It’s Not Rocket Science; It’s Simple Latte

Team 55 Project Technical Report for the 2018 Spaceport America Cup

University of Ottawa Student Team of Aeronautics and Rocketry*

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The University of Ottawa Student Team of Aeronautics and Rocketry (uOSTAR) will be competing in the Intercollegiate Rocket Engineering Competition at the 2018 Spaceport America Cup under the 10,000 ft AGL apogee with commercial-off-the-shelf (COTS) solid or hybrid rocket propulsion system category. The team has designed, tested, fabricated, and assembled a rocket by the name of “Simple Latte”. The vehicle is propelled by a Cesaroni M2505 solid rocket motor with a peak thrust of 2952.6 N and total impulse of 7450 Ns. The vehicle is designed to marginally overshoot the target altitude. This error is dynamically reduced, during cost, through means of a student researched and developed (SRAD) air brake system. A Model Predictive Control (MPC) schema is used to actuate the air brakes accordingly. The rocket will descent under a reefed, dual-speed parachute and will concludes the mission by landing gently and safely. To achieve the goals of this mission, the vehicle will carry onboard a SRAD avionics stack as well as a redundant COTS recovery computer. Simple Latte has a 5.5 inch diameter and spans 2.17 m in height. The body is made by combining two sections of COTS Blue Tube 2.0. Similarly COTS in nature, a 5.8:1 Von Carmon nose cone was selected. A sandwich composite with a solid aluminum core and carbon fiber wrap was selected for the SRAD fins. The vehicle will carry a simulated payload during the mission; this payload consumes a volume of 3447.2 cubic centimeters. Several means of analysis have been conducted on the subsystems of Simple Latte. They include physical testing of subsystems, materials and prototypes, flight simulations of developed mathematical models and finite element analysis (FEA) simulations of CAD models. This vehicle is one of the several results achieved by the team during the first two years of operation. The technical and administrative skills gained from the development of this vehicle and mission will aid future iterations of the team to strive for more experimentation and attempt different concepts surrounding sounding rocket design and development.

Nomenclature

A	=	area
a	=	speed of sound
AR	=	aspect ratio
C_D	=	drag coefficient
v	=	velocity of rocket
W_t	=	weight of rocket
S	=	canopy reference area
ρ_{air}	=	density of air
V_f	=	fin flutter boundary speed
G	=	shear modulus
G_{13}	=	out-of-plane shear modulus
G_E	=	shear modulus
t	=	thickness
c	=	root chord
λ	=	taper ratio
P	=	pressure
P_0	=	initial pressure
T	=	temperature
$d_{parachute}$	=	parachute diameter

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I. Introduction

THE University of Ottawa Student Team of Aeronautics and Rocketry (uOSTAR) is a student-run organization recognized by the University of Ottawa. Founded in 2015, this organization is committed to providing the opportunity for students of all disciplines to study, design, build, and launch reusable sounding rockets. Through continuous designing, building, and testing, uOSTAR aims to cultivate the skills of our student members and develop future industry leaders in the new North American space age. In addition to improving and refining technical skills, uOSTAR aims to develop the communication skills of its members by conducting design reviews, writing technical reports, holding weekly team meetings, and collaborating with local industry partners. As the University of Ottawa does not offer an Aerospace Engineering program, uOSTAR members are constantly researching new concepts and developing their self-guided learning skills.

A. Academic Program

uOSTAR operates as a student organization that is recognized by the University of Ottawa. As a result, uOSTAR members have access to campus equipment and facilities that are offered to all Engineering student teams. uOSTAR also have access to available funding for student initiatives, thanks to the support of the Centre for Entrepreneurial Engineering Design, the Brunsfield Centre, the Engineering Endowment Fund, and the Faculty of Engineering. The goal of these funds are to enhance the quality of the engineering students' education and university experience, and the intention is to meet this goal through student-focused projects and initiatives. Although uOSTAR is entirely an undergraduate-level team, the funds listed above can be used by both undergraduate and graduate students from the Faculty of Engineering to support any project of initiative which benefits the student body.

While funding is available through the university to support various student organizations, uOSTAR largely operates on sponsorships and donations. The team is able to create, store, and build most of its rocket in the Project Integration and Team Space (The 'PITS'), a collaborative space that provides engineering students involved in pre-professional competitions with the ability to work on large scale projects. The PITS provide student teams with space so they can work on their projects. Due to certain hour restrictions to this facility, the team must carefully plan and coordinate their operations with the facility supervisors to ensure that set deadlines are achieved. To support testing of various components, the team has established several contacts across Canada's Capital Region. uOSTAR aims to continue developing relationships with the Aerospace industry in Canada to develop future industry leaders in the new North American space age.

The University of Ottawa does not offer an Aerospace Engineering program. As a result, uOSTAR members are constantly researching novel concepts and the team excels at self-guided learning. The team is made up of members from all Engineering programs offered by the University of Ottawa, from Mechanical and Civil Engineering to Software Engineering and Computer Science. uOSTAR strives to offer a unique, interdisciplinary learning experience to its team members and members are not limited to working on a task in their principal field of study. For example, Mechanical Engineering students design control systems, Electrical Engineering students analyze airframes, and Chemical Engineering students work on computer-aided design and manufacturing problems. Senior students have the opportunity to enrich their technical knowledge through various technical electives offered in their last year of education such as courses related to aerodynamics, manufacturing, computational methods, finite element analysis, and industrial engineering. uOSTAR also offers its younger students the opportunity to develop their technical, communication, and teamwork skills at an early stage of their academic career.

B. Stakeholders

As previously stated, uOSTAR operates on available University funding for student initiatives and also on sponsorships and donations. Most sponsors make a single donation, which is either an in-cash or an in-kind contribution. Sponsors receive a predetermined level of recognition based on the value and type of their contribution. uOSTAR has received financial, material, and facility use donations from the sponsors represented in Fig. 1.

Figure 1. uOSTAR Sponsors

Finally, uOSTAR recognizes the impact of the Aerospace industry within Canada's Capital Region on the team. uOSTAR draws inspiration and motivation from the Canadian aerospace industry with the goal of developing future leaders within the industry. As both the team and its members continue to develop, companies which hire current and former members will benefit from the experience gained by the student during their time with uOSTAR. A compilation of local and global companies current members aspire to work for in the near future are illustrated in Fig. 2.

Figure 2. Canadian Aerospace Industry Leaders and Employers

C. Team Structure

The University of Ottawa Student Team of Aeronautics and Rocketry consists of fifteen undergraduate-level students from all Engineering fields offered by the University of Ottawa. To maintain, manage, and improve the knowledge and skills acquired by its members, uOSTAR has created an organizational structure that facilitates both individual knowledge transfer and team growth.

The uOSTAR organizational structure is depicted in Fig. 3. The senior management group consists of two senior student leads, a professor as a faculty sponsor, and the student engineering teams advisor. Senior student leads have multiple years of experience on the team, which includes management experience. Senior student leads are responsible for setting the overarching objectives, assigning tasks to members, and providing updates on team progress through effective communication. The faculty sponsor provides counseling to the senior student leads and oversees the major projects undertaken by the team. The student engineering teams advisor ensures that uOSTAR is able to realize its goals and is the main line of communication between the student team and the Faculty of Engineering at the University of Ottawa.

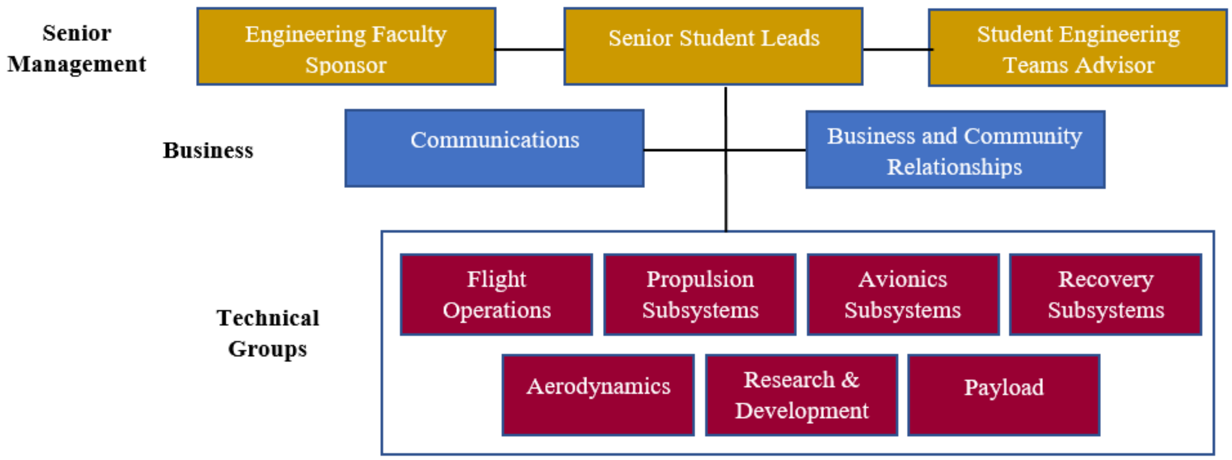


Figure 3. uOSTAR Organizational Structure

As uOSTAR aims to cultivate all-around excellence in each of its members, each member plays a role in both the business development and the technical aspects of the organization. The business development role is necessary for the team financially and all members have a role in fostering positive relationships with potential sponsors, communicating with prospective team members, and marketing the current progress of the organization. Since uOSTAR operates similar to a start-up company, members are provided with the opportunity to develop their entrepreneurial mind and communication skills in a professional environment through direct contact with potential sponsors or donors.

The core focus of all uOSTAR members resides in the main technical are also outlined in Fig. 3. Tasks are divided into seven main technical areas and members are assigned tasks according to their interests, current activity, and complexity. As previously stated, uOSTAR strives to offer an interdisciplinary learning experience to its team members and members are not limited to working on a task in their principal field of study. Each technical area, however, is led by a knowledgeable member with expertise in the area to act in an advisory role.

Since conception of the team in 2015, uOSTAR has adopted a democratic management approach, offering all members an opportunity to engage in meaningful decision-making. While senior team members are still tasked with the final decision-making, this democratic approach works best for complex decisions that may have a variety of outcomes. In situations where democracy slows down decision-making, the team adops a laissez-faire approach where all members are allowed to make decisions on their individual tasks, with senior members providing guidance as needed. These individual decisions encourage uOSTAR members to take a risk and explore their creativity and inventiveness, fostering innovative thinking. Individual decisions are then discussed at weekly team meetings, where suggestions or final team decisions are made.

D. Team Management Strategies

To ensure effective communication, efficiency and transparency between members and the organization, uOSTAR uses several tools for an effective management strategy. The use of these tools allows for unambiguous communication between members, provides a sense of accountability for members assigned certain tasks, and helps seamlessly integrate new members joining the team. Primary means of communication is done digitally through Facebook on the private group page or through the group Messenger chat. The team has a team-wide channel, and each technical area manages their own channel for relevant discussion related to their work. Weekly in-person meetings are also held where each technical area provides an update on their accomplishments, current goals, and any other outstanding information that may be relevant to uOSTAR. All members are encouraged to participate in the discussion to demonstrate their understanding of current tasks, fostering clear and effective communication between all members.

Written documentation compiled through accomplishing various tasks or goals is stored in a working directory in a University-based Google Drive. Documentation in the forms of build guides, reports, analysis, and media files are kept here for all team members to view and read. uOSTAR members have complete access to the compilation of information gathered since conception, which provides junior members with an abundance of reading material to bring them up to speed with current operations. To hold members accountable and for transparency, the team uses a self-made Gantt chart in Microsoft Excel to record and monitor timelines, identify immediate and long-term goals, and assign tasks to its members.

Computer-aided design is largely done through Solidworks, and design files are shared and communicated through GrabCAD. GrabCAD is a useful CAD collaboration solution that is cloud-based and helps engineering teams upload and share files. GrabCAD also offers the unique option of saving each new edit as a different version, so members can look at the development of the component from its first version up to the current version.

II. System Architecture Overview

1. Integrated Vehicle

Fig. 4 details the University of Ottawa uOSTAR Team 55 entry into the 2018 IREC/Spaceport America Cup student competition. For the first year attending competition, the team chose to compete in the 10,000 ft AGL apogee with commercial-off-the-shelf (COTS) solid or hybrid rocket propulsion system category. Each specified system in Fig. 4 will be discussed in the ensuing sections of this report.

