings

The parachutes' colour and design will be different from each other, as it will assist ground-based observers in visual tracking of the rocket and post-landing recovery. The drogue and main parachutes are packed in a flame resistant wadding along with the risers and the shock cords.

C. Parachute sizes

The overall size for each of the parachutes is determined by the relationship between the surface area of the parachute and the drag force required to slow the rocket with mass.

D. Drogue Design

The required descent velocity for the rocket when the drogue is deployed is approximately 30 m/s. Therefore, based on OpenRocket data, required descent speed, and international standard atmosphere data, the parachute area can be calculated from the equation below:

Drag (up) = Weight (down)

$$\frac{1}{2}\rho S_R C_D {V_D}^2 = mg \tag{1}$$

$$S_R = \frac{2mg}{\rho C_D {V_D}^2} \tag{2}$$

Therefore from equation (2):

$$S_R = \frac{2 \times 23 \times 9.81}{0.4671 \times 1.5 \text{ x } 30^2} = 0.498\, m^2 \tag{3}$$

Using this required area for the drogue, the diameter is found as a function of the area:

$$D = \sqrt{\frac{4S}{\pi}} \tag{4}$$

Therefore from Equation (4):

$$D = \sqrt{\frac{4 \times 0.498}{\pi}} = 0.796\, m$$

Suppose shroud lines are $1.15 \times D = 1.15 \times 0.796 = 0.92\, m$

E. Main Parachute Design

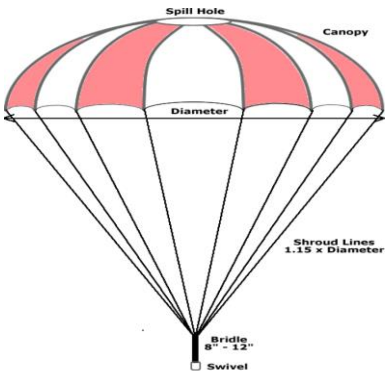

Figure 1: Parachute design

The required descent velocity for the rocket when the main parachute is deployed is approximately 6 m/s. This is also the impact velocity of the rocket with the ground. It allows for a quick enough descent so that the rocket does not travel big distances due to winds but also small enough so that the impact energy does not fracture the body tubes or any other extruded parts such as the fins, engine tail, or nose cone. Therefore, based on OpenRocket data, required descent speed, and international standard atmosphere data:
ρ – Air density at 1477 ft. (450 m) = 1.1673 kg/m^3
V_D – Rocket descent speed assumed = 6 m/s

Equation (2) gives:

$$S_R = \frac{2 \times 23 \times 9.81}{1.1673 \times 1.5 \times 6^2} = 7.16\, m^2 \tag{5}$$

Equation (4) gives:

$$D = \sqrt{\frac{4 \times 7.16}{\pi}} = 3.02\, m \tag{6}$$

Suppose shroud lines are $1.15 \times D = 1.15 \times 3.02 = 3.47\, m$

F. Summary

Table 1: Summary of the parachute dimensions

	Area (m^2)	Diameter (m)	Shroud Lines (m)
Drogue	0.498	0.796	0.92
Main Parachute	7.16	3.02	3.47

V. Flight Simulation and Aerodynamics of HELEN

A. OpenRocket

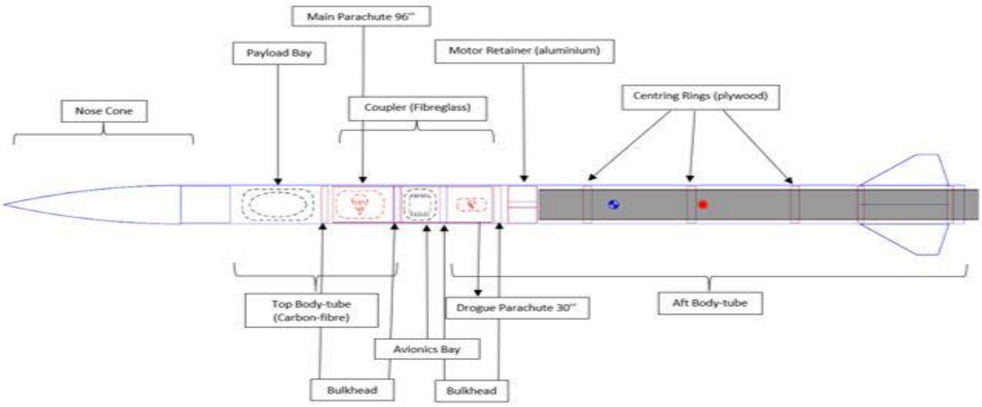

Figure 2: OpenRocket design of HELEN

Figure 2 above illustrates the design modelled on OpenRocket to conduct flight simulation, gain insight on the flight characteristics of HELEN and to identify the specifications obtained from the simulation complies with the requirements set by SAC in the rules and regulations documentation. The requirements are as follows:

- Flight Stability Margin: 1.5 - 2.0
- Ground Hit Velocity < 9 m/s
- Payload Mass: at least 8.8 lb
- Reach an Apogee of 30,000 ft.

Table 2: HELEN's specifications obtained from OpenRocket Simulation

Stages	1
Mass (with motor)	29.364 kg
Stability	2.01 cal
CG	1.721 m
CP	1.973 m
Altitude reach	36264 ft
Flight time	134 s
Time to Apogee	43 s
Velocity off-pad	42 m/s
Max velocity	719 m/s / 2.10 Mach No.
Ground Hit Velocity	7.68 m/s

Table 2 above illustrates HELEN’s specifications that were obtained by simulation ran in OpenRocket. The simulation confirmed that the values obtained from OpenRocket complied with the requirements set by SAC. Shown below are plots of the uncorrected OpenRocket model.

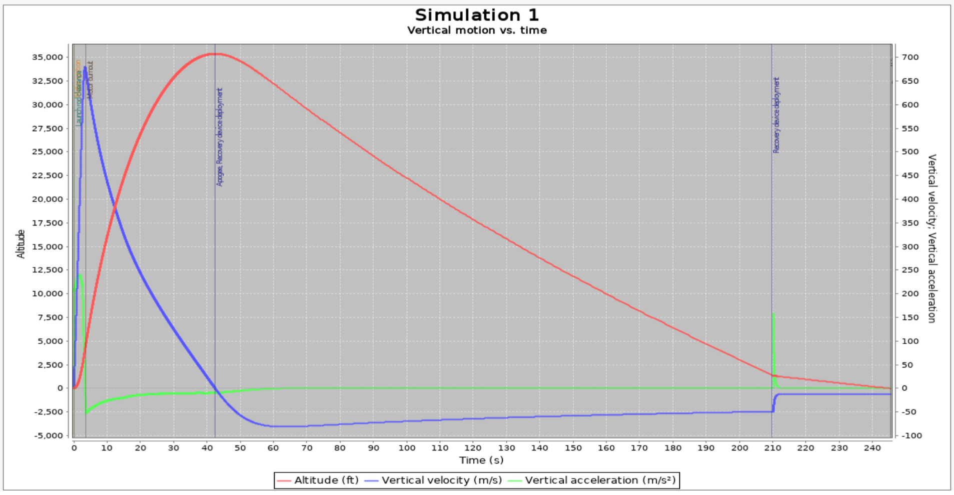

Figure 3: Flight simulation plot of HELEN

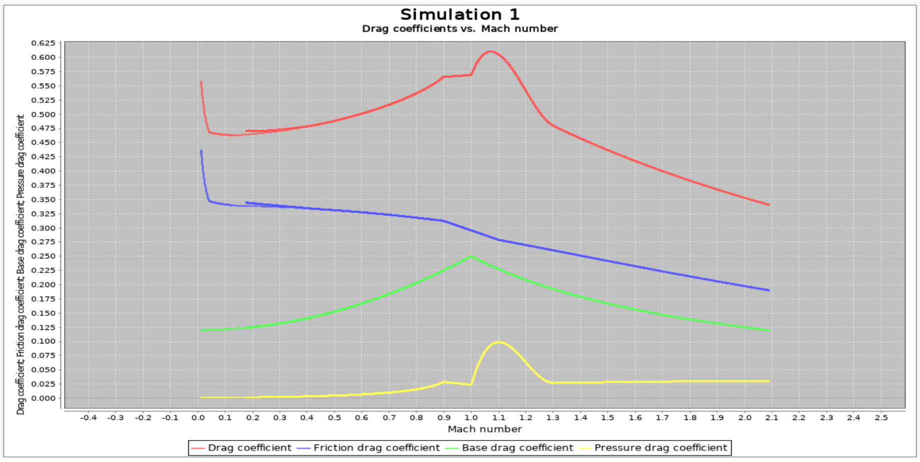

Figure 4: Simulated Drag Characteristic of HELEN

As shown in Table 2 above, preliminary OpenRocket model predicts an apogee of 36,264ft. This is higher than will be achieved due to the fact that the effects of wave drag acting on the nose cone and body tubes are not entirely accurate. This can be seen in the *Drag Coefficients vs Mach Number* graph, shown in Figure 4 above, in which the pressure drag coefficient increases suddenly as the rocket enters the transonic region (Mach 0.8-1.2). To handle this a CFD analysis was performed as detailed in the CFD Aerodynamic Analysis section.

B. CFD Aerodynamic Analysis

A 3D density-based CFD simulation was performed on an IGES assembly detailed in the design section. Shown in Figure 5, 6 and 7 below are contours of density (shock), dynamic pressure and static temperature respectively at Mach 2.15.