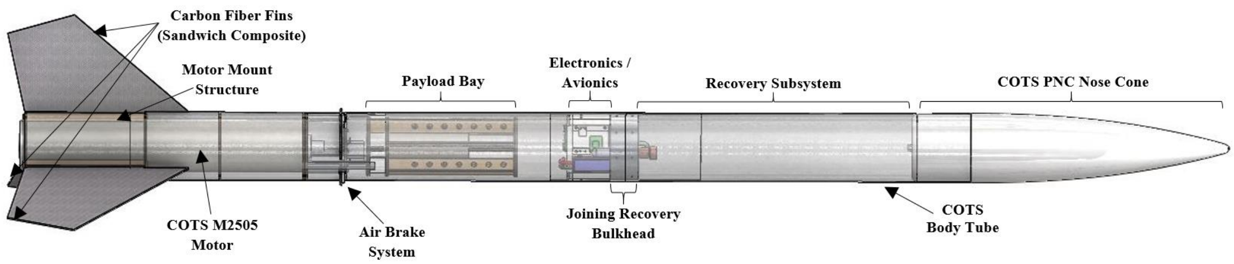


Figure 4. Simple Latte - 2018 IREC/Spaceport America Cup Configuration.

A. Propulsion Subsystems

1. Motor Selection Mandate

After the uOSTAR decision to use a COTS rocket propulsion system, selection criteria to satisfy IREC/SAC mandates were identified. The motor selection process was further refined by considering additional criteria identified by uOSTAR team members. Appropriate motor selection was identified to ensure rocket stability at initial launch, achieving a higher launch velocity than the required 30.5 m/s off the launch rail, and obtaining a subsonic or transonic maximum velocity. Additional considerations included using a COTS rocket propulsion system that was non-toxic, easy to unload and reload in the system architecture, achieved a AGL apogee as close as possible to the target 10,000 ft. A secondary goal identified by uOSTAR members was to select a motor with simple geometry for minimal design and manufacturing considerations in designing and fabricating the motor mount. Departure from the launch rail at a minimum velocity of 30.5 m/s was identified as a paramount requirement to ensure that <Simple Latte> follows a predictable and successful flight path. As a result, required thrust values were determined for the rocket to reach the minimum velocity while also achieving target AGL apogee.

2. Selected Cesaroni M2505 Rocket Motor Properties

After extensive motor evaluation, analysis, and considerations comparing four candidate M-Class solid fuel motors, uOSTAR members selected the Cesaroni M2505 Rocket Motor from the Pro38 line of reloadable high-power rocket motors by Cesaroni Technology Incorporated. The motor fuel selected is a 3 Grain Cesaroni Pro 98, and the motor can be inserted in an accompanying 3 Grain Cesaroni Pro 98 Gen 2 Casing, both available for purchase from Moto Joe. The Material Safety Data Sheet (MSDS) for the Cesaroni M2505 Rocket Motor was thoroughly examined to ensure the selection complies with all IREC/SAC rules and regulations, and was determined to be a valid selection.

Table 1 summarizes the Cesaroni M2505 Rocket Motor mass and thrust properties of the complete motor assembly. A summary of the target parameters and range values for a series of OpenRocket simulations with the M2505 Rocket Motor at a 6 degree launch angle and 10 km/h wind speed are also listed. The motor dimensions for the M2505 motor assembly are illustrated in the Engineering Drawings Appendix, where DIM 'B' is measured to be 21.58 in, as per the 3G variant.

Table 1. Properties and Performance values of the Cesaroni M2505 Rocket Motor.

Mass Property	Value (kg)	Thrust Property	Value
Full Mass	6.258	Burn Time	3.00 s
Fuel Mass	3.873	Total Impulse	7450 Ns
Empty Mass	2.835	Maximum Thrust	2952 N
		Average Thrust	2491 N

Parameter	Target	M2505 Rocket Motor
AGL Apogee	3048 m	3280 m – 3310 m
Velocity off 15 ft launch rail	> 30.5 m/s	35.5 m/s
Max Velocity	Minimized	33.4 m/s (~ Mach 1.0)
Velocity at Deployment	Minimized	3.61 m/s – 16 m/s*

*OpenRocket simulates a deployment velocity of 24 m/s, however OpenRocket does not consider the airbrakes used in our system architecture.

3. *Motor Selection Procedure*

uOSTAR selected OpenRocket as the model rocket simulation software for its numerous competitive advantages in comparison to other commercially available programs. The fully featured model rocket simulation software is both free and reliable, advantageous to an organization funded primarily by sponsorships and donations. Comprehensive user guides are also available online, allowing uOSTAR members to become adept with the software and use it correctly for accurate simulations. Furthermore, OpenRocket features advantageous and state of the art Six-Degrees-of-Freedom flight simulations with more than 50 possible variables. OpenRocket compatibility with SolidWorks is also advantageous, allowing for effective replication of CAD structures and features into the OpenRocket model or design. The dominant advantage of OpenRocket, though, is its ability to optimize designs for certain characteristics. This tool proved to be useful in determining an appropriate motor that meets all IREC/SAC competition requirements while attaining an AGL apogee of 10,000 ft.

A reliable and predictive model was developed in OpenRocket to simulate different COTS motor properties, evaluate their ability to obtain target parameters, and satisfy IREC/SAC competition mandates. To adhere to the motor selection criteria outlined in Section A-1, motor selection was restricted to motors with high thrust and low burn time. Extensive OpenRocket simulation revealed that Simple Latte would need an M-Class motor, as any motor below this class would not attain the target AGL apogee of 10,000 ft. Moreover, any motors classified as N-Class or higher would subject the rocket to supersonic velocities, which uOSTAR members wanted to avoid for design considerations. Further investigation of M-Class motors revealed that a shorter propellant burn time is desirable; otherwise, the rocket will travel far beyond the target AGL apogee.

Four candidate Cesaroni Rocket Motors and various properties for consideration were identified and are listed in Table 2. Of the four rocket motors listed, all four provide Simple Latte with the required minimum rail departure velocity. Where they differ, however, is in all other aspects of their performance. The M1450 had the longest burn time of all four motors but significantly overshoots the target AGL apogee as a consequence. The fins and air brake systems discussed further into this report would need to impose considerable drag onto the rocket system architecture to obtain target apogee, thus imposing significant mechanical stresses onto the rocket itself. The M6400-VM motor obtained simulated tests that were too powerful and would produce a supersonic flight velocity, which was undesirable for proposed system design. While the M2505 and M4770-VM motors perform comparably the M2505 was selected since it has a longer burn time while producing less thrust and, consequently, a greater apogee at a slower velocity where the magnitude of mechanical stresses imposed on the system from acceleration are lesser. As a result, the Cesaroni M2505 Rocket Motor was selected after careful review and design considerations.

Table 2. Summary of test values for 4 motor candidates for Simple Latte.

Motor	Burn time	Max Thrust	Average Thrust	Max Velocity	Apogee	Max Acceleration
M4770-VM	1.53 s	5854 N	4811 N	356 m/s (1.07 Mach)	3065 m	267 m/s^2
M2505	3.00 s	2952 N	2491 N	334 m/s (1.00 Mach)	3120 m	140 m/s^2
M1450	6.75 s	2416 N	1474 N	338 m/s (1.03 Mach)	4085 m	96.7 m/s^2
M6400-VM	1.36 s	7245 N	6351 N	400 m/s (1.20 Mach)	3445 m	341 m/s^2

For the purpose of simulation and analysis in OpenRocket, the simulated thrust curve of Simple Latte was approximated using a 12-point curve and is illustrated in Fig. 5. The simulated flight with the M2505 motor proved to closely match the official representative CMT Thrust Curve, illustrated in Fig. 6, in both pattern and magnitude, suggesting a correct motor selection decision was made.

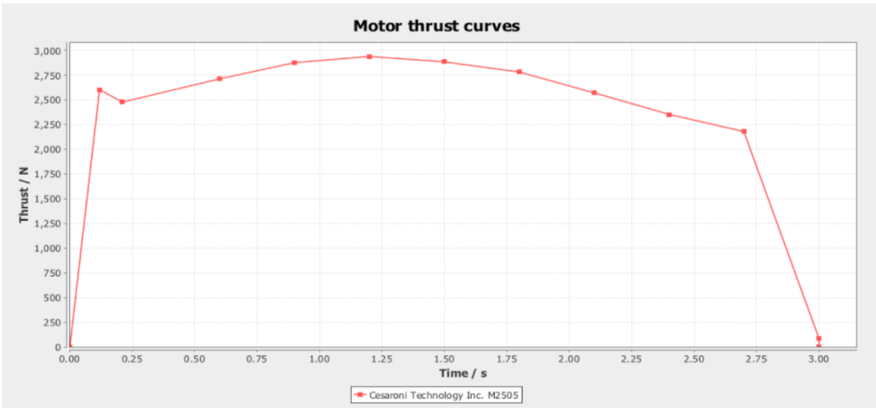


Figure 5. 12-point approximation of the Cesaroni M2505 thrust profile for Simple Latte.

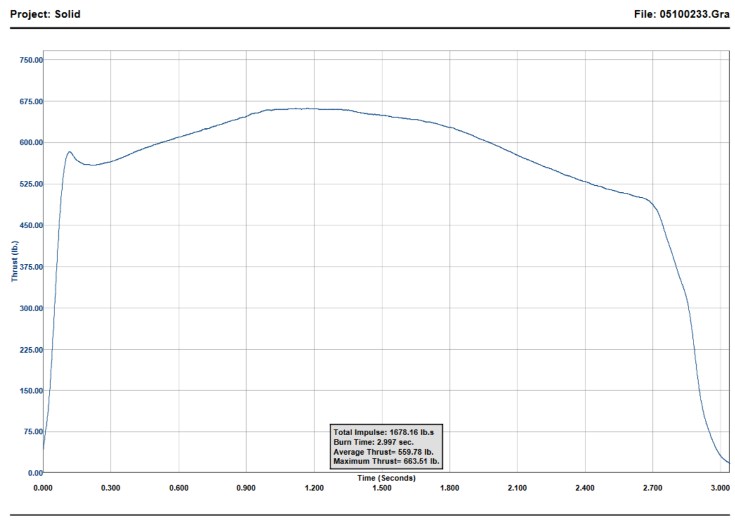


Figure 6. Official representative CMT Thrust Curve for Cesaroni M2505 Rocket Motor.

All rocket motors from the Cesaroni ProX series have non-toxic propellants, as mandated by IREC/SAC rules and requirements. Cesaroni ProX kits use an Ammonium perchlorate composite propellant (APCP), thus adhering to competition regulations.

4. Motor Mount – Design Considerations

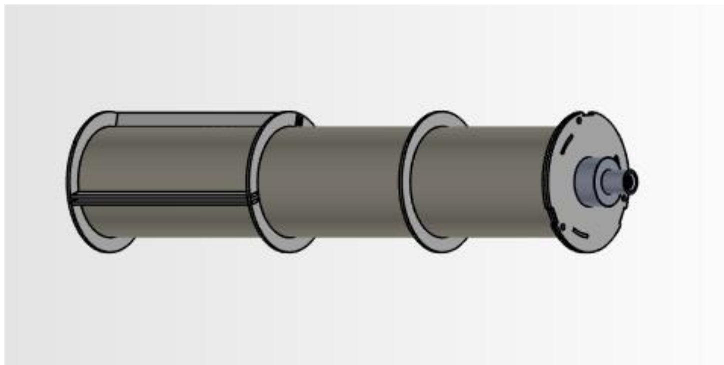


Figure 7. Finalized Virtual Motor Mount Assembly.

The main subject of attention for the motor mount design was centered on having a low mass and high strength. The primary focus of the motor mount is to house the motor, while withstanding the thrust force it generates. Additionally, the motor mount should be able to bear the force caused by deceleration from the air brakes. Other design considerations were to limit the vibrations caused by the engine and the heat transfer from the engine, should both the engine casing and phenolic tube fail.

The geometry of the motor mount must allow for a clearance for the topmost section of the engine casing, the ignition tracking head, with a diameter of 47.75 mm. Otherwise, the mount had to allow for the length of the engine to be flush with the inside of the rocket body wall. Knowing the dimensions of the COTS Cesaroni M2505 motor, the overall length of the motor mount was determined to be 567.18 mm. Its outer and inner diameters were determined to be 136.14mm and 101.6mm, respectively. The phenolic tube is circled with centering rings to account for the spatial difference between the motor mount and Blue Tube. A cross-sectional transparent view of the motor mount configuration in the bottom Blue Tube, housing the M2505 rocket engine, is illustrated in Fig. 8 below.

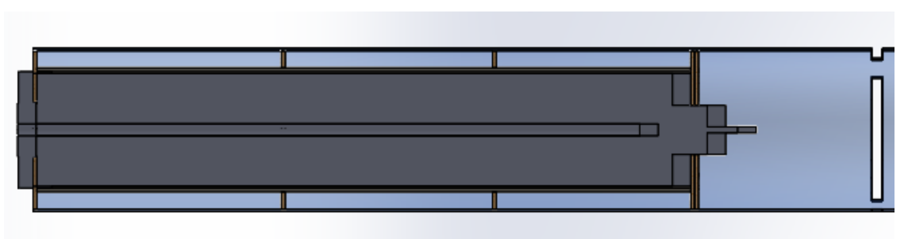


Figure 8. Motor mount configuration in bottom rocket body, including mock engine flipped sideways.

In the event that the phenolic tube and motor casing fails, the motor mount acts as a last-resort heat transfer mechanism. This motor mount design creates a space for convective air pockets to absorb heat, reducing direct conductive heat transfer to the Blue Tube and avoiding its potential combustion. This geometry between the Blue Tube and phenolic casing is illustrated above in Fig. 8 by the light grey sections.

The motor mount design must withstand a maximum impulse force of 2953 N at initial rocket launch. It must also endure downward forces exerted by the air brakes when operational. As the air brakes are likely to be in operation and exerting 350 N downwards while the motor is maintaining relative acceleration to the rocket body deceleration, the motor mount bulkhead must be rigid to imposed bending forces. Due to vibration caused by air flow on the air brakes and the explosive nature of the engine, the motor mount must be flush with the inner rocket body wall to avoid dislocation of the attachments holding it in place. This further allows the for natural damping by the more massive elements in middle of the rocket (e.g. the recovery system). A full vibration analysis was not completed due to the relatively small nature of the vibrations caused by an amateur rocket engine and low probability they would induce harmonic oscillation enough to damage the rocket body coupling as the engine is only active for 5 seconds. Though harmonic oscillation could occur due to aerodynamic eddies from the air brakes in a two-brake system, a three-brake system minimizes these risks. In either case, the real bearer of vibrations is the rocket body, not the motor mount, so these are discounted for this section.

Regarding the forces for the motor mount, these were assumed to act in shear, bending, flexure, and compression. Therefore, an analysis of the critical points and joints (contacts between engine and bulkhead, between bulkhead/epoxy and blue tube) were vital. Since stresses are applied axially and not radially to the bulkhead, any stress concentration factors are neglected because the force vectors are orthogonal to the surface, therefore plate geometry is neglected. All forces are measured below in Table 3, their points of action being the critical joints or points along the bulkhead namely the innermost opening (compressive stress), the middle (bending/flexure), outermost edge (shear):

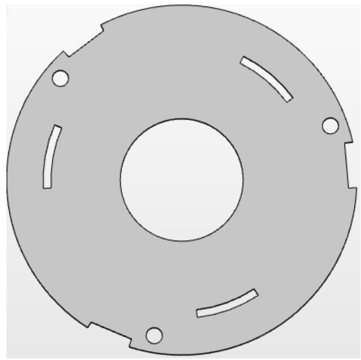


Figure 9. Top View of Finalized Bulkhead schematic.

Table 3. Maximal stresses on plywood and epoxy at critical points. Limiting epoxy stress (28.6 MPa) and limiting stress (44.3 MPa) are highlighted.

Stress Type/ Material	Max Tensile/ Compression	Max Shear	Max Bending	Max Flexural
Epoxy	N/A	28.6 MPa	14.13 MPa	N/A
Birch Plywood	1.17 MPa	28.6 MPa	13.6 MPa	44.3 MPa

In order to achieve minimal weight of the fabricated pieces, it is essential to select from the most lightweight, low-cost materials available. Candidates for material selection and their properties are examined in Table 4. Although titanium and other alloys have high material properties, they are effectively ruled out due to high expense. From the perspective of material strength proper, composites are desirable for the immediate area of exposed stress. However, the difficulty in mating and manufacturing different geometries of composites causes significant problems this also rules out composites as anisotropic materials are undesirable for this type of application. Therefore, compared to the next strongest material in its class, aluminium is the leader with regards to material properties, costs, and ease of manufacturing for the recovery mount and plywood with its orthotropic properties comes second for the motor mount.

Table 4. Cost vs Material property table for various construction materials [via Matweb]

Material	Cost	Density	Yield Strength	Ultimate Strength	Machinability
Titanium	High	4.94 g/cm³	160 MPa	258 MPa	High
Wood	Low	0.55 g/cm³	N/A	6.3 MPa	High
Aluminium	Medium	2.78 g/cm³	290 MPa	440 MPa	High
Steel 1020	Medium	7.87 g/cm³	330 MPa	450 MPa	High
Carbon composite	High	2.00 g/cm³	N/A	1400 MPa	Low

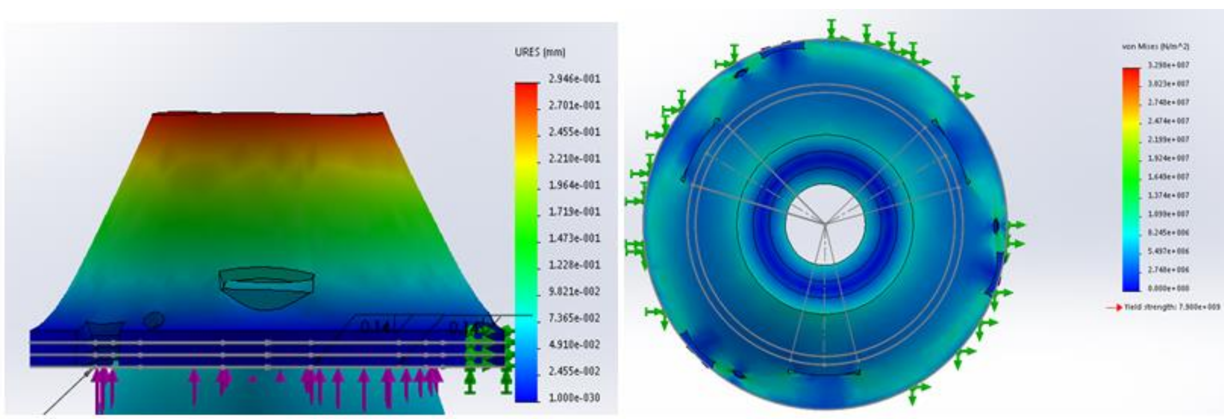
The primary construction of the Motor Mount is laser cut birch plywood for load bearing components, along with a Kraft paper tube to radially support the motor. The assembly is held together using West Systems Epoxy and is epoxied permanently into the bottom blue tube. The Kraft paper tube's properties were not known from any source and so approximations based on literature had to be made. The plywood was tested on an Instron machine to get the values needed for bending modulus. Results of Instron testing are shown in Table 5.

Table 5. Birch Plywood Material Properties (15% moisture)

Property	Theoretical Value
Tensile Modulus	4.5 GPa
Shear Modulus	1.78 MPa
Bending Modulus	66.54 MPa
Density	650 kg/m^3
Poisson Ratio	0.697

5. Motor Mount – Analysis

As per the listed limiting stresses in Table 3, the plywood has to be able to endure the stresses noted. An FEA study to confirm these results was completed in order to verify the need for reinforcement. Results illustrated in Fig. 10 were conclusive.



a) b)

Figure 10. Displacement (a) and stress analysis (b) on the bulkhead of the motor mount.

6. Motor Mount – Manufacturing

Using applicable design for manufacturing and assembly (DFMA) techniques, motor mount manufacturing was split into several component areas; the top bulkhead, the phenolic tube containing the rocket engine, the concentric centering rings, and the fin spars. Components were individually manufactured and later assembled using a bonding agent.

Design calculations were largely based on the top bulkhead as it is subject to the largest flexure, axial, and shear stresses. To sustain the forces endured by the motor mount, an estimated minimum of 10 mm of birch plywood was necessary. Using 3mm birch plywood sections, three bulkhead parts were laser cut to accommodate openings for both the motor, the struts holding the air brakes, and the phenolic tube. The phenolic tube needed no direct fabrication from the team, as it is a commercial off-the-shelf (COTS) component. However, modifications were necessary in order to properly fit it with the laser cut bulkhead pieces. Therefore, the topmost portion of the phenolic tube was cut down in three sections down to a height of 10 mm in order to create extrusions which would then mate with concordant intrusions laser-cut into the bulkhead wood. This cutting was achieved with a dremel in a relatively short period, and sanding of the cut part was also dremel-driven.

The fin spars and the concentric rings were also laser-cut, albeit with only one thickness of 3 mm plywood. Four concentric rings were created to stabilize the motor mount, with three of them incorporating intrusions for the fin spars and most being of 3 mm only with the notable exception of the lower centering rings, which were stacked in a cross-grain manner to account for fin forces.

The total assembly was centered around the phenolic tube, and by extension the motor; three bulkhead layers being inserted on top of the phenolic tube thanks to their incorporated inserts; four centering rings, with two at the bottom of the fin spars, one at the top and the remaining ring aligned in the middle of the remaining distance.

B. Aerostructures Subsystems

The aerostructures of uOSTAR's Simple Latte were designed and fabricated all while considering essential theory in aerodynamics such as aeronautical speed regimes and test parameters, drag forces, effects of gravitational force (G-Force loading considerations). Structural and manufacturability considerations such as material strength, weight, cost, and design for manufacturing and assembly (DFMA) were examined in the material selection and manufacturing of components. While major components such as the Blue Tube and nose cone were COTS purchases to be implemented in Simple Latte, uOSTAR members were also involved in fabricating several components of the final system. Consequently, keeping costs low and manufacturing processes relatively simple were two principal motivators in the design and manufacturing of the organization-made components. Design for assembly (DFA) techniques were employed to assist the design teams in the design of components that transition to production at a minimal cost, focusing on the number and complexity of parts, handling, and ease of assembly. Similarly, design for manufacturing (DFM) techniques ensured optimization of manufacturing processes to select the most cost-effective material and simplicity of parts to form the final product after their assembly.

1. Body Tube

A COTS 98 mm LOC MMT body tube was purchased to house the M2505 motor and all aerostructure subsystems, manufactured by LOC Precision Rocketry and purchased from Apogee Components. These tubes have have thick walls and are made from quality Kraft paper. Not only were they sized to carry larger motors such as the M2505, but the tubes are also easy to cut, glue, or modify. These tubes are also advantageous for their cheap price, allowing uOSTAR members to experiment with several designs and construction techniques. As the body tube of Simple Latte is two separate tubes held together using a bulkhead coupler, two individual tubes were purchased.

2. *Nose Cone – Design and Manufacturing Considerations*

The most important consideration when designing a nose cone for subsonic speed is to minimize drag. An extensive literature review of nose cone designs and their applications suggested an elliptical nose cone as the preferable solution for Simple Latte.[1,2] High performing nose cone designs for transonic speeds such as $X^{1/2}$ Power Series, Von Karman, and LV-Haack designs were also studied but were phased out of consideration due to their higher cost and added difficulty in manufacturing.

Due to the abundance of commercially available nose cones for purchase from reputable companies in the model rocket industry, cost-benefit and time-value analyses were used as an approach to compare the relevant costs of purchasing a nose cone versus taking the time to design and manufacture a nose cone in-house. COTS nose cones are relatively inexpensive; uOSTAR would have only saved a small amount of money after purchasing the materials and manufacturing one in-house, at the expense of both time and human resources. Furthermore, the risk associated with team member inexperience in injection molding or plastics manufacturing largely outweighed the benefits of purchasing a commercial nose cone. This is largely due to the inaccessibility of an injection molding machine at the University of Ottawa for use by undergraduate engineering student teams. For the above-mentioned reasons, a decision to purchase a COTS nose cone from a reputable supplier in the model rocket industry was made.

The nose cone selected for Simple Latte is the PNC-5.38 inch – LONG Model 20123, a commercial solution offered by Apogee Components.[10] This inexpensive nose cone offers a unique set advantages that harmonize with the overall rocket system architecture, as illustrated in Fig. 11. This nose cone also fits Blue Tube 5.38 inch diameter bodies, which was selected as the body tube for Simple Latte. The nose cone is blow-molded out of a Polypropylene plastic to give it hollow interior, while still remaining a durable component.

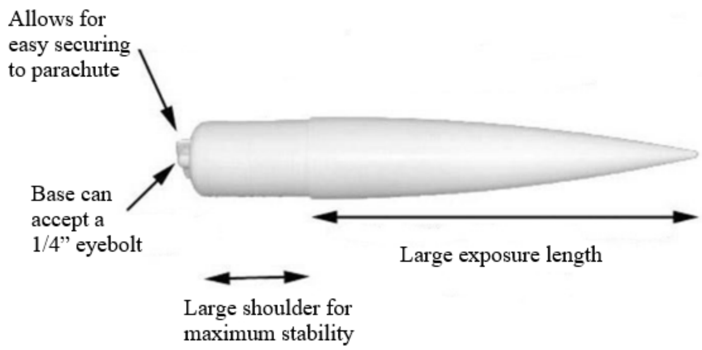


Figure 11. PNC COTS Nose Cone used for Simple Latte.

3. Fins - Design

Fins are used for stability in sounding rockets and ensures rocket flight is safe, predictable, and tracks true off the launch rail. The needed stability comes at a consequence of added weight and drag, which can have a significant effect on the rocket system and its mission operations. It is therefore best to design fins that are as small as possible, while still maintaining stability. As Simple Latte travels largely at subsonic or transonic velocities the rocket is also subject to aerodynamic characteristics in the transonic regime, such as wave drag and unsteady flow. uOSTAR fin design choices are based not only on what works from the literature, but also on what the team aims to accomplish; leaving the launch rail at a required minimum velocity, obtaining a predetermined maximum altitude, while remaining subsonic.