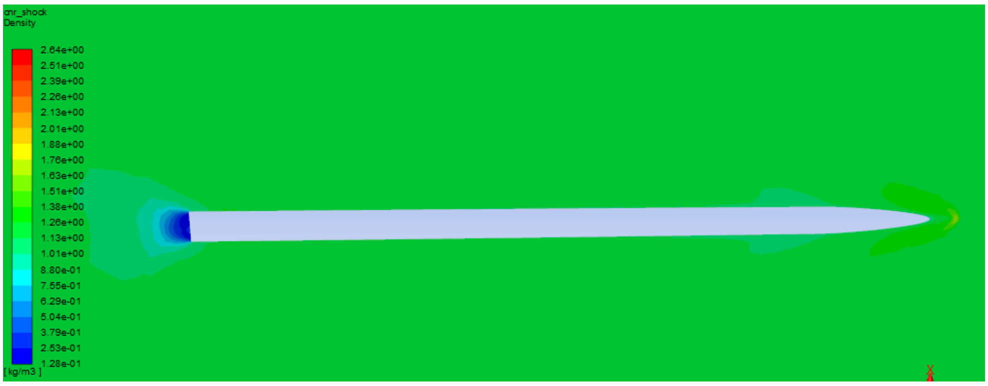

Figure 5: Contours of density (Shock)

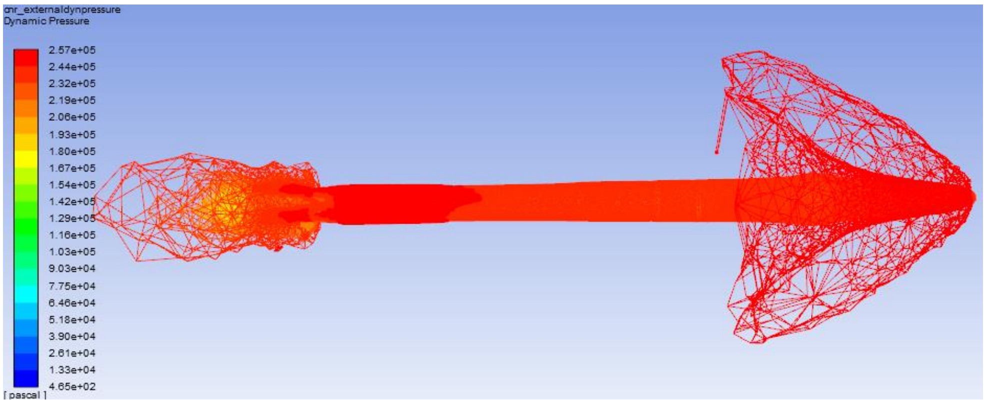

Figure 6: Dynamic Pressure plot

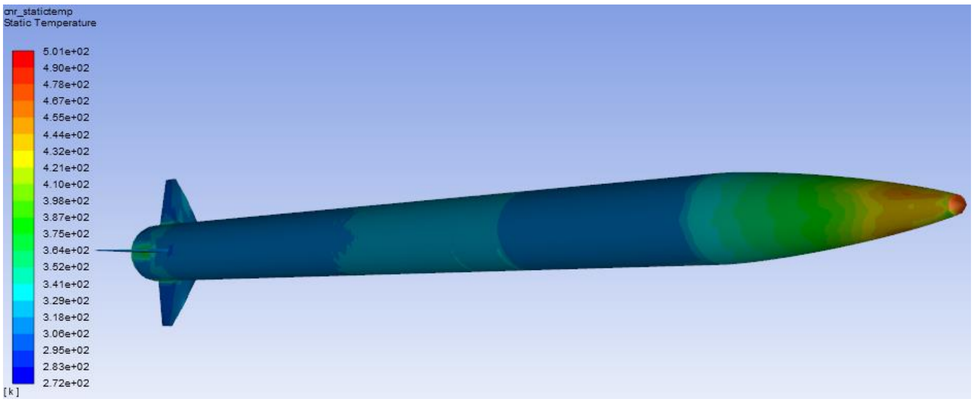

Figure 7: Static Temperature Plot

The increase in static pressure is caused by the isentropic relation between total temperature and static temperature as governed by the flow velocity:

$$c_p T_0 = c_p T + \frac{u^2}{2} \tag{7}$$

Shown below, the drag coefficients from the CFD model were determined by taking the total surface axial drag, simulation air density of 1.2kg/m³ and reference area of 123cm² using the drag equation:

$$C_D = \frac{2D}{\rho v^2 S} = \frac{2D}{\rho M^2 \gamma R T S} \tag{8}$$

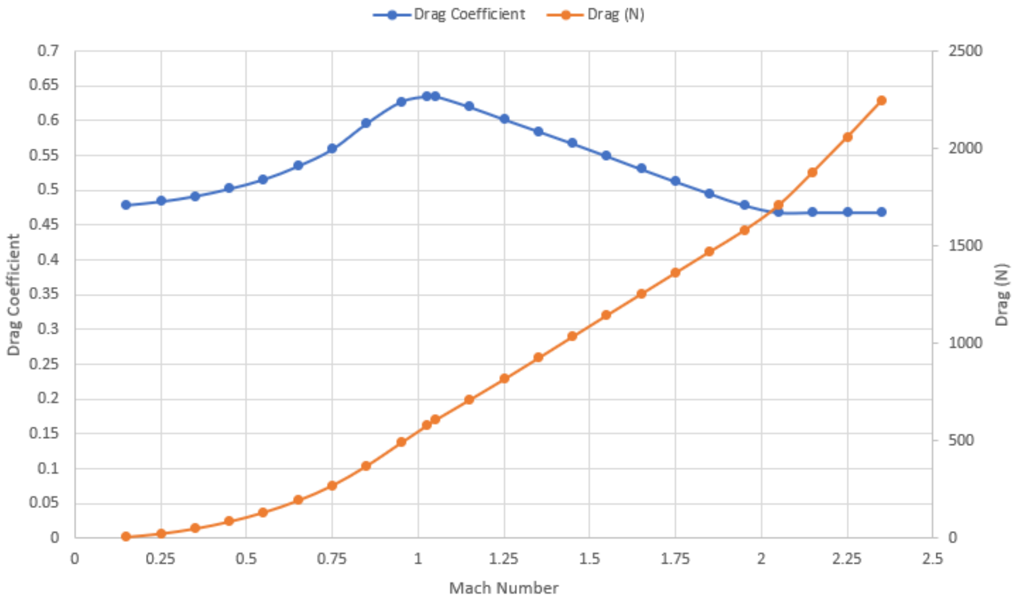

Figure 8: Drag Coefficient & Drag vs Mach Number Plot

Table 3: Parameters from flight model

Mach	CD	Drag	Mach	CD	Drag
0.15	0.47943	9.363487	1.25	0.60261	817.3089
0.25	0.48456	26.28799	1.35	0.58534	925.9886
0.35	0.49218	52.33472	1.45	0.56784	1036.315
0.45	0.50288	88.39328	1.55	0.54971	1146.376
0.55	0.51624	135.5523	1.65	0.53112	1255.135
0.65	0.53527	196.3042	1.75	0.51314	1364.086
0.75	0.55961	273.236	1.85	0.49585	1473.071
0.85	0.59655	374.1232	1.95	0.47914	1581.472
0.95	0.62766	491.7015	2.05	0.46872	1709.823
1.025	0.6355	579.553	2.15	0.46872	1880.703
1.05	0.63574	608.3983	2.25	0.46872	2059.721
1.15	0.62042	712.2154	2.35	0.46872	2246.876

C. Drag-Amended OpenRocket Analysis

Using the CDOverride Java Plugin for OpenRocket, the behaviour of the flight model can be overridden. This gives a revised apogee of 30,409ft and characteristics as shown in Figures 9-12 below:

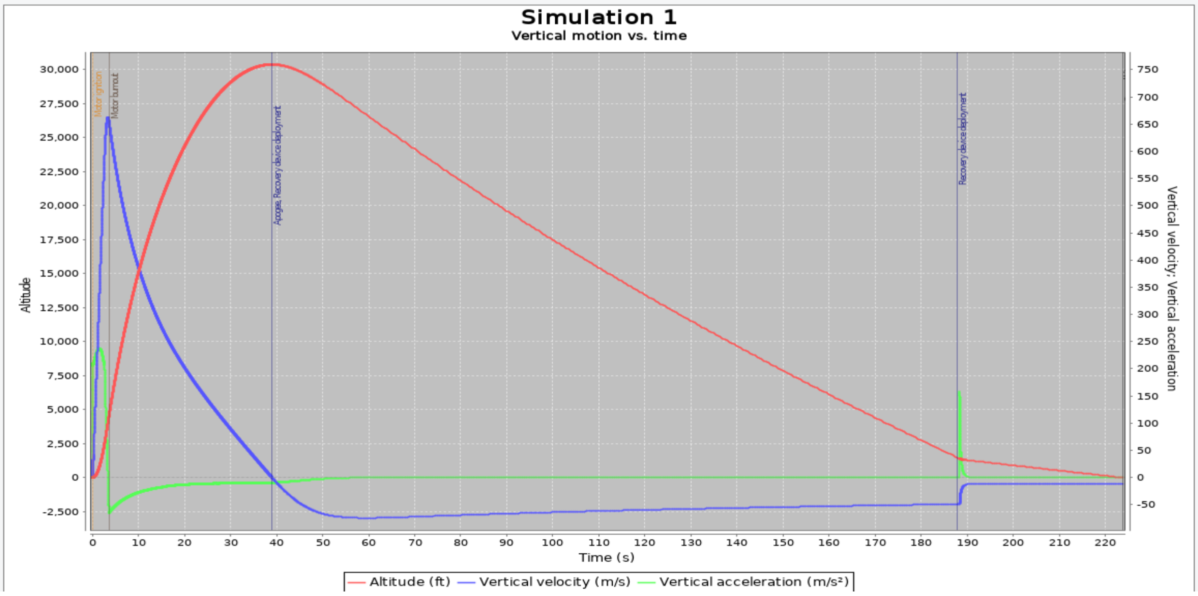

Figure 9: Revised flight simulation of HELEN (30,409 ft apogee)