Important design considerations for fin design include stability and various independent variables, such as atmospheric density and temperature. Fin design can be further optimized to minimize drag, maintain structural integrity, maximize the fin joint strength, and for structural strength while maintaining their passive stability.

An important consideration for rocket stability is defined through its static margins. Literature suggests that a rocket is considered stable when the static margin is above a value of 1, as the restorative drags and lift forces must be greater than external wind forces acting on the rocket. Conversely, overstability can occur if the restorative forces are too large, overcorrecting and amplifying changes to trajectory. Overstability is likely to occur with a static margin value above 6, therefore the fins were designed around a conservative static margin value of 1.5.

The shape of the fin was largely controlled by the competition-required static margin of at least 1.5 body calibers for the entire ascent at an estimated ground wind speed of 3 m/s. Two main fin designs were selected for consideration; a standard trapezoidal fin and a swept-back freeform fin. The freeform fin design selected for Simple Latte, manufactured from a Carbon-6061 Aluminum sandwich composite, is illustrated in Fig. 12.

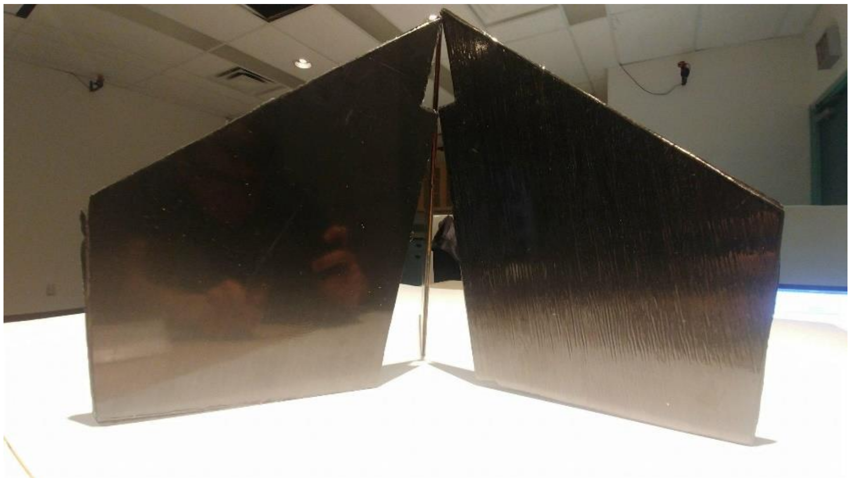


Figure 12. Manufactured freeform fins for Simple Latte.

4. Fins – Analysis

An analysis comparing the impact of trapezoidal and freeform fin designs on the OpenRocket simulation yielded the results listed in Table 4. The trapezoidal fins were smaller in every dimension and, by extension, lighter; however, they showed inconsistencies in their static margins and vertical orientations that could not be resolved. The freeform design was selected since the lower taper ratio is less susceptible so shear forces. A longer root chord also increases the predicted AGL apogee relative to the trapezoidal fins, despite their additional weight.

Table 6. OpenRocket comparison of trapezoidal and freeform fin properties

Properties	Trapezoidal Fins	Freeform Fins
Static Margin @ launch rail	1.45 +/- 0.1	1.5
Max height	18 cm	18.9 cm
Area	305 cm^2	469.7 cm^2
Taper ratio	.41	.54

A material selection analysis for choosing fin materials was based on the plane shear modulus, weight, price of material, and ease of manufacturing. Three materials were selected for further analysis; 6061 Aluminum, a HEC200/SE70 carbon-epoxy composite, and a carbon fiber composite. Literature models were used to predict the speed at which destructive fin flutter occurs, given by the Eqs. (1) and (2).[3] Additionally, the thickness was kept at a constant 5mm for an accurate comparison of the materials. The results obtained from this analysis are provided in Table 5.

$$V_f = a\sqrt{\frac{G}{\frac{1.337AR^3P(\lambda+1)}{2(AR+2)(\frac{t}{c})^3}}} \tag{1}$$

$$V_f = a\sqrt{\frac{G_E}{\frac{39.3A^3}{\left(\frac{t}{c}\right)^3(A+2)}\left(\frac{\lambda+1}{2}\right)\left(\frac{P}{P_O}\right)}} \tag{2}$$

Table 7. Fin Materials Comparison Analysis

Properties	6061 Aluminum	HEC200/SE70	Carbon-Al Sandwich
Critical Speed (1958)	644 m/s	245 m/s	392m/s
Critical Speed (current)	869 m/s	330 m/s	529 m/s
Shear Modulus G_{13}	25.99 GPa	4.49 GPa	11.51 GPa
Weight (per fin)	416.15 g	231.19 g	292.8 g
Ease of manufacturing	Simple	More difficult	Most difficult
Cost	$$$	0	$

The results, consistent with the literature, suggest that Aluminum performs extremely well in out-of-phase shear compared to the carbon-epoxy composite because of its homogeneous structure. The performance aspects of Aluminum come at the expense, however, of cost and added weight. On its own, the carbon composite suffers from its unidirectionality and poor out-of-plane shear properties. By combining the excellent shear properties of Aluminum with the stiff and light properties of the carbon composite, optimal fins for Simple Latte were obtained. Using a sandwich composite increases the fin resistance to harmonic vibrations and oscillations as the core damps the harmonic resonance of the faces. Though this sandwich composite would normally come at an increased cost, the team was fortunate enough to acquire the carbon composite through a generous donation from Dr. François Robitaille, Associate Professor at the University of Ottawa.

5. Fins – Manufacturing

Once the shape of the fins was determined, three fins were laser cut from an aluminum sheet. Special manufacturing techniques were applied to manufacture the carbon-aluminum sandwich-structured composite. The aluminum core is bonded to the carbon-fiber skin using a brazing technique, essentially cooking the carbon-fiber onto the aluminum core. Brazing is performed in a negative pressure environment, achieved using powerful vacuum pump. Sandwich composites are widely used in aerospace because of their ability to decrease weight while markedly improving mechanical properties by combining the properties of various materials. The faces carry the bulk of the tensile and compressive forces, where as the core keeps the faces from buckling and takes most of the shear forces. Importantly for this context, assuming that faces and the core are isostrain, the effective out-of-plane shear modulus of this composite can be calculated by the rule of mixture.[4-6] An image of the carbon-fiber layer directionality brazed onto the laser-cut aluminum shape is outlined in Fig. 13.

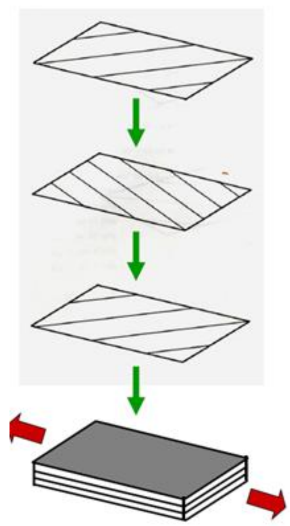


Figure 13. Outline of carbon-fiber layer directionality when brazed onto the aluminum fin.

Unidirectional composites have many advantages, but also have many weaknesses. When analysing laminate structures, it is essential to understand its strengths and apply them to their fullest while mitigating their weakness. Composites such as carbon fiber are extremely light (1.5 g/cm^3) compared even to the lightest of metals, aluminum is nearly twice as heavy (2.7 g/cm^3). Composites also offer the flexibility of strengthening only the required directions by altering layup directions. In the context of the fins, it allows us to stiffen the bending and torsion directions without adding significant weight. Unfortunately, despite their high in-plane stiffness and strength, laminate composite structures suffer under bending and torsion loads due to layer separation. As the layers of fibers are held together by the epoxy matrix, flexural, bending, or torsion loads are supported mostly by the matrix.[7-9] For this reason, two-dimensional composite laminates are often combined with metal or foam core which can withstand larger shear stresses.

6. Joining Recovery Bulkhead – Design and Analysis

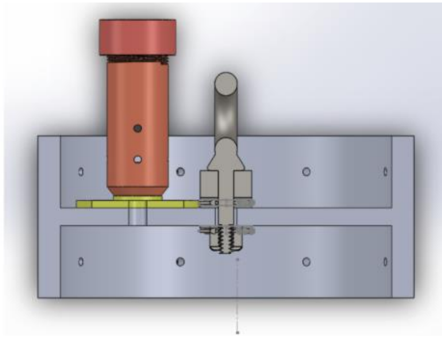
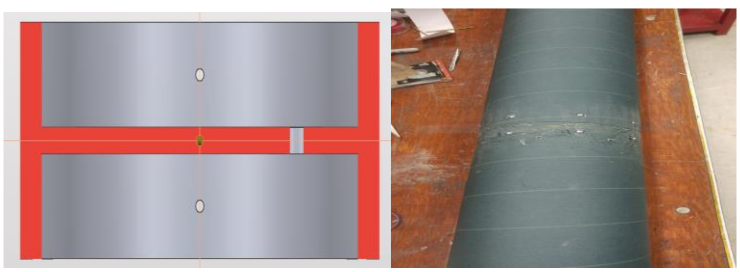


Figure 14. Cross section of recovery mount with attached CO_2 ejection system and eye-bolt with lock-nut.

The joining recovery bulkhead was designed to satisfy three criteria. First, it was to act as a coupler that can withstand external stresses while keeping the top and bottom Blue Tubes connected. Second, it would be used to hold the parachute shroud lines. Lastly, the joining recovery bulkhead would incorporate the mechanism used for successful parachute ejection. Limiting factors such as the stresses experienced on the bulkhead during parachute deployment, weight, and access to University of Ottawa machining equipment were considered in the design of the joining recovery bulkhead.

Bulkhead geometry was designed such that it slides into the body of the rocket with minimum tolerance. As a result, the outer diameter of the mount needed to match the inner diameter of the Blue Tube of 136.18mm. The joining recovery bulkhead takes on the shape of a cylindrical H-shaped tube, illustrated in Fig. 15, with the thin side walls bolted in from the outside of the body, securely fastening the two Blue tubes and the bulkhead together.



a) b)

Figure 15. a) Cross-section view of the recovery mount in early stages. b) Fully functional recovery system coupling two blue tubes with screws (holes not reinforced).

In the final design, the thickness of the walls were taken as one-quarter inch and a stress analysis was conducted with varying bolt sizes to determine safety factor. Maximum stresses on the blue tube and bolts had to be determined to choose the correct type of coupler. After the bolt stress analysis to determine minimum size for a stress of 174 N each it was concluded that M3 bolts would suffice, which are 3 mm (~0.11 inch) in diameter, giving a safety factor of two using 8 bolts (four on the top tube and four on the bottom). However the decision was made to double the number of bolts to provide even more stability. A thread diameter analysis was performed in order to determine the best size thread to use. Fig. 16 below displays the bolt thread analysis and Fig. 17 shows the ANSYS analysis of the recovery mount with the bolt holes, used to determine any areas of failure and to verify that maximum stresses would not exceed the safety factor.

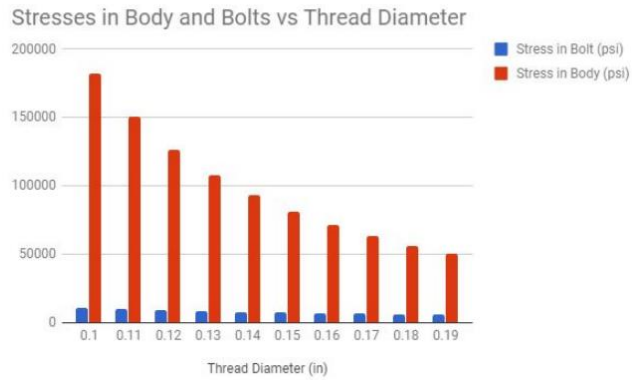


Figure 16. Excel spreadsheet analysis determining bolt diameter vs. stress.