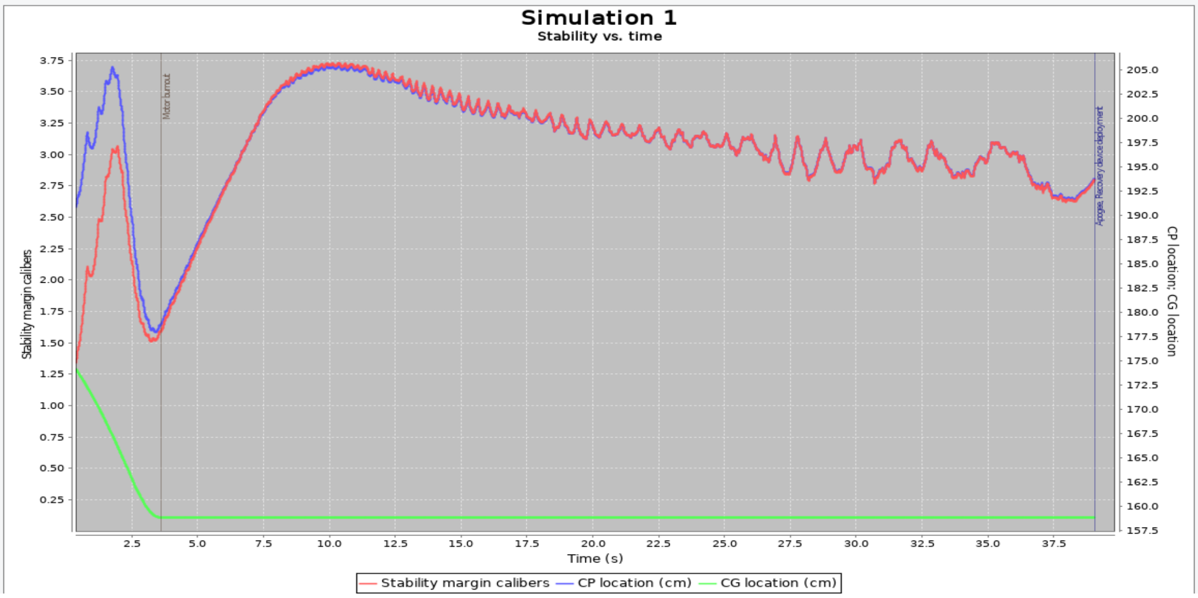

Figure 10: Stability margin vs Time plot

Table 4: Helen's specifications obtained from revised drag amender OpenRocket simulation

Stages	1
Mass (with motor)	30,547 kg
Stability	1.78 cal
CG	1.760 m
CP	1.980 m
Altitude reach	30409ft
Flight time	223 s
Time to Apogee	39 s
Velocity off-pad	49 m/s
Max velocity	671 m/s / 2.03 Mach No.

Figures 9-10 above illustrated the revised flight simulation of HELEN with an addition of mass on the fins and with improved drag-amended analysis. Table above show the specifications of the revised drag-amended OpenRocket analysis with a much accurate target apogee of 30,409 ft.

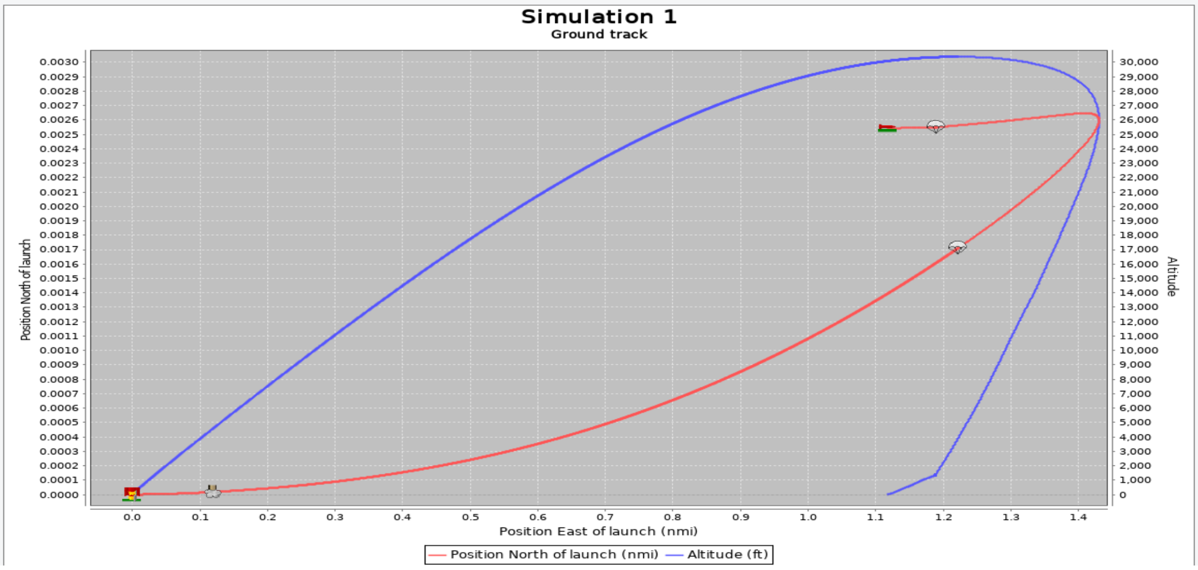

Figure 11: Ground track of HELEN

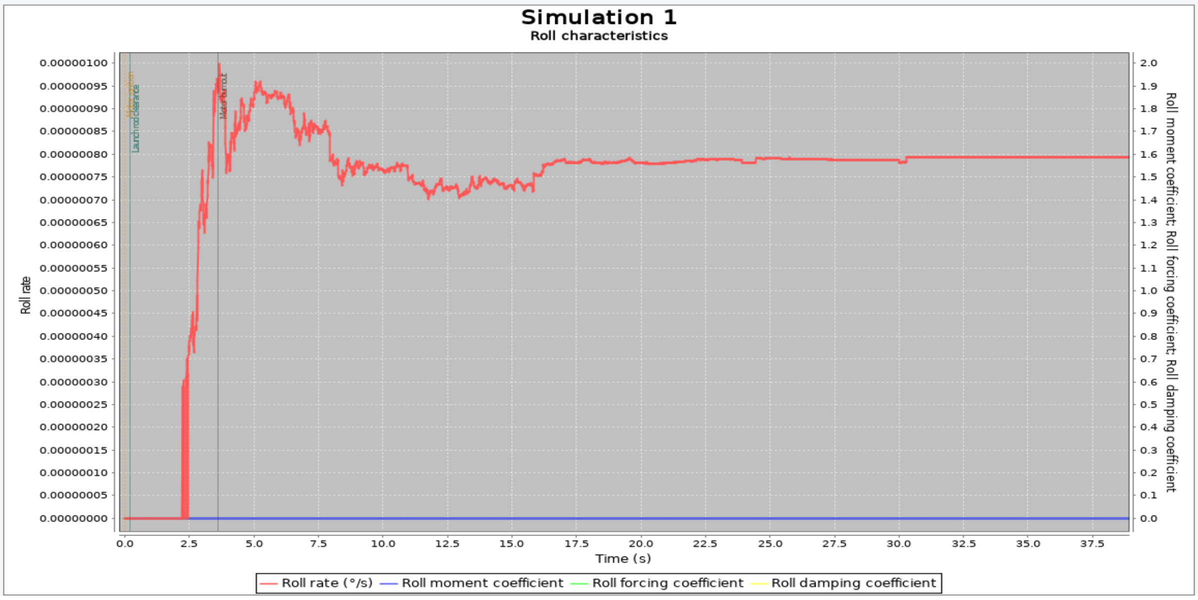

Figure 12: Roll characteristics of HELEN

The increased drag results in a lower apogee, primarily caused by the fins and lack of boat-tail. The launch site conditions in OpenRocket were set to represent those of Spaceport America, by using a WGS84 Ellipsoid geodetic model with the longitude and latitude of Spaceport America, a field height of 1400m and temperature of 30ºC. This results in a decreased air density, and hence proportionally lower drag.

The maximum drag experienced by the vehicle is 1222N at Mach 2.03 following motor burn-out. With a burn-out mass of 21,122g the deceleration experienced at this point is 5.93m/s². After 1.5s post-launch, a maximum acceleration of 239m/s² (24.36G) is experienced.

D. Fin Aerofoil Analysis

The root of the aerofoil was selected as the NACA 65A-003 symmetric low camber aerofoil such that the fins would have sufficient lift authority in the early stages of flight, whilst ensuring that drag at high Mach numbers was minimised. To verify this, JavaFoil was used to perform a 2D inviscid analysis. Below figure 13 shows a distribution of pressure coefficients at a 5-degree angle of attack at Mach 0.5.

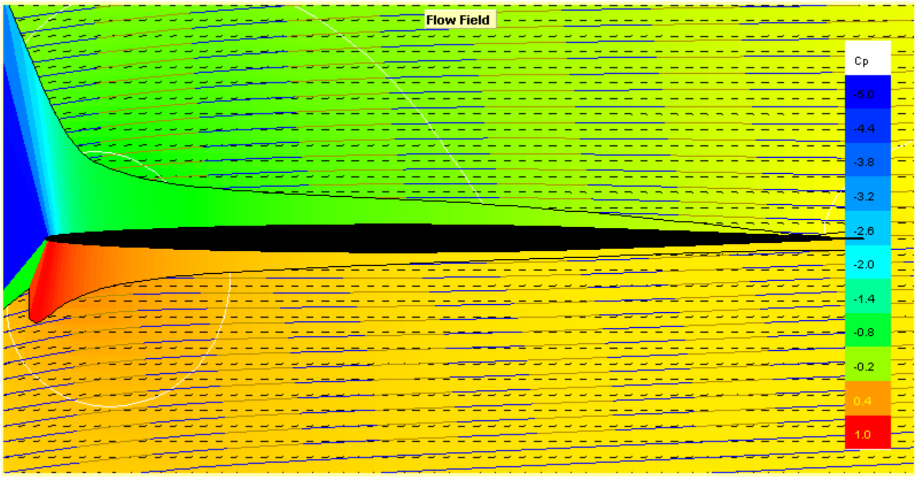

Figure 13: Distribution of pressure coefficients at 5-degree angle of attack at Mach 0.5 of Fin Aerofoil

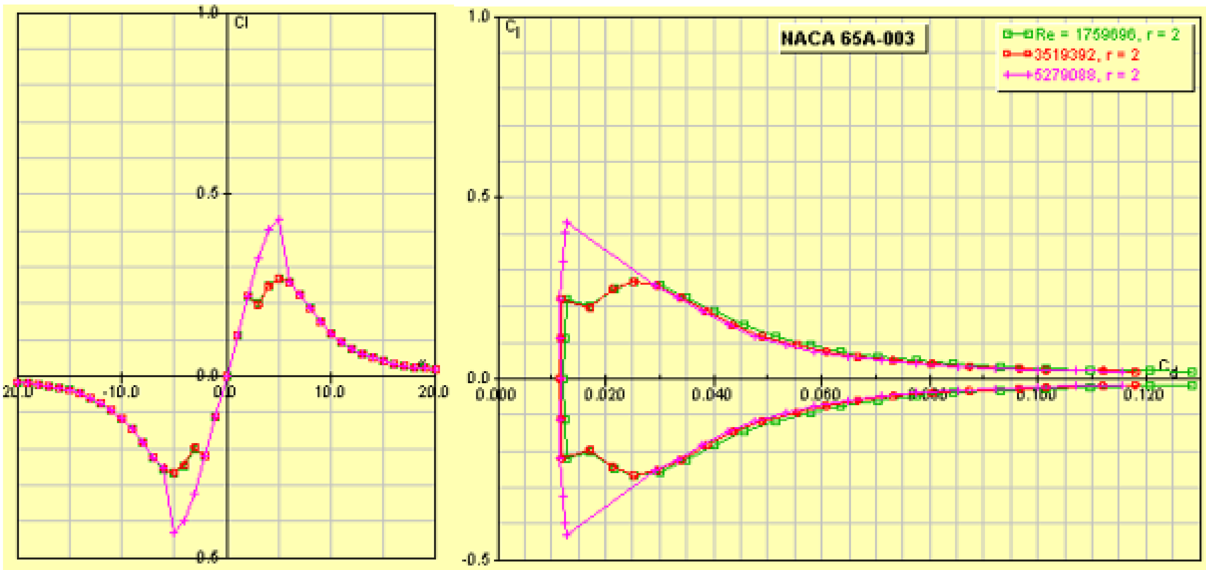

Figure 14: NACA 65A-003

Reynolds numbers were calculated for a 25cm chord length and velocities at 100m/s, 200m/s and 300m/s respectively using the Equation 9 below:

$$Re = \frac{\rho v l}{\mu} \tag{9}$$

E. RASAero

Some initial flight simulation was done using RASAero, a combined aerodynamic analysis and flight simulation software package for sounding rockets was utilised as the software's aerodynamic prediction methods are the most accurate available. They also are of equivalent accuracy to professional engineering method aerodynamic analysis codes used for missiles, sounding rockets, and space launch vehicles. This software was particularly good for supersonic simulation. In testing in comparison with high power rocket barometric altimeter data, optical tracking data, accelerometer-based flight data, and GPS flight data, the average RASAero altitude prediction error was 3.38%. The following simulation was carried out and the specifications are illustrated in Table 5 below.

Table 5: RASAero simulation

Maximum Altitude	30,082 ft
Time to apogee	38 s
Maximum velocity	660 m/s

F. Design

This section explains the design process that was undertaken to create the components of the rocket. All of the components were designed and modelled using Solidworks and Fusion 360 softwares.

A. Nosecone

Figure 15: Carbon Fibre Nosecone with Metal nose Tip

The nose cone consists of two parts; The airframe of the nose cone and the nose tip which is shown in Figure 15. The nose cone is a Haack series designed on using the LD-Haack equation, also known as Von Karman equation in order to minimize aerodynamic drag, where R denotes the outer radius of the nose cone base, and L is the length from the centre of the base up to the top of the nose tip. For the particular design, the radius is 62.5 mm and the length is 500mm and C is 0. The nose cone shoulder is a simple tubular design with a length of 140 mm and an outer radius of 59.5mm. The thickness of the nose cone was set to 3 mm for both the airframe and the shoulder, using the shell feature of the software. The material of the airframe is CFRP infused with a bio-resin. For the manufacturing process a mandrel was avoided due to its relatively high cost, therefore a cheaper alternative method was explored. The process of choice followed the steps: First, an epoxy clamshell tooling block was machined using a 5-axis CNC machine. Second, The CFRP and GFRP plies are staggered on each other to create the tubular shape. Third, the mould was sent for CFRP and GFRP processing and was vacuum bagged and heat cured in an autoclave to produce the finished component.

Figure 16: Metal Nose Tip

As shown in Figure 16 above, the nose tip has a length of 40mm. The material of the nose tip is Aluminium. The reason behind the introduction of the metal nose tip is the extreme temperature rise caused by shockwaves developed when the sound barrier is broken at the speed Mach 1. The carbon fibre composite of selection would not withhold this range of temperatures and therefore the need for a ductile and thermally conductive material. Aluminium is a common material choice for nose tips of rockets that reach supersonic speed, and therefore was the first 'obvious' choice to be investigated. The thermal analysis proved that it will be appropriate and therefore the investigation stopped at that point. The component is CNC machined and the attachment of the nose tip to the airframe is achieved using 3M's Scotch-Weld structural epoxy adhesive EC-9323 B/A and an M6 Eye-bolt that goes through the airframes top base and halfway in the nose tip's length.

B. Airframe

Figure 17: Carbon Fibre Body Tube

Top Body tube: The top body tube has a tubular design with a length of 600mm and an outside radius of 62.5mm, consistent with the outer radius of all the tubes. The thickness is 3mm giving an inner radius of 59.5mm. In the top body tube, the nose cone shoulder will be inserted and right underneath the bottom of the shoulder, the payload will be hosted inside the tubular payload bay. That consists of two thick plywood bulkheads which will be bolted at each side of the payload to the airframe, in order to avoid any sort of movement or vibrational behaviour. The payload is functional and is described in more detail about it are included in a different section of the technical report.

Bottom (Aft) Body tube: The bottom or aft tube of the rocket has a tubular design of 1460mm and an outside radius of 62.5mm, consistent with the outer radius of all the tubes. The thickness is 3mm giving an inner radius of 59.5mm. Four slits with a length of 260mm were cut from the base of the aft tube upwards. Those are to allow for the fins to slide through and to give some extra space for a securing cap to be put in the end. The cap will withhold the bottom end of the aft tube together and also provide further support in keeping the fins in place.

Figure 18: Avionics Bay and Coupler

Middle section: The middle section in terms of tubing, consist of two different concentric tubes. The inner tube is made of Fibreglass with a length of 450mm and an outer radius of 59.5mm. Its thickness is 3mm. Inside the tube, the electronics bay will be hosted. This tube also acts as a coupler that connects the top and aft body tubes. It was designed to be larger than 1 body length in order for the coupler to split and resist the forces during explosion of the black powder charge. The outer tube is called a middle body tube and is made of Fiberglass with a length of 150mm and an outer radius of 62.5mm. Its thickness is 3mm. The choice of materials for these two is not random. The carbon fibres block the signals from the antennas inside the electronics bay and live data transmission and location of the system upon landing would not be possible. Fibreglass allows RF electromagnetic signals to go through them and therefore, for the specific application were deemed most appropriate.

The manufacturing process used for the airframe tubes was the same as the one used for the construction of the nose cone.

C. Fin-can and Fins

Figure 19: Fin-Can

The fin-can is made up of two 15 mm thick centring rings made of solid Aluminium, that hold the motor tight. The fin-cans were enforced by M5 threaded steel rods and bolted to the body tube.

Figure 20: Aluminium fin design

The fins are shaped like a hybrid between delta clipped and trapezoidal and are 3D printed aluminium moulds, designed to be attached to the inner braces, to ensure the maximum stability and rigidity of their structure. The aerofoil of the fins changes from NACA 65A-003 to diamond shape at the tips to accommodate the subsonic and supersonic speeds. The fins bottom is made to be curved with the same curvature as the outer body tube to avoid most causes of vibrations in the fins.

D. Cap

Figure 21: Aluminium Cap

The cap is a ring that fits at the bottom of the fin-can to further secure the fins in place and to avoid the fins from detaching due to the dynamic pressures experienced during flight. It is made up of 13mm thick aluminium with a 3mm chamfer which is CNC machined and has extruded joints which are epoxied to the slits at bottom section of the fin-can.