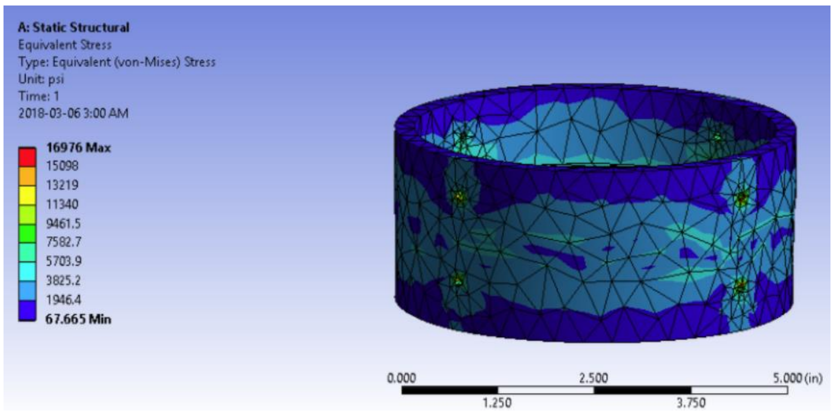
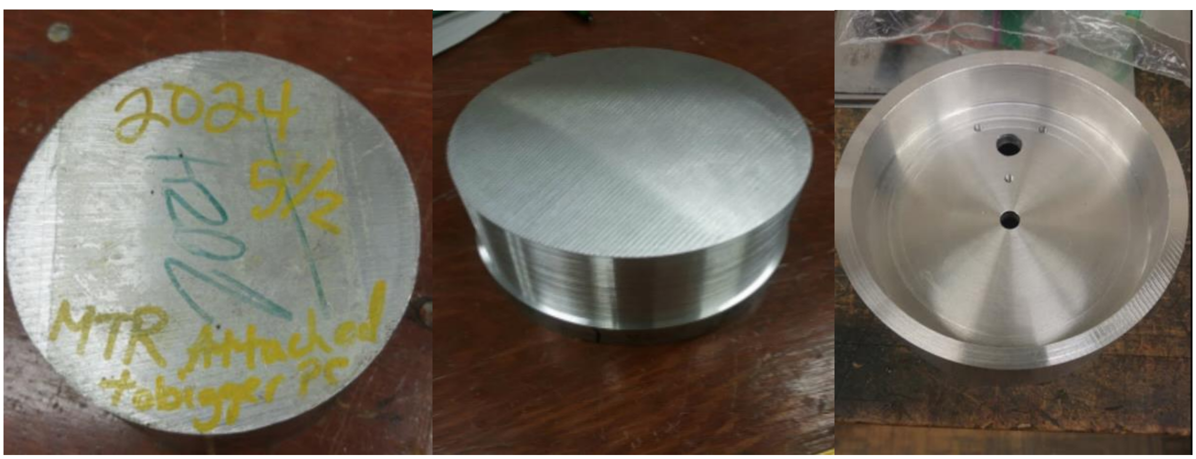


Figure 17. ANSYS FEA analysis of recovery mount.

7. Joining Recovery Bulkhead – Manufacturing



a) b) c)

Figure 18. Progression in the manufacturing of the recovery mount. a) the cylindrical raw aluminium 2024 piece. b) the piece with initial facing done on the outside and turning done on the outside diameter. c) with full turning operations done on both sides and bore holes for the center eye-bolt and off-centre CO_2 ejector.

The recovery mount was manufactured from a solid cylindrical piece of aerospace-grade aluminium, larger in size than was required. The first step in manufacturing the piece was to lathe the outside diameter of the raw material to the inner dimensions of the main rocket body (the Blue Tube). Next, it was necessary to bore the inner diameter on both sides of the mount with a lathe. This would create the outer ring thickness prescribed by design calculations, while allowing a center span to remain in the middle of the part. All turning and boring operations were completed with the lathes available at the Brunsfield Centre.

The center span had a facing operation performed on both sides, before proceeding to the drilling of the holes for both the eye-bolt and CO_2 canister. Both were completed with a drill-press, and tapped with a hand-tap to ⅜" diameter for the canister holes (the central hole needed no tap). Finally, the outer screw holes needed to hold the recovery mount in place were done with an indexing machine to ensure precision of the hole placement.

8. Airbrakes – Design and Manufacturing

Once a rocket's fuel is expended, it takes the form of a ballistic projectile, unable to meaningfully alter its flight path. This is not ideal when attempting to achieve an exact altitude as there are many flight variables that are difficult if not impossible to account for prior to launch. To increase the chance of achieving our target altitude, a novel airbrake solution was introduced. The solution's goals were for the system to be fully controllable, light, structurally sound, volume efficient, and inexpensive. The result is a three-leaf airbrake which can protrude from out of the rocket body, perpendicularly to the flow of air. Fully extended, the airbrakes have an area of 110.4 cm^2. At a deployment speed of 250 m/s this area would provide 219.9 N of braking drag force; at slower speeds of 100 m/s, the braking force falls to 32.6 N. Each leaf of the airbrake is plate aluminum epoxied to a laser cut plywood gear. This gear train is powered by a servo, giving our flight computer the ability to modulate the extension of the leaves.

The focus of the design was to maximize the area of the leaves without compromising the strength of the rocket body or taking up too much room. This was achieved through several motions. Originally, the gear train was integrated directly into each leaf as show in Fig. 19.

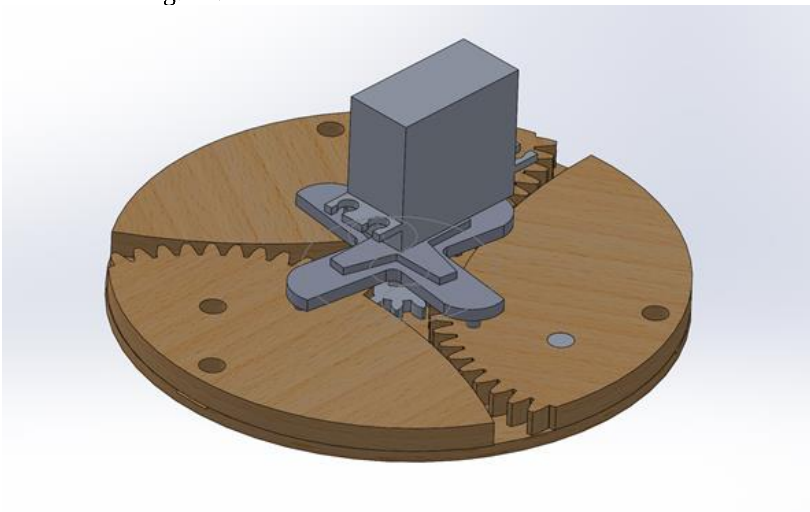


Figure 19. Original Air Brake Design.

This design was found to have many flaws due to the high friction between the leaves and the bottom and top plates. Additionally, to accommodate our 180-degree servo, a planetary gearbox was required to achieve the required extension. This added complexity and risk of failure to the air brakes. Finally, because of the leaf being part of the gear train, the area of the leaves was limited to 40 cm^2. The redesign shown in Fig. 20 aimed to iterate on the concept and address the previous issues.

Figure 20. Final Air Brake Design

The main change of the second iteration was the separation between the leaves and the gear train. This allowed us to move the pivot point the extremity of the top plate. Moreover, it allowed the leaves to fully take advantage of the area within the tube. These modifications increased the effective area of the extended leaves to 110.4 cm^2, an increase of over 275%. The extra area also warranted a change of material for the leaves as plywood is limited in its strength. Aluminum was chosen for the leaves as it is stiff for its weight. To address the friction between plates and the leaves, the bottom plate was removed, and a nylon PTFE impregnated bushing was added between the top plate and the gear. Other notable concerns for the airbrake was the deformation of the standoffs and the leaves themselves. An FEA was therefore run on the airbrakes simulating the pressure of the airflow pressing on the airbrakes as can be seen in Fig. 21.

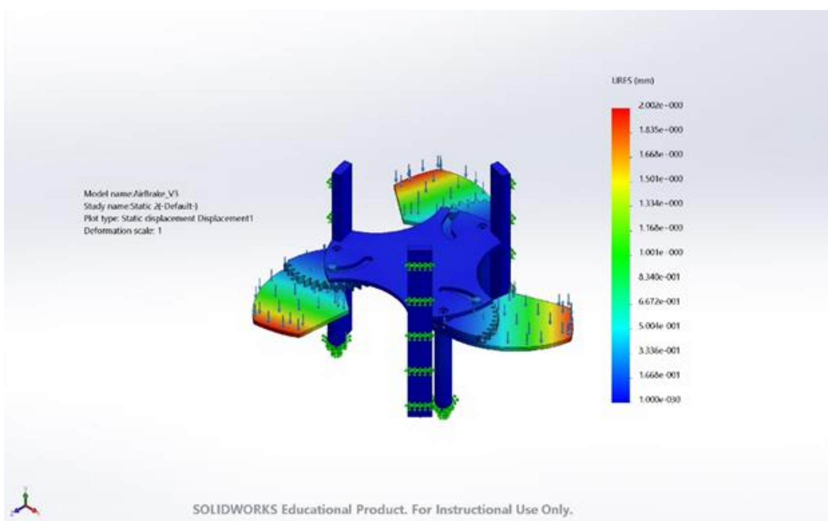


Figure 21. Deformation of airbrake leaves under 200m/s load.

The maximum deformation of the leaves was found to be 2 mm which was deemed an acceptable amount of deflection. Furthermore, the aluminum standoffs did not appreciably suffer from buckling. The full material parts list can be seen in Table 6 below.

Table 8. Material components for airbrake manufacturing.

Part	Material	Thickness	Elastic Modulus (GPa)
Top Plate	Plywood	3 mm	(See plywood prop.)
Centre Gear	Plywood	6mm	(See plywood prop.)
Leaf Gears x3	Plywood	6mm	(See plywood prop.)
Leaf x3	Aluminum	3mm	68.9
Spars x3	Aluminum	6.35mm	68.9
Standoff x3	Aluminum	12.7mm	68.9
Guide Pin	Delrin	6.35mm	
Spektrum A6180 Servo	Plastic	n/a	n/a
Bushings x6	Nylon w/ PTFE	n/a	n/a
M3x5 Screw x3	Zinc-plated Galvanized Steel	n/a	n/a

Further concerns with the airbrakes are the holes in the body that would have to be cut to accommodate the system. Each cut in the body is 95 degrees in length, leaving only 75 degrees of rocket body where the leaves deploy from the tube do not deploy from the tube. This may compromise the body tube and measures had to be taken to significantly reinforce the body tube. To stiffen and reinforce the blue tube, 6.35 mm aluminum spars, measuring 15 degrees each were epoxied to the inner circumference.

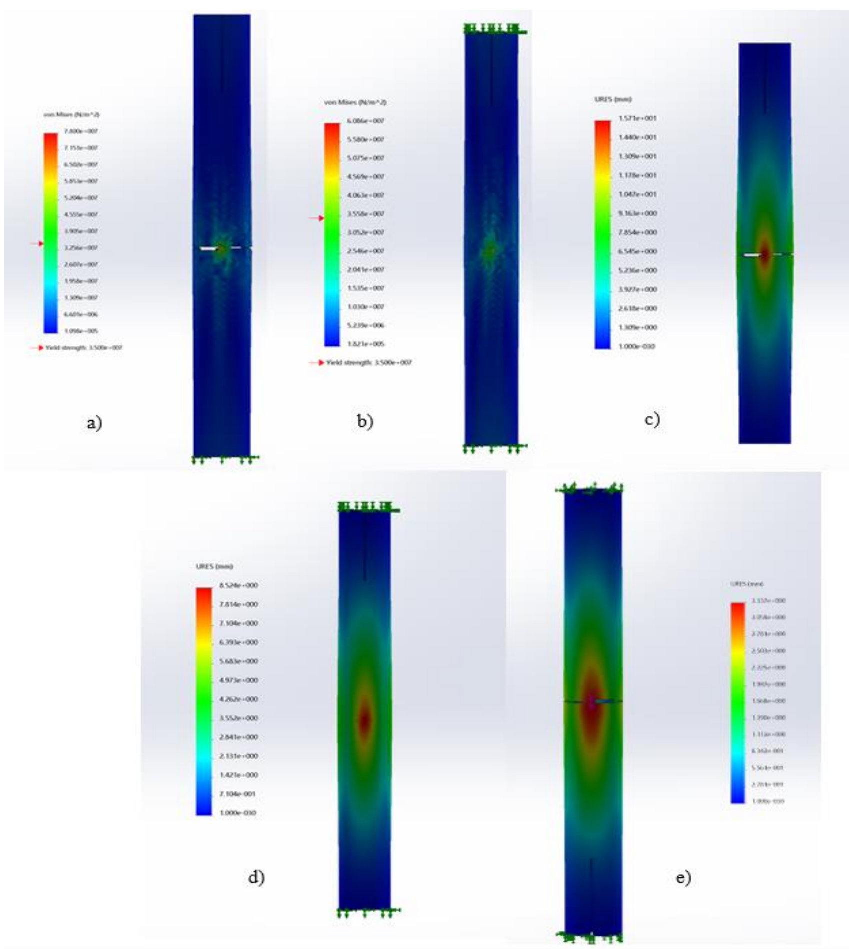


**Figure 22. a) Blue Tube with no reinforcement – Yield Strength 35MPa;
b) Blue Tube with no slits, no reinforcement – Yield Strength 35MPa;
c) Defection with slits – Max deflection 15mm (1kN load);
d) Deflection without slits or e) reinforcement – Max Deformation is 8.52mm (1kN load).**

C. Recovery Subsystems

1. Subsystem Design Considerations

As per IREC/SAC rules and regulations, a successful recovery system must meet the following specifications:

- Protects the rocket from impact when descending to the ground.
- Guarantees the safety of IREC/SAC participants, the launch site, and all surrounding areas
- The rocket can be found within a reasonable distance from the initial launch site.

A meticulous methodology for design, analysis, and testing was employed to ensure the recovery system is able to satisfy all prescribed requirements. More specifically, the aspects for the required descent profiles are velocities between 23 m/s and 46 m/s when above 1,500 ft. AGL and no more than 9 m/s below 1,500 ft. AGL.