E. Propulsion

For the 8.8 lb scientific payload to be transported by the rocket up to an altitude of 30,000 feet, we have decided to use a single-stage N-class solid motor. We chose to use the rechargeable Cesaroni Pro98 20146N5800-P motor with a total impulse and burnout time of 20368 Ns and 3.50 sec. The dimensions for this single-stage N-class motor are 98mm for the diameter and 1239mm for the length. The motor is fixed in place using three centering rings made of 18 mm plywood and a motor retainer made of Aluminium, which was approved to be strong enough to take the pressure developed during lift-off and distribute it to the rest of the structure.

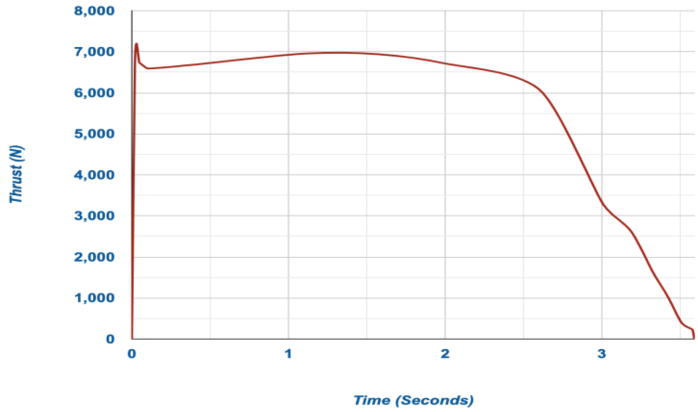

Figure 22: Thrust Curve of Cesaroni N5800-P motor

F. Motor Retention

The engine block is an additive measure to ensure that the motor will not shoot forwards in the rocket upon ignition. The requirements are simply maximizing strength under compression while minimizing the mass and the amount of material used. Some of the constraints were the diameter of the block as it had to be flush with the body tube to maximize the surface area of contact between the block and the inner tube surface. This in turn will allow for greater resistance to incoming shear stresses and further structural integrity. The current engine block design follows an iterative design process coming off the previous SunrIde mission.

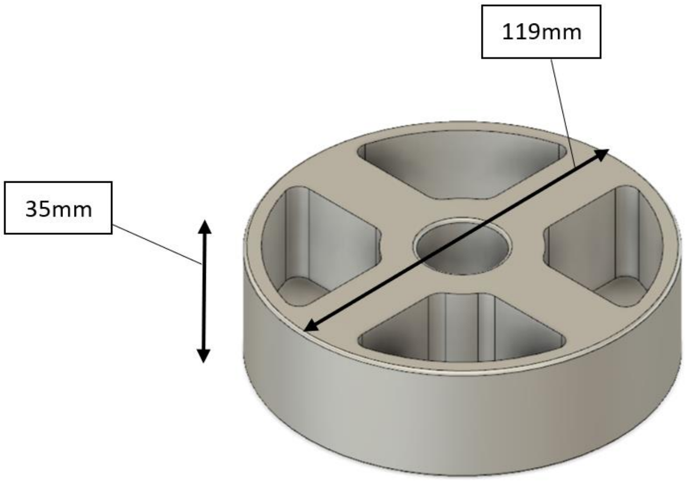

Figure 23: The 3D model for the engine block. The component itself is machined out of an aluminium block of metal using a CNC machine, having a 119mm (4.685 inches) diameter and standing at 35mm (1.378 inches) in height

The 3D-model was constructed in Fusion 360 and the final design is the one that managed to retain a high level of strength while minimizing the mass, currently weighing only 0.600gr (1.323 lbs).

1. Finite Element Analysis (FEA)

To ensure that the design was strong enough to withstand the maximum thrust of approximately 7000N (1573.66 lbf) produced by the N5800 motor, extensive FEA was carried using Fusion 360 as the main tool.

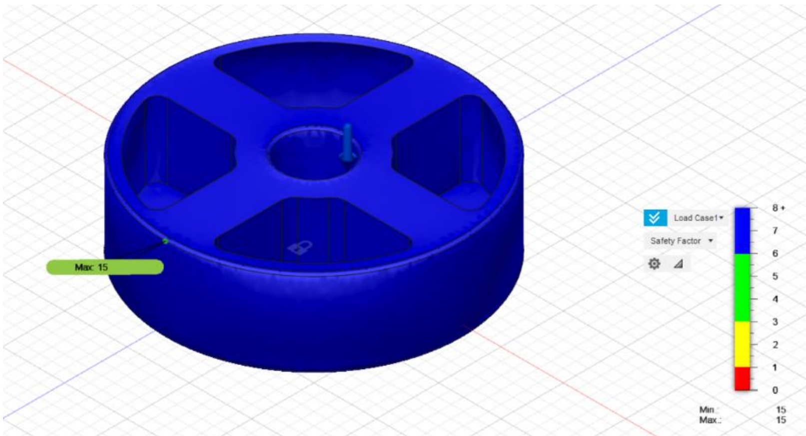

Figure 24: FEA analysis showing the safety factor for the design. A conservative approach was taken for this one, and although given the option to remove material, the team decided to go with an overengineered design with a safety factor of 15, given the structural importance of the component.

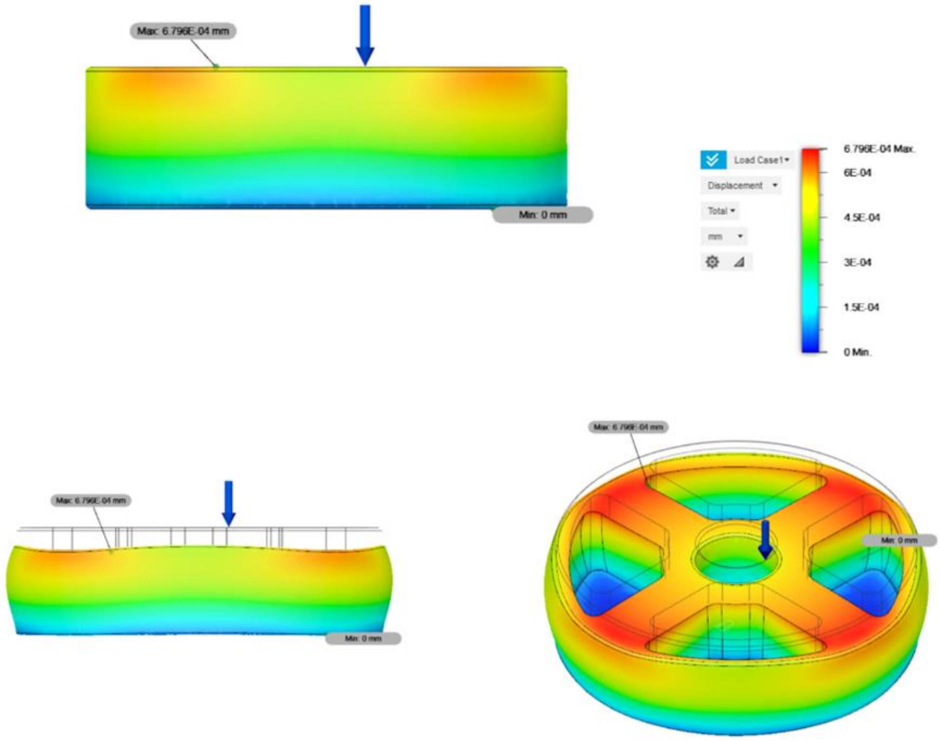

Figure 25: The simulation results for the displacement shown in actual scale (top) and adjusted for visualization purposes (bottom). The deformation is insignificant at only 0.000679mm (0.0000267 inches)

One of the main concerns was the amount of deformation of the engine block under the thrust of the motor. In particularly, given that the block itself is flush with the carbon-fiber body tube, any amount of deformation will cause the block to expand out radially. This may result in structural damage on the body tube itself, such as the formation and propagation of cracks which can lead to a CATO event. However, simulation results are shown in Figure 25 imply that the amount of deformation that will be experienced will be too insignificant to cause any amount of considerable radial expansion. This verifies that the type and amount of aluminum used in combination with the design's shape are more than capable of handling the N5800 motor's thrust.

2. Assembly

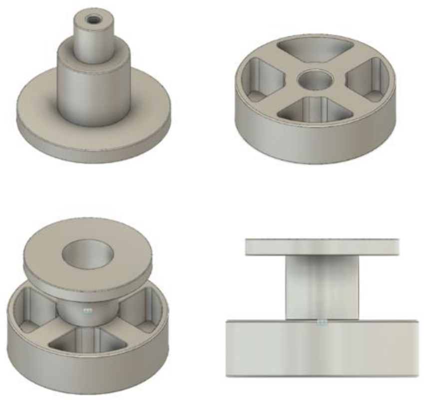

Figure 26: The motor retention assembly. It consists of the aluminium engine block and the aluminium motor screw-fix used in the previous iteration of the project

The motor retention assembly consists of the aluminium engine block and an aluminium screw-fix taken from last year's project. the components are screwed tighlty using an M10 eye-bolt going through the bottom of the engine block and into the top opening of the screw-fix. In addition to the engine block preventing the motor shooting forwards, the screw-fix will ensure that upon burn-out the motor will not shoot backwards.

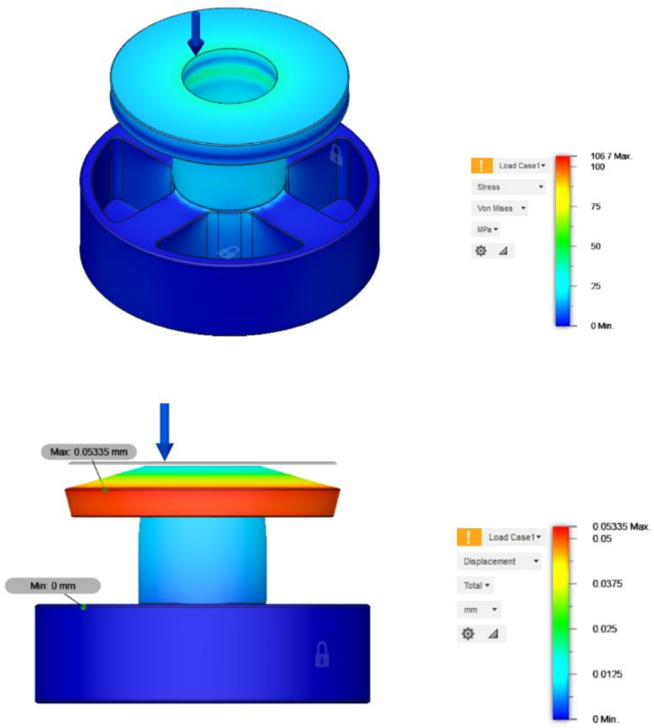

Figure 27: FEA analysis of the motor retention assembly. Once again, the load applied is the maximum thrust of the motor, which is 7000N (1573.66 lbf). The top part shows the stress concentration throughout the entire assembly. The bottom part shows the shows the deformation in response to the applied (adjusted for visualisation purposes).

Stress analysis shows that the majority of the stresses are applied at the screw-fix. The maximum stress is 106.7MPa (15.5_{x10}^6 psi), which for a material such as aluminium raises no concern and this can be seen from the colour contours from Figure 28. This was expected as the part itself is directly attached to the bottom part of the engine casing. This raises some concerns in terms of the screw-fix being the possible point of failure instead of the engine block itself. This is further verified by looking at the expected deformation. The screw-fix base is expected to deform by 0.053mm (0.0021 inches), which is insignificant. However, the assembly itself is marginally stable, with a minimum safety factor of 2.32 at the screw-fix base. The simulation does not take into the account any variations in the material's temperature, which are expected given the proximity of the components to the motor itself. The possibility however of external factors such as the temperature causing failure are also minimal as the melting temperature of aluminium is around 660ºC (1220ºF). At no point in the rocket itself is the temperature expected to reach anywhere near that range, hence it can be safely assumed that the overall assembly will not fail during ignition and burn-out.

G. Avionics

A. Flight avionics - Altimeter & Telemetry System

The rocket avionics has 2 major functions, firstly ensure accurate dual deployment (main and drogue parachute) and secondly provide the rocket's location both inflight and once it has landed. The overall avionics design can be seen in Figure 29 below.

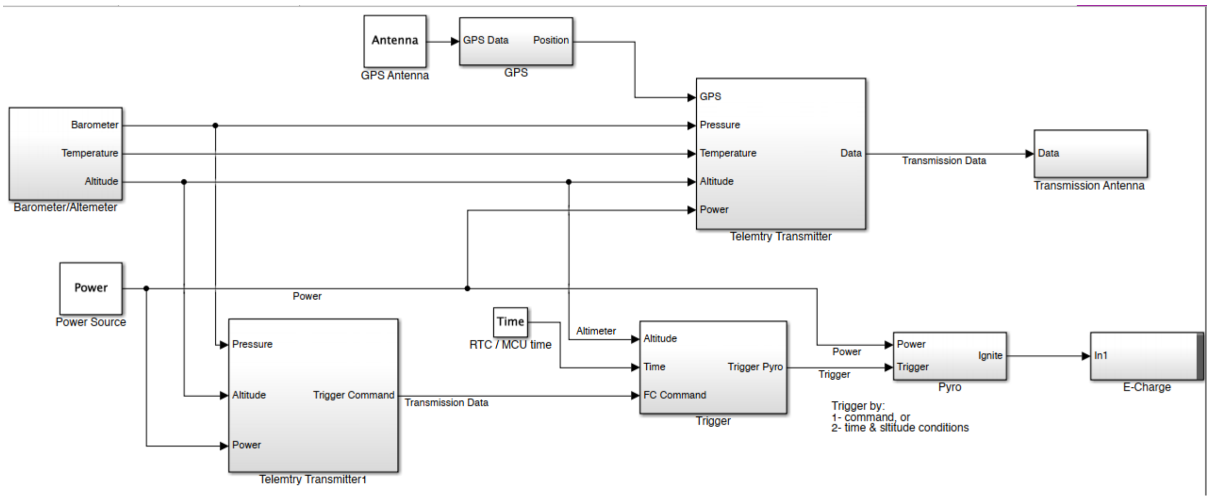

Figure 28: Block Diagram of overall Avionics Design

The initial plan was to design the team's own electronic system in order to meet the above mentioned functionalities. A deployment system comprising of an Arduino UNO (as the main microcontroller), RFM9x LoRa Radio (for receiving and transmitting data signals), Adafruit Ultimate GPS breakout- 66 channel (to determine the position) and the MPL3115A2- Barometric Pressure/Altitude/Temperature sensor. However, after the rocket design was finalized, a size limitation on the avionics bay made it difficult to implement the system. In addition, the system proved to be complex to implement in the given time.

Thus the team has adopted to move to commercially available electronics for dual deployment and telemetry systems of the rocket. The compact size and reliability proved to be a plus point. A Stratologger CF will be used for dual deployment and to assure contingency a redundant Eggtimer system will be used. For the telemetry, an Eggtimer system will be used as the main and as a redundant to account for contingencies. These will be discussed below.

B. Altimeter

In order to record the maximum altitude and the velocity achieved by the rocket we have made use of the StratologgerCF Altimeter. The altimeter comes with two output ports for to deploy the drogue chute for drift minimization and the main parachute closer to the ground. The StratologgerCF gives the flexibility to deploy the parachutes at a chosen altitude. During the test, we received a the temperature, altitude and battery voltage readings from the flight at rate of 20 samples per second recorded by the StratologgerCF. The decision of choosing the StratologgerCF for our altimeter is mainly because the built-in voltmeter which means the altimeter can log a data of up to 15 flights (18 minutes each) even once the battery has been removed. The data logged is accurate and precise by the industrial standards.

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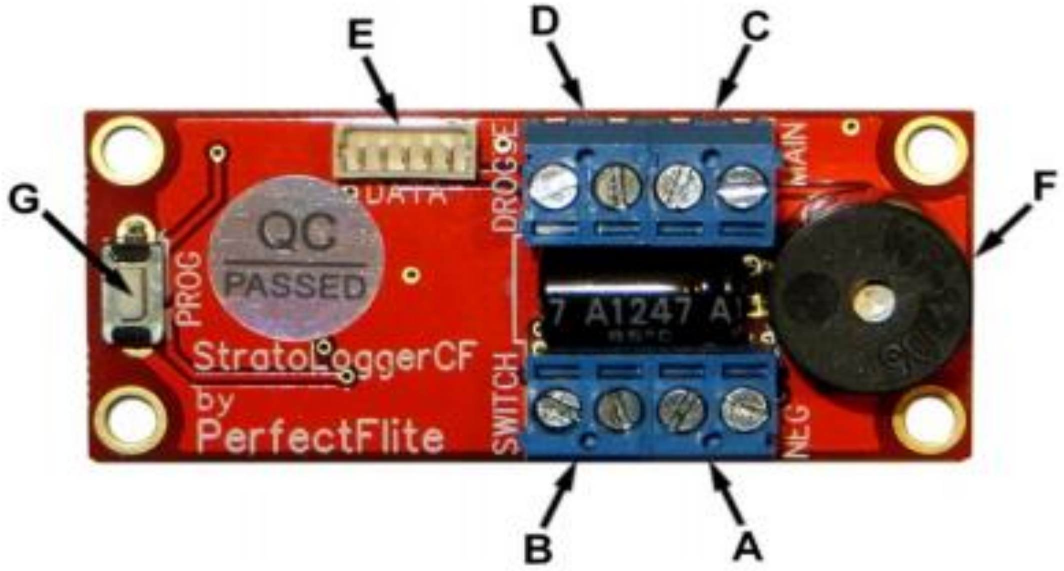

Figure 29: Altimeter (Source: StratologgerCF User manual, http://www.perfectflite.com/SLCF.html)

A - Battery Terminal Block.
B - Power Switch Terminal Block.
C - Main Ejection Output Terminal Block.
D - Drogue Ejection Output Terminal Block.
E - Data I/O Connector.
F - Beeper: Audibly reports settings, status, etc. via a sequence of beeps
G - Pre-set Program Button

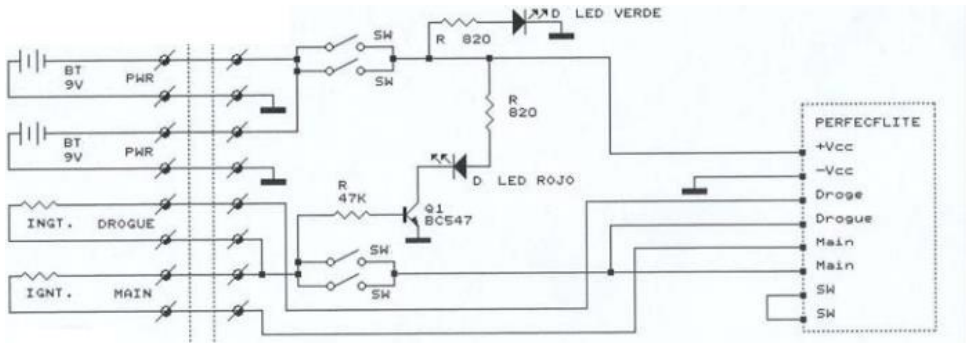

Figure 30: Circuit diagram of Stratologger

This figure above shows the circuit diagram that will be used to power the Stratologger. It contains the main power switch, an arming switch and LED for visual identification for the state of recovery device.
The Eggfinder TRS Tx, Rx and the LCD receiver are have been chosen for the recovery of the rocket. The TRS uses the HOPE RF module for the GPS tracking. The transmitter sends the data to the receiver which uses the 5 dB dipole stick antenna to retrieve the signal once every second. This data is logged on a desktop application or smartphone (depending on the need).