A dual-deployment system consists of a two-stage parachute deployment procedure. First, an inverted reefed parachute is deployed at apogee. Disreefing occurs at a pre-determined altitude during the descent. Using an inverted reefed parachute configuration allows Simple Latte to fall at a faster speed after apogee than if the disreefed parachute were immediately deployed at apogee. As this gives less time for the system to travel with the wind, this also minimizes displacement from the initial launch site. Disreefing occurs and the main parachute is deployed at 1500 ft. AGL, preparing the rocket for a soft, safe landing. Using an inverted reefing configuration is necessary since only deploying the main, disreefed parachute ate 1500 ft. AGL would cause a significant impulse force from parachute inflation – this could prove harmful to Simple Latte.

Simple Latte's recovery method includes a SRAD, reefed parachute with two COTS (one per each stage of deployment) devices used to actuate each descent stage. The recovery system is controlled by a SRAD flight computer described in the Avionics section, and is backed up by a COTS dual-event recovery device. Fig. 23 outlines the flight profile of the vehicle, visualizing the three major recovery events; ejection of the reefed parachute, de-reefing, and landing. The ejection of the reefed parachute is done via the commercially available CD3 CO_2 ejection system. While both recovery event devices are considered COTS components, the parachute used on Simple Latte is completely designed and fabricated by student members on the team.

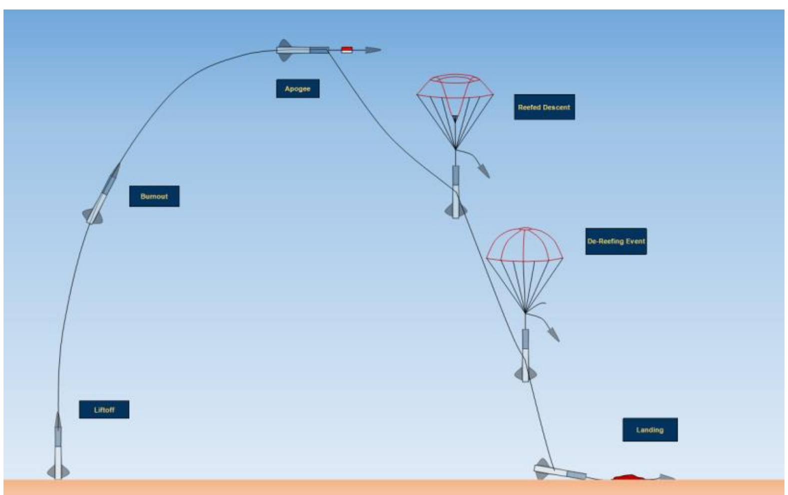


Figure 23. Graphic of Flight Mission Profile.

Deployment stages of the recovery system were all considered in the design and fabrication of the recovery subsystem. Deployment of the recovery system occurs as described below:

1. <Simple Latte> reaches AGL apogee of 10,000 ft. and shifts to a horizontal orientation.
2. The flight electronics system detects apogee, activating the CD3 CO_2 ejection system to push the inverted reefed parachute out of the top of the rocket.
3. The inverted reefed parachute inflates, slowing the system descent to a velocity of approximately 90 ft/s.
4. <Simple Latte> continues to descent at this velocity until it reaches 1500 ft.
5. At 1500 ft. AGL, the flight electronics system releases the Tender Descender to disreef the parachute.
6. The parachute takes its fully inflated form and Simple Latte slows to its terminal velocity of approximately 9 m/s.

7. The system safely reaches the ground and is retrieved by uOSTAR members.

2. Inverted Reefing Parachute Design & Fabrication

When evaluating candidate canopy shapes and designs, various aspects such as the drag coefficient, stability, ease of design, and simple manufacturing methods were the main considerations. Two highly considered parachute configurations were solid and slotted canopies. As solid canopies are less porous and have a higher coefficient of drag, it was identified as a great choice for the main parachute. Slotted canopies feature multiple horizontal vents and have a higher porosity than solid canopies and are commonly used for high-speed drogues. uOSTAR's parachute design drew inspiration from both the solid and slotted canopy designs to design and manufacture a custom, hybrid parachute. This parachute features a slotted canopy design in its reefed stage, and transforms into a solid-slotted hybrid when disreefed and fully inflated. While inversely reefed parachutes are normally used for increasing drag, a slotted canopy design allows for a significant reduction in drag. This is due to the slots acting as a vent ring and disabling the inner surface area of the parachute during the inversely reefed configuration. Following industry standard for parachute design, the material selected was a zero-porosity rip-stop nylon purchased from an online supplier named Ripstop By The Roll.

A simple force-balance between the approximate weight of the rocket under gravity and the drag created from the parachute allows for the derivation of an expression for parachute. Drawing inspiration and knowledge from Richard Nakka's *Experimental Rocketry* Web Site, the vertical descent rate provided by a parachute in stable descent is given by the following expression:

$$v = \sqrt{\frac{2W_t}{SC_D\rho_{air}}} \quad (3)$$

, where W_t is the total weight of the rocket and parachute and S is the canopy reference area (ft^2), evaluated using the density of air.[10] From this expression, it is evident that the drag force is dependent on the diameter of the parachute, the drag coefficient of the parachute, and the dynamic pressure created by moving air impacting the parachute canopy.[4] Rearranging this expression into a two-dimensional projection of the parachute allows for the parachute diameter to be determined using the following expression:

$$d_{parachute} = \sqrt{\frac{8W_t}{\pi v^2 C_D\rho_{air}}} \quad (4)$$

Using the information above, parachute design specifications were determined and are listed in Table 7. An image of the drag characterization test is provided in Fig. 24.

Table 9. Parachute Design Specifications

Characteristics	Fully Deployed Configuration	Inversely Reefed Configuration
Measured Drag	190 N at 9 m/2 descent	200 N at 25 m/s descent
Shroud Line Rating	500 lbs/line (x12 lines)	500 lbs/line (x24 lines)
Surface Area	6.12 m^2	-
Drag Coefficient	-	-

Figure 24. Successful parachute testing to measure drag and the drag coefficient.

As previously stated, the parachute was fabricated in-house since the hybrid design suggested by the team was not available commercially. Following Richard Nakka's design and fabrication instructuons available on his website, instructions were followed to obtain a semi-ellipsoid canopy shape. The parachute is comprised of twelve panels, individually cut from rip-stop nylon. These individual panels were sewn together to form the canopy. For added strength and to prevent unravelling, panels were hemmed along each side before being sewn together. Furthermore, seam bindings were sewn on each seam to eliminate any unwanted porosity from any potential slight imperfections associated with in-house fabrication. To ensure there would be no unravelling between panels, a bonded 3-ply 100-percent nylon threat was selected and a zig-zag stitching pattern was used for additional strength.[11]

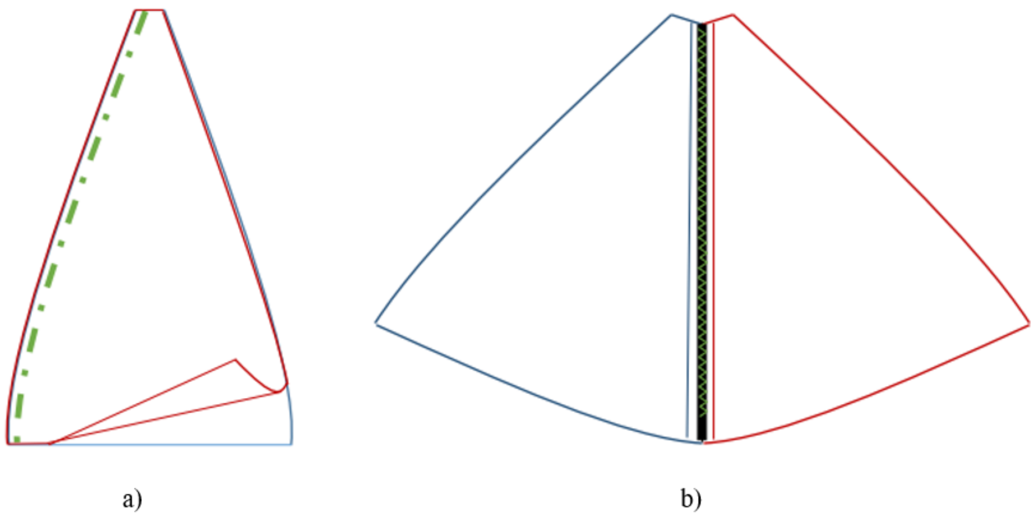


Figure 25. a) Two panels are placed on top of each other and a straight, longitudinal stitch is applied; b) The gores are then spread out and the seam binding and zig-zag stitch are applied.

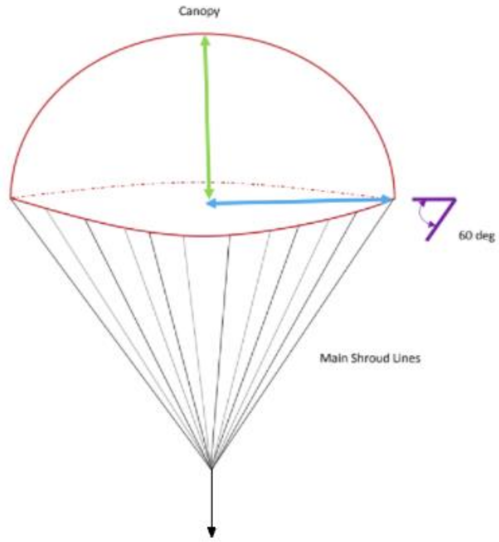


Figure 26. Schematic of the deployed parachute canopy, shroud lines, and acting forces.

3. Ejection Mechanisms

Ejecting the inversely reefed parachute is done using a COTS CD3 CO_2 ejection system. This device uses a much smaller amount of pyrogen than traditional ejection systems that do not utilize CO_2. The CD3 CO_2 ejection system, illustrated in Fig. 27, uses a 16 g CO_2 cartridge for this mission. The de-reefing event is achieved using a Tender Descender, also commercially available and commonly used by model rocketeers.[12] The reefing lines are attached to the recovery mount through the Tender Descender, which is also used as the mechanism for disreefing the inversely reefed parachute to allow for full parachute deployment.

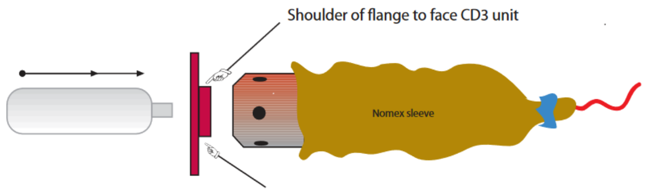


Figure 27. COTS CD3 CO_2 Ejection System Schematics.

Both of these devices were tested to validate functionality. Nose cone ejection was successful, as illustrated in an action-shot taken during experimental testing. The Tender Descender was validated during this test campaign, however it is not shown in the image. Furthermore, and while not clear from the image, this test was conducted entirely via the SRAD avionics system in Simple Latte that is described in the ensuing section of this Technical Report. While the field ejection tests were conducted using the SRAD avionics system. Other lab tests were conducted to validate the functionality of the redundant, COTS RC3 Dual Deployment Altimeter. Simulated resistances were used in place of E-matches for these tests. The device matched all printed specifications thus validated and deemed flight worthy.

Figure 28. Successful CO_2 Ejection Testing.

4. Recovery Mounting Considerations

The final criteria crucial to the recovery mount was housing the ejection system of the rocket. The CD3 Adventurer Kit Carbon Dioxide (CO_2) Ejection system was bought from Apogee Rockets for this purpose after much research. Since they did not provide dimensions, each component needed to be measured accurately with a Vernier Calliper and then modelled on SolidWorks. With regards to mounting the CO_2 system on the recovery mount, necessary components were provided by the supplier to attach the CO_2 system to any surface. Further analysis of the recovery bulkhead mount can be found in the Aerostructures section of this technical report.

The main shroud line needed to be able to swivel around the vertical axis, according to IREC/SAC rules. A design was proposed to use eye bolts and have two thrust-needle roller bearings on each side of the mount, to avoid undue friction from its contact with the mount. As such, axial thrust bearings are introduced in order to minimize the resistance to the torque exerted by the parachute on the shroud lines. Additionally, a lock nut was installed on the eyebolt to prevent the nut from screwing itself off while swivelling.

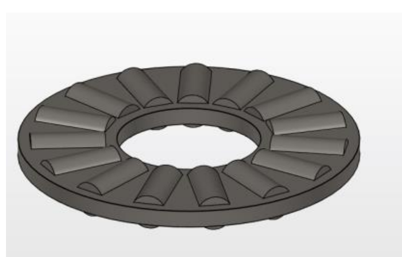


Figure 29. Axial thrust bearing.