C. Telemetry

For receiving real-time in-flight data and tracking the rocket's location once it has landed, the Eggtimer TRS flight computer, which uses an Atmel ATMEGA328P-PU processor, will be used. The Eggfinder TRS uses the RF module in the 902-928 MHz ISM band. The given band of frequency is high of range reliability for the targeted altitude of 30,000 ft. The ground station module, TeleDongle, provides USB connectivity to monitor the flight data and is compatible with any 5 dB dipole antenna. The Eggfinder TRS uses the stick antenna for the given apogee of the rocket recovery. With its ability to support dual deployment and pyro charges, Eggfinder TRS will also serve as a redundant recovery system.

D. Static Pressure Sampling Holes

These holes will be drilled in the airframe into the avionics bay to allow outside air pressure to be sampled by the altimeter. These holes will be as far away from the nose cone shoulder and other body tube irregularities as possible to minimize pressure disturbances being created by turbulent airflow over the body tube. Four smaller holes distributed at 90-degree intervals around the airframe's circumference will be made instead of a single larger hole. When using four holes, each hole will be ½ the size of a single hole as noted in the table. This will minimize the pressure variations due to wind currents perpendicular to the rocket's direction of travel. The following static sampling hole size will be chosen based on a calculation using Equations 10 and 11 below:

$$\text{One large sampling hole size} = D \times D \times L \times 0.016 \tag{10}$$

$$\text{One of 4 small sampling hole size} = D \times D \times L \times 0.0008 \tag{11}$$

Table 6: Static pressure sampling holes

Avionics Bay Diameter	Avionics Bay Length	Single Port Hole Size	Four Port Hole Size
4.9”	5.9”	0.227”	0.113”

E. Estimated Ejection Charge

To estimate the amount of black powder needed to pressurize and eject the parachute compartment, the ideal gas law equation will be used:

$$PV = m_b R T_b \tag{12}$$

$$m_b = PV/RT_b \tag{13}$$

$$m_b = FV/ART_b \tag{14}$$

The relationship between the force F and mass m_b of the black powder will be established by hit and trial method during the ground testing of the ejection system. The calculated black powder for the drogue parachute is 3 grams and for the main parachute is 3.6 grams. Ejection testing is required to get the exact amount of black powder for both parachutes.

F. Payload

The launch vehicle will carry a dedicated, functional scientific payload. The initial purpose of the experiment was to demonstrate the feasibility of employing a new way of ejecting equipment off a rocket that will later be used for further scientific research or more practical applications. The payload was to be attached to a helium filled balloon with an estimated diameter of 78.74 inches (after inflation). The balloon would be ejected at the rocket's apogee of 30,000 ft and the payload bay will then have carried a scientific camera that was capable of analysing samples across different wavelengths of visible light, a GPS module and a radio transmitter. The payload attached to the balloon would have provide the ground station with information. After carrying rigorous feasibility studies and speaking with the experts in the UK, the team decided to abort the initial idea of ejecting a balloon capable of carrying a scientific camera at the apogee and opted for a more feasible design. The final design for the scientific payload will be dedicated towards obtaining and analysing data to be used by team SunrIde and the University of Sheffield for further research and consequent iterations of the project.

It was decided that measurements of the vibrations of the airframe and the payload bay during flight will be recorded and stored in a dedicated micro-SD card which will be later processed using software such as MATLAB. The motivation for this experiment comes from the lack of available information on the subject that the team encountered when researching into vibrational frequencies and what ranges should be expected during flight. The results will be used for further improving the design of future iterations of the project as well as further research. The data will be primarily used by the team to improve upon the rocket design in terms of minimising those effects in order to implement more delicate payloads for future projects. Having knowledge of the vibrational frequencies experienced will allow for more efficient rocket designs in terms of material choices as well as pave the way for experimenting with more sensitive scientific equipment that is prone to vibrational damage.

A. Requirements

1. It shall perform a scientific experiment
2. It shall be secured in a dedicated retrievable compartment in the rocket
3. It shall have a TubeSat configuration
4. It shall have a minimum weight of 8.8lbs
5. It shall not interfere with the vehicle's stability and performance

B. Validation

1. It shall perform a scientific experiment

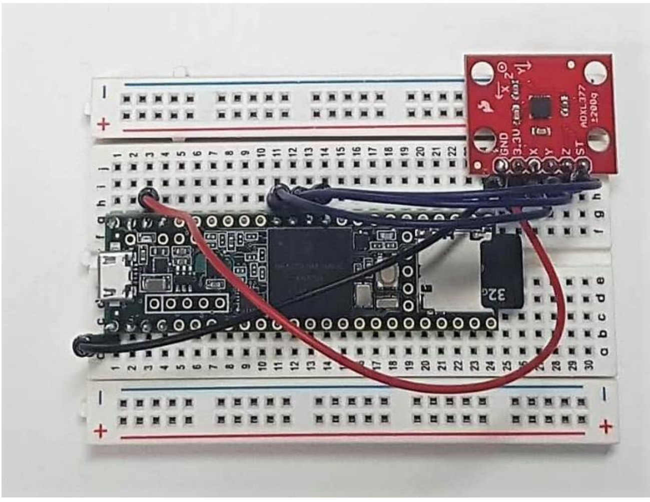

Figure 31: Breadboard circuit for one of the IMUs connected to the Teensy microcontroller

Low-frequency vibrations pose a challenge for microgravity environments such as in the case when rockets reach Low Earth Orbit (LEO) heights. The aim of this experiment is to address the damage caused to the rocket and subsequent subsystems as a result. The payload itself will consist of a number of 9-DOF Inertial Measurement Units (IMUs) with a micro-SD slot that will be securely attached at different points of the inside surface of the airframe and at certain points of the payload bay. The IMUs will be connected to a Teensy 3.6 microcontroller with a 32-bit 180 MHz ARM Cortex-M4 processor. The microcontroller unit will communicate with the sensors and run the flight code for storing the data. The whole configuration will be powered by a 9V Lithium Battery.

Post processing of the data will occur upon retrieving the rocket and the payload. After retrieving the micro-SD from the microcontroller slot, the accelerometer data will be analysed by importing it into MATLAB. Consequently, the principal vibrational frequencies in the rocket's airframe and payload bay will be identified using mathematical tools and techniques such as wavelet analysis. The results will be used to prevent consequential damages to the rocket and its components for future design applications using condition-monitoring principles.

2. It shall be secured in a dedicated retrievable compartment in the rocket.

The payload compartment will be comprised of two bulkheads connected by three aluminium rods and it will be placed in the top section of the rocket. It will be secured in place by bolting it through the top and the bottom bulkhead to the two supporting bulkheads that will be glued to the airframe on top and below it. This ensures a modular design that allows for the payload bay to be inserted and removed with relative ease.

3. It shall have a TubeSat configuration

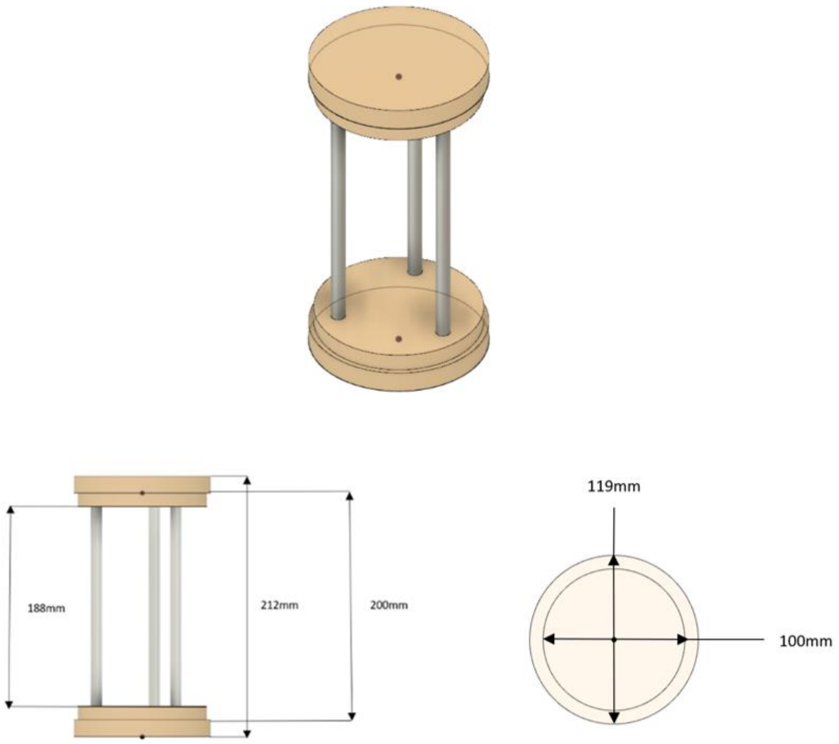

Figure 32: The payload bay. The two 119mm (4.685 inches) bulkheads are there to provide extra support as well making sure that the entire bay will fit tightly within the body-tube, which also has a 119mm inner diameter. The smaller 100mm (3.937 inches)

The assembly will be TubeSat compliant as further illustrated in Figure 20 above.