D. Avionics

The avionics subsystem carried aboard Simple Latte has three major functionalities. The first is to actively control the air brakes during the coast. The second is to robustly actuate the recovery system to satisfy the dual rate descent requirement. The third is to transmit important data back to a ground station. To achieve these goals effectively, the avionics subsystem is composed of a SRAD constituent and a COTS constituent.

The SRAD device utilizes a Raspberry Pi computer running the Raspbian operating system. It also includes a nine degree of freedom IMU, a barometric altimeter, a GPS module as a part of its sensor suite. Additionally, it includes the vehicle's Xbee based radio communications system. Finally, it attaches to the servo that actuates the air brakes as well as the E-matches that deploy the different stages of the recovery scheme. The entire SRAD avionics device is powered from a 3S, 2200 mAh, lithium polymer battery via a 25 Watt DCDC buck converter. A schematic of the SRAD avionics can be seen in the appendices. The COTS device is much more simple. It consists of the RRC3 Dual Deployment Altimeter. The device is powered by a singly 9V battery. It connects only to the E-matches that deploy different stages of recovery. A circuit schematic of the COTS avionics system can be seen in the appendices. The routes from both the SRAD and COTS devices to the E-matches using in recovery are diode protected so that the two systems are electrically isolated, for all purposes and powers seen in Simple Latte. A Full list of devices and components used in the overall avionics subsystem is included in the appendices.

1. Actuation of the Recovery System

As described previously, the recovery system has two deployment devices: each using an E-match as the actuator. Both the SRAD and COTS devices are used to redundantly and non-similarly deploy the parachute. The RRC3 altimeter will be programmed to send the deployment signals at targeted apogee and at 1500 ft AGL. The SRAD device will attempt to intelligently trigger the E-matches based on altitude and state estimated vertical speed. Therefore, it can be said that the RRC3 altimeter is the main method of actuating the recovery system deployment and the SRAD device is the backup, and experimental, means. As mentioned previously, both systems have been validated via participation in ejection testing.

2. Active Control of Air Brakes using Model Predictive Control

The second major objection of the avionics subsystem is to actively control the air brakes for the duration of the coasting period in flight. In order to attempt a trajectory ending more precisely with respect to apogee, Simple Latte is designed to overshoot a little. This error is then be dynamically corrected through the use of the air brakes.

In order to achieve effective control over the air brakes and achieve the abstract goal of hitting the target altitude more precisely requires a adaptive, and non-linear, control schema: that is, one that can adapt with varying rocket parameters without having to retune the gains for each change. An emerging approach for vehicle trajectory control is the Model Predictive Control (MPC). In this schema, a real-time model of the rocket is simulated to predict the final apogee based on the current states (position, speed, orientation) of the rocket as estimated by the sensors. This prediction of apogee is then compared to the desired final altitude (10 000 ft AGL) and a figure for error is calculated. This error is then used in conjunction with the air brake drag model (as determined by CFD simulations) to determine the most optimal air brake deployment angle. Finally, a signal is generated to actuate the servo motor attached to the airbrakes. A diagrammatic visual of the control schema is provided below.

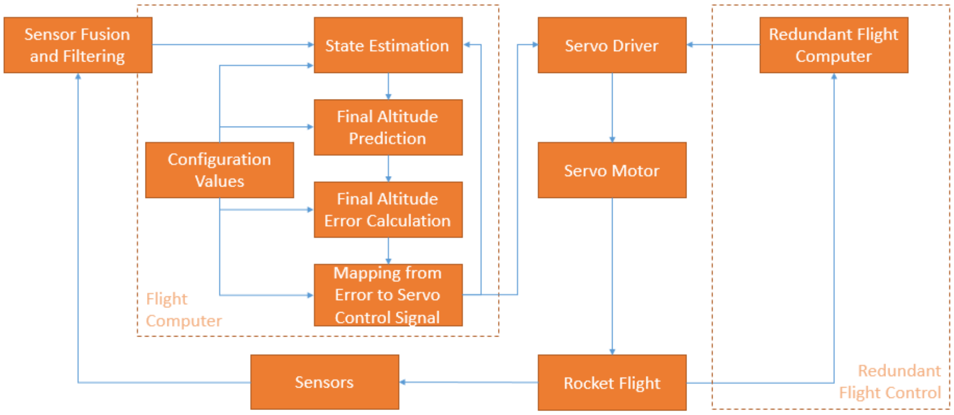


Figure 30. Diagrammatic visual of Avionics Control Schematic.

While the air brakes and the control thereof have been tested in simulations, there has been no true was to test without a flight (which is particularly difficult to schedule in Canada). Therefore, this is one aspect of the project that a lot of data is being collected during flight. In other words, Simple Latte's mission at IREC 2018 will partially be to experiment with this air brake and model predictive control schema for minor trajectory corrections.

E. Payload Subsystems

IREC/SAC 2018 requirements state that all rockets must carry a removable and non-essential, 8.8lbs payload with the form factory of three CubeSats (3U), which measure 10 cm by 10 cm by 30 cm when stacked. Due to time and resource constraints, a simulated payload is carried on Simple Latte and is illustrated in Fig. 31 below. The cylindrical payload occupies a volume if 3447.2 cm^3 in the body tube of Simple Latte; acknowledging that the payload does not adhere to the 3U configuration mandated by IREC/SAC competition regulations, the overall volume of the used payload occupies a volume greater than the required 3000 cm^3.

Figure 31. CAD rendering of payload and plywood used to hold the payload.

A better perspective of the payload assembly is illustrated in Fig. 32, showing how the payload rests on the aluminum blocks located in the payload section of Simple Latte. Plywood is used to hold the payload structure, a 2.5 inch diameter and 6.35 inch long steel stock used as the mass section At the bottom, the payload structure will be resting on machined aluminum blocks, which are resting on the aluminum struts and epoxied to the inner wall of the Body Tube. To ensure the payload is fastened during the mission, the payload uses a locking mechanism by rotating 30 degrees to fix axially and fastens a screw into a flange nut to be rotationally fixed.

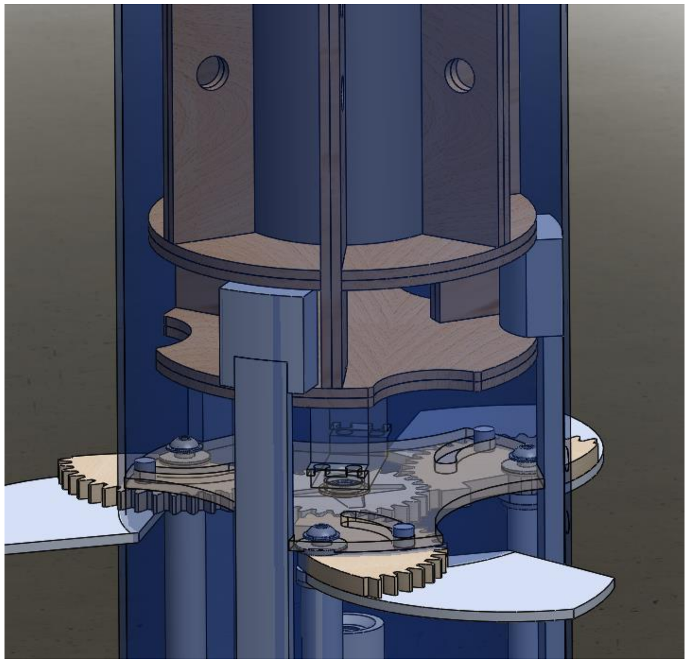


Figure 32. Transparent view of payload assembly, above the airbrake system.

In designing the payload, induced stresses were analyzed to determine the main failure load. It was determined that the main failure mode would be from the result of the axial load induced by the steel mass at the highest acceleration. Knowing that the largest acceleration value of 140 m/s^2 for Simple Latte occurs 1.25 seconds after motor ignition, a maximum force of 560 N will be applied where the steel payload would sit. Finite element analysis was employed to evaluate the feasibility, structural stability, and safety of the payload and also to determine the safety factor of the payload structure. The results are illustrated in Fig. 33. Three fixture points were established where the aluminum posts would be supporting the payload. Holes in the payload spars were added to optimize the design. As is evident from the FEA, there is very low stress on the upper portion of the spars so holes were added to the material to remove mass and unnecessary material. The coincidence centering rings and spares were also glued together in opposite fiber directions to reverse the anisotropic properties of wood. Knowing that the safety factor can be determined by examining the ratio of the maximum allowable stress to the maximum stress applied from acceleration, a safety factor of 3.145 was determined.

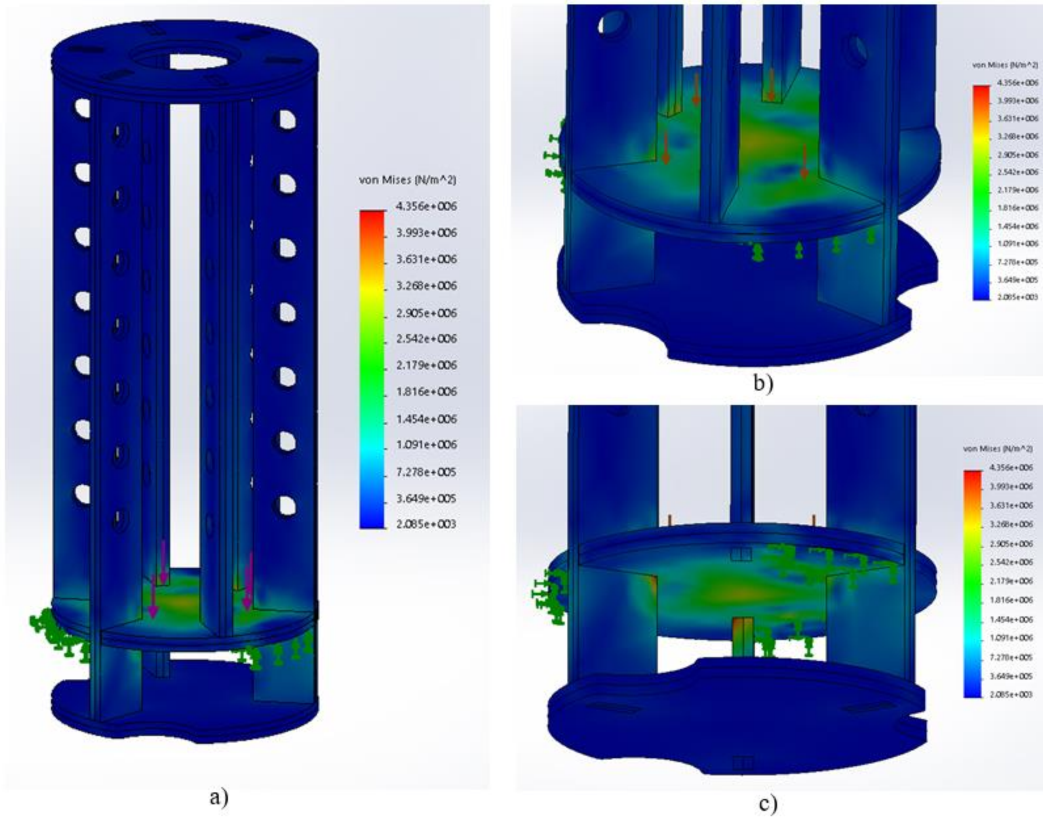


Figure 33. FEA Results of Simple Latte Payload Structure.

F. Aerodynamics and Flight Performance Simulations

Aerodynamic simulations were completed with the assistance of an OpenRocket model with Solidworks CAD variables for structures and properties, such as material type and density, imported and replicated into the OpenRocket design. A high-level internal layout of Simple Latte components and subsystems is illustrated in Fig. 34. From tip to tail, the internal layout starts with the nose cone, followed by the recovery subsystem, avionics bay, payload, and finally the motor mount. This illustration provides a high-level overview of the geometry used for simulations in OpenRocket.

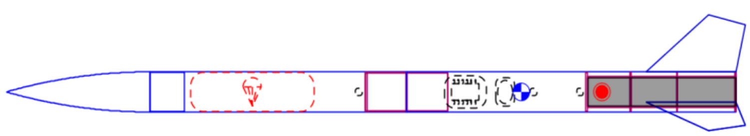


Figure 34. High-level internal layout of simulated OpenRocket Geometry for Simple Latte.

1. Basic Flight Characteristics, Expected Conditions

Key dimensions and measurements for Simple Latte are summarized in Table 8. These are important as they allow for accurate OpenRocket simulations to be performed to evaluate all flight characteristics of the system.

Table 10. Important Simple Latte dimensions and measurements.

Dimension	Value
Diameter	14 cm
Length	274 cm
Full Mass	20.632 kg
Empty Mass	3.992 kg (8.8 lbs)
Empty Mass	13.029 kg

All aerodynamic flight characteristics are computed for the duration of a flight at expected conditions, identified in Table 9. Expected conditions were identified based on historical meteorological data obtained for the city of Truth or Consequences, New Mexico.

Table 11. Expected Simulation Conditions for Simple Latte.

Condition	Value
Launch Angle	6-degrees
Wind Speed	10 km/h
Temperature	40 ºC
Turbulence	10% (Medium - High)

2. Center of Gravity and Pressure

The center of gravity, measured as a distance from the tip of the nose cone, is plotted as a function of time in Fig. 35. Vertical lines indicating the time of motor ignition, clearance from the launch rail, and motor burnout are also indicated to identify the center of gravity at the various time-stages of the system.

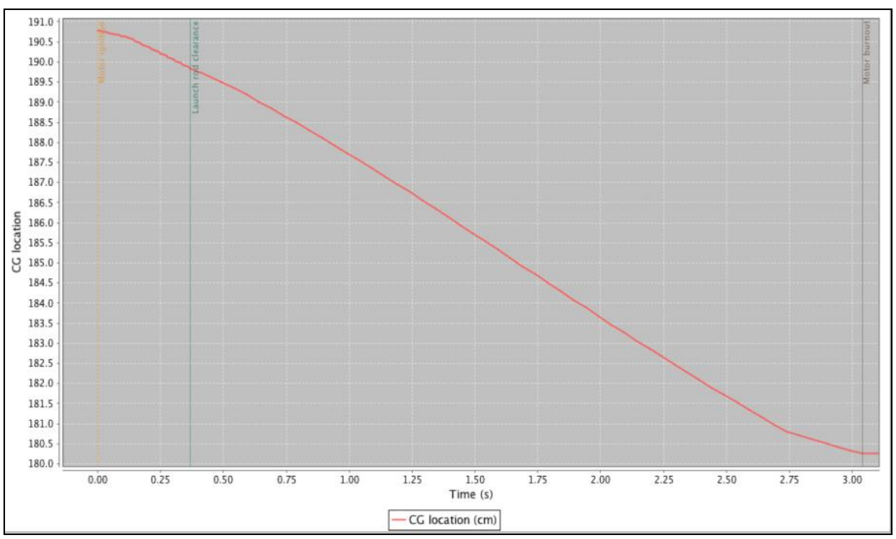


Figure 35. Simple Latte center of gravity during flight operations.

The center of pressure, measured as a distance from the tip of the nose cone, is plotted as a function of time in Fig. 36. Vertical lines indicating the time of ignition and clearance from the launch rail, motor burnout, and apogee and recovery deployment are also indicated to identify the center of gravity at the various time-stages of the system.

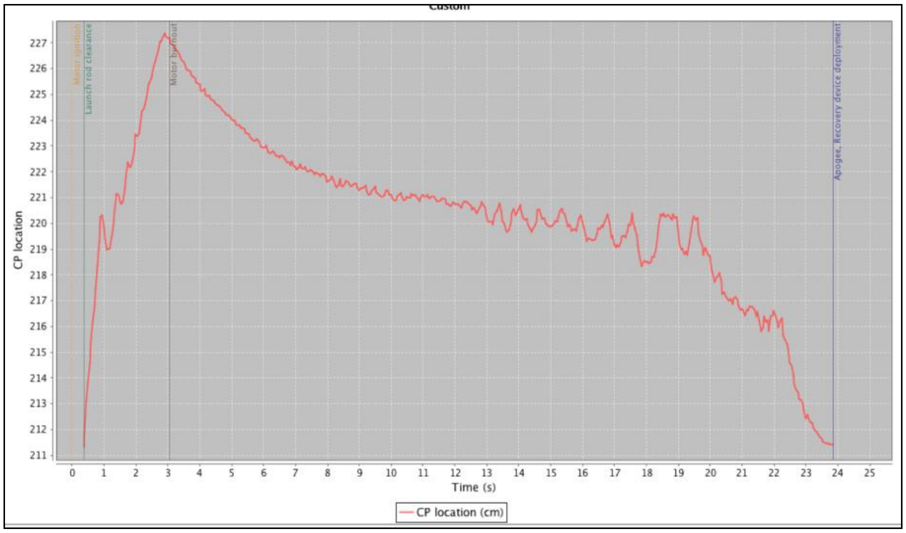


Figure 36. Simple Latte center of pressure during flight operations.

3. Static Margin

The static margin, or stability margin, is measured as the number of body calibers the center of pressure is away from the center of gravity. Doing to characterizes the stability condition of the rocket. Typically, a static margin between values of 1 to 2.5 is considered stable. Fig. 37 illustrates a plot of the stability margin of Simple Latte, from launch rail departure until flight apogee. The stability margin is at 1.55 at the time of launch rod clearance and reaches 2.22 at the time of apogee, adhering to IREC/SAC competition requirements. The increasing static margin is characteristic of a normal flight pattern, as both the velocity and the stabilizing aerodynamic forces decrease while approaching apogee. A higher stability margin at lower speeds can be obtained using strategic air brake positioning in Simple Latte by shifting the center of pressure rearward.

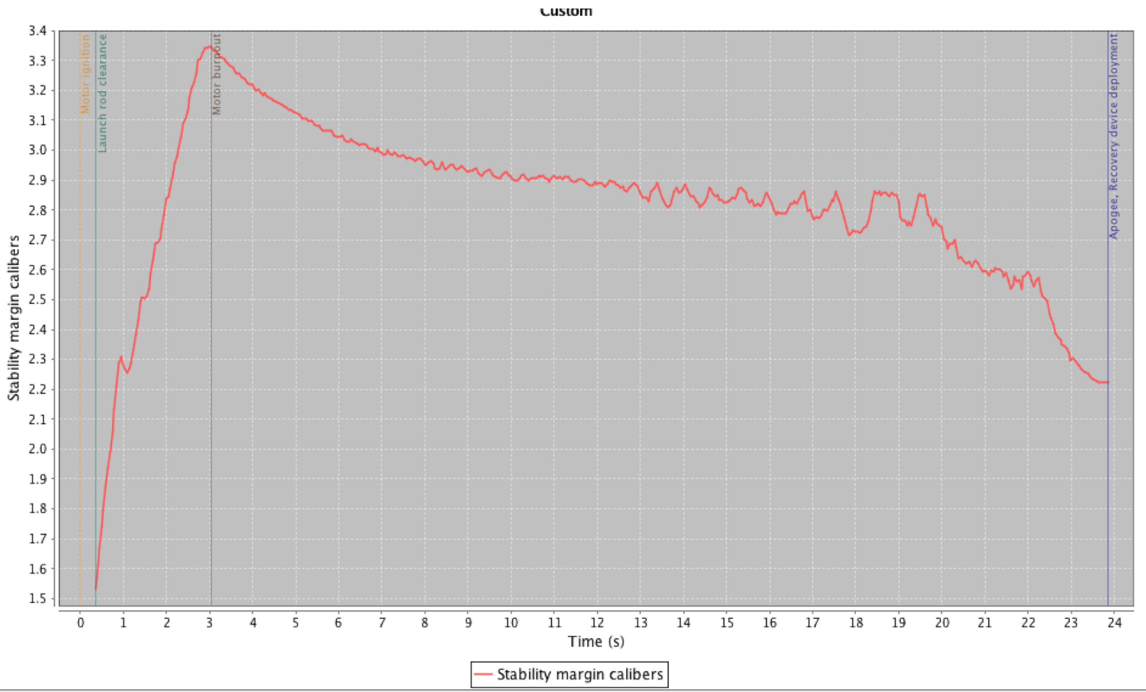


Figure 37. Static Margin of Simple Latte during the various mission phases.

4. Vertical and Total Velocity

Total velocity is the combined velocity of all components. Comparing it to the vertical velocity provides an estimate of the horizontal velocity component. The optimized goal is to have the majority of the vertical velocity component to contribute to the total velocity. This, by consequence, will limit the horizontal displacement of Simple Latte during its mission. Fig. 38 illustrates a plot of the vertical velocity and total velocity from initial launch to steady-state descent.

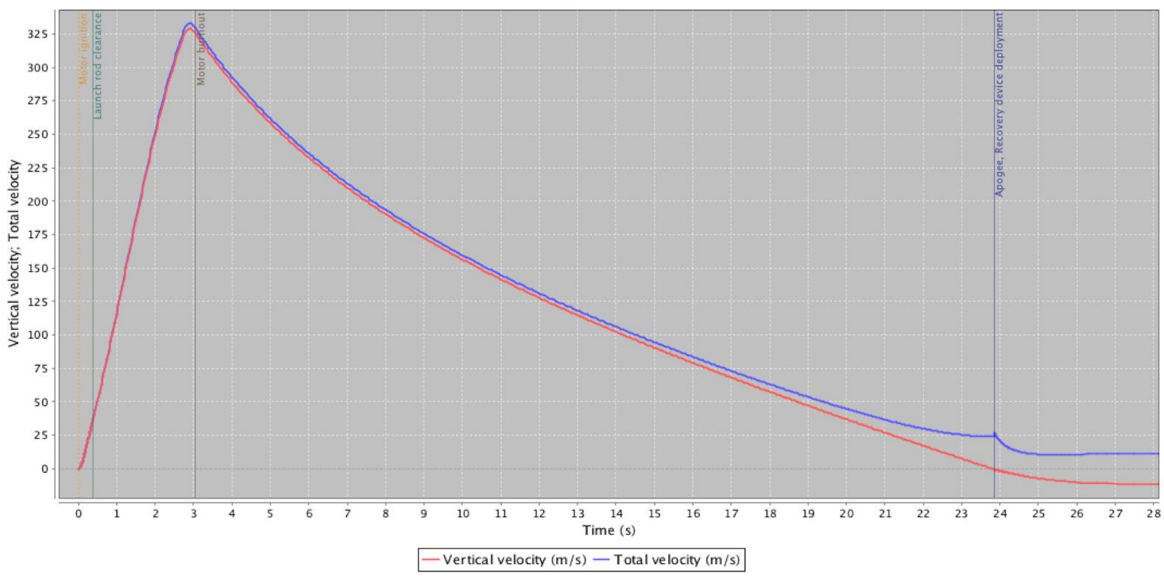


Figure 38. Vertical and Total Velocity Profiles of Simple Latte from initial launch to steady-state descent.

5. Flight Performance Envelope

Flight characteristics of the performance envelope when operating outside expected conditions are also examined in the ensuing sub-section of this report to ensure safety and functionality of Simple Latte when encountered with different or adverse weather conditions.

5.1 Launch Angle Impact

Table 12. Impact of Launch Angle on Simple Latte flight performance characteristics.

Launch Angle	Velocity off Rod (540 cm)	Max Air Speed	Apogee (m)	Velocity at Parachute Deployment (m/s)	Max Acceleration (m/s^2)
70	35.7 m/s	Mach 0.99	2720	67.2	141
77.5	35.6 m/s	Mach 0.99	2973	45.5	141
80	35.6 m/s	Mach 0.99	3045	36.9	140
85	35.5 m/s	Mach 0.99	3137	20.8	140

III. Mission Concept of Operations Overview

A. Description & Definitions

The major systems involved during launch operations as the following: The Launch Base Station (LBS), the Rocket Propulsion Element (RPE), the Rocket Onboard Avionics (ROA), Rocket Recovery System (RRS), and the

Rocket Air Brake System (RABS). A brief description of each is included here. The LBS consists of a flight monitor as well as all required ground communication equipment. The LBS is responsible for communicating with the rocket during all stages of operation and relaying essential information to the ground crew. In order to account for the potentially long wait to launch window, the rocket can be put into a sleep state to conserve energy via the LBS. The RPE consists of the rocket motor (M-2505) and its supporting infrastructure as well as the ignition method (E-match). Both these components are commercially available and the standard procedures for their operation will be followed. The RABS consists of the inline, custom air brake assembly, and a servo motor. The servo motor is commanded by the ROA. The primary purpose of the RABS is to dynamically lower the final altitude of the rocket such that a more precise target (10000ft) can be achieved. The ROA consists of a custom flight computer, a redundant recovery control computer, onboard communications equipment, numerous sensors and the energy storage system (LiPo battery). The ROA system is responsible for collecting and logging data, performing state estimation to accurately keep track of rocket trajectories and commanding actions such as deploying air brakes and the recovery system. The RRS consists of the parachute as well as the corresponding ejection and release mechanisms. It is responsible for the effective deployment of the parachute in the reefed configuration as well as de-reefing when commanded by the ROA. The parachute in the reefed configuration is responsible for slowing descent to a brisk 25 m/s. After de-reefing, the parachute is responsible for slowing descent to a comfortable 6m/s.

B. Mission Phases

The following tables define each phase of Simple Latte's mission. The initial conditions present prior to events defined in the table are as follows: vehicle is assembled and installed vertically on pad.

1. System Prime & Checks

Defining Mission Event: Initial power up of LBS and ROA

LBS	RPE	ROA	RABS	RRS
Powered	*Idle*	*Powered*	*Powered*	*Idle*
Flight Monitor: *Verify RF connectivity* **Flight Monitor**: *Command self check reports from ROA*	**Motor:** *Not burning* **E-Match:** *Safed*	**Flight Computer**: *Perform initial checks as commanded* **Sensors:** *Idle*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

2. System Idle

Defining Mission Event: Sleep command given by LBS

LBS	RPE