4. It shall have a minimum weight of 8.8lbs

The payload will weigh in at 8.8lbs as per SAC regulations. Should the assembly not meet the mass requirements, additional weight will be added in the form of excess material such as aluminium sheets to make up for it. This is also an additional measure for improving the overall stability of the rocket after the fuel is depleted.

5. It shall not interfere with the vehicle's stability and performance

Upon burnout the centre of mass tends to fall back towards the aft end of the rocket, however adding extra mass on the top section of the rocket should minimise that effect and the rocket shall maintain adequate levels of stability. Additional mass can be added to the payload assembly, as the electronics required for the experiment do not take a lot of volume. However, adding excessive mass could counter-act the desired stability requirements by making the rocket over stable, so there is a limit to as to how much mass can be added while maintaining a good flight performance.

Appendix A:

Hazard Analysis Appendix/Risk Assessment

Hazard	Risk	Possible Causes	Risk of Mishap and Rationale	Mitigation Approach	Risk of Injury after Mitigation
Explosion of solid-propellant rocket motor during launch with blast	Flying debris causes injury to participants, including eye injuries or blindness	Cracks in propellant grain/ Debonding of propellant from wall/ Gaps between propellant sections and/or nozzle/ Chunk of propellant breaking off and plugging nozzle/ Motor case unable to contain normal operating pressure/ Motor end closures fail to hold	Medium; Limited testing of endurance of the equipment under hardship circumstances / Poor evaluation and choice of materials	Test of the motor case under pressure 1.5 times the maximum expected pressure it will experience/ Visual testing for cracks on the grains, any gaps during and after the assembly/ Only trained personnel allowed in the assembly process/ Use of ductile material for the motor case/ Crew must be at least 200 feet away from the launch site	Low
Rocket deviates from nominal flight path	Comes in contact with personnel at high speed and cause severe injury/death	The stability of the rocket affected due to poor manufactured fins. The launch rail was not anchored to the ground properly, which caused a change in the angle of launch	Medium; Non-trained personnel responsible for mounting the rocket/ Possible calibration errors made due to technical problems	The fins of the rockets should be well manufactured to ensure good stability of the rocket during flight. Inspect the launch rail before launch and ensure the launch rail is anchored in the ground properly. Ensure the angle of launch rail complies to SAC's regulations	Low
Ground Fire	Could cause several skin injuries	Motor ignition and Initial Thrusting	Medium;	Ensure the launch area is not in close proximity to dry grass or plants	Low

Catastrophic failure of motor casing; Injury to participants	Projectiles could cause injuries/ death			Fire-extinguisher on-standby	Medium
Charge powder catches on fire	Explosion and fire could cause skin and other injuries/ death	Powder in tight containment will catch on fire due to high pressure	Medium	Store the powder in a non-metallic container with a lid that will pop-off if powder catches on fire	Low
Recovery system fails or partially fails to deploy, rocket or payload comes in contact with personnel	Severe body injuries/ death	Failure of stratologger in determining altitude Failure of the gps device to detect the apogee point	High	Ensure the electronics are programmed correctly Ensure parachute knots are not tied too tightly	Low
Recovery system deploys during assembly or pre-launch, causing injury	Severe body injuries/ death				
Main parachute deploys at or near apogee, rocket or payload drifts to highway(s)	Dangerous as a distraction or cause of injury for drivers		Low	Mandatory adherence to minimum clearances from operating highway(s). No flight in elevated wind conditions.	Low
Rocket does not ignite when command is given (“hang fire”), but does ignite when team approaches to troubleshoot	Fire and projectiles from the explosion could cause serious skin or body injuries/ death	Electronic failure/ Bad electronic system design	Medium	Check of the electronics before ignition, protective goggles and clothes worn by crew members	Low
Rocket falls from launch rail during pre-launch preparations	Could cause equipment damage and also staff injuries	Improper mounting of the rocket/ Safety measures not followed	Low	Inspect and ensure the launch pins of the rocket are mounted to the launch rail	Low

Appendix B:

Accelerometer Code

```
//Set up configuration  variables
int scale = 200; //Full scale of the accelerometer measured in g forces for the ADXL377
                 //i.e. +/- 200g
boolean micro_is_5V = false; //We are using a 3.3V microcontroller

double mapf(double val, double in_min, double in_max, double out_min, double out_max) {
    return (val - in_min) * (out_max - out_min) / (in_max - in_min) + out_min;
}

void setup()
{
  //Initialize serial communication in order to use the Serial Monitor
  Serial.begin(115200);
}

void loop() {
  // Get raw accelerometer data for each axis
  int rawX = analogRead(A2);
  int rawY = analogRead(A1);
  int rawZ = analogRead(A0);

  float scaledX, scaledY, scaledZ; //Scaled values for each axis (decimal)

  //Scaling X-axis measurements:
    if (micro_is_5V) //Microcontroller runs off 5V
    {
        scaledX = mapf(rawX, 0, 675, -scale, scale); //3.3/5 * 1023 = 675
    }
    else //Microcontroller runs off 3.3V
    {
        scaledX = mapf(rawX, 0, 1023, -scale, scale);
    }

   //Scaling Y-axis measurements:
    if (micro_is_5V) //Microcontroller runs off 5V
    {
        scaledY = mapf(rawY, 0, 675, -scale, scale); //3.3/5 * 1023 = 675
    }
    else //Microcontroller runs off 3.3V
    {
      scaledY = mapf(rawY, 0, 1023, -scale, scale);
    }
  //Scaling Z-axis measurements:
    if (micro_is_5V) //Microcontroller runs off 5V
    {
        scaledZ = mapf(rawZ, 0, 675, -scale, scale); //3.3/5 * 1023 = 675
    }
    else //Microcontroller runs off 3.3V
    {
      scaledZ = mapf(rawZ, 0, 1023, -scale, scale);
    }

  // Print out raw X,Y,Z accelerometer readings
  Serial.print("X: "); Serial.println(rawX);
  Serial.print("Y: "); Serial.println(rawY);
  Serial.print("Z: "); Serial.println(rawZ);

  // Print out scaled X,Y,Z accelerometer readings
  Serial.print("X: "); Serial.print(scaledX); Serial.println(" g");
  Serial.print("Y: "); Serial.print(scaledY); Serial.println(" g");
  Serial.print("Z: "); Serial.print(scaledZ); Serial.println(" g");

  delay(1000);

}
```

Appendix C:

Project Test Reports Appendix

The rocket systems have been tested individually on ground and together in a flight test. The flight test is carried with a lower thrust engine and without the payload focusing the test on recovery systems, electronics, reviewing on-field procedures and materials. The flight test will be carried on before the competition. The ground tests consisted on: bulkhead and material tests, electronic test, parachute ejection test, fin test. Bulkhead and material test: structural component were tested against lateral and longitudinal loads ensuring adequate level of manufacturing quality was maintained. As some materials used by the team had never been used before, this test allowed for all team member to acquire necessary skill for independent work. The test was successful. Electronic test: The team tested the electronics that was soldered. During the first test some minor issues were found, some components didn't have soldering up to standards and had to be redone. The electronics was then ground tested simulating an ejection test and everything worked successfully. Parachute ejection test: The purpose of the test is to size the correct quantity of black powder to pressurize the ejection compartment allowing for the ejection of the parachute. The test is carried out varying the masses of the sections below and on top to guarantee a margin of robustness for the actual flight. Multiple tests are done practicing procedures of parachute packing and safety handling black powder. The test are carried out under the supervision of the UKRA level 3 mentor. Fin test: As for the general material test, the quality of the manufacturing was tested varying procedures and reviewing results. Strength of the fin was tested to reduce as much as possible the effect of fluttering in flight. General procedures have been under constant review, especially since the introduction of the UKRA mentor to ensure the continuity of the project next year and the passing of the skill set and knowledge acquired to the new team.

Appendix D

Assembly, Preflight, and Launch Checklists Appendix

The fifth Project Technical Report appendix shall contain Assembly, Preflight, and Launch Checklists. This appendix shall include detailed checklist procedures for final assembly, arming, and launch operations. Furthermore, these checklists shall include alternate process flows for dis-arming/safe-ing the system based on identified failure modes. These off-nominal checklist procedures shall not conflict with the IREC Range Standard Operating Procedures. Teams developing SRAD hybrid or liquid propulsion systems shall also include in this appendix a description of processes and procedures used for cleaning all propellent tanks and other fluid circuit components.

Competition officials will verify teams are following their checklists during all operations – including assembly, preflight, and launch operations.Therefore, teams shall maintain a complete, hardcopy set of these checklist procedures with their flight hardware during all range activities.

The following must be checked before arriving at the launchpad and initiating countdown:

1. Assemble the rocket appropriately.
2. Conduct telemetry test with the rocket vehicle outside the launchpad.
3. Arrival at the launchpad: mating of rocket vehicle to the launch rail.
4. Elevate the launch rail to 84 degrees.
5. Evacuate non-essential personnel from the launch pad.
6. Insert the igniter into the engine and leads anchored to the launch pad.

Arming of the rocket systems:

1. Turn on power to the electronics
2. Turn on control computer.
3. Turn on telemetry and verify the transmitted signal.
4. Activate actuator circuit.

Launch:

1. All personnel evacuate from the launchpad.
2. Connect igniter to the firing circuit
3. Confirmation from RSO of a “Go for launch.”
4. Audible countdown of at least 5 seconds in 1 second intervals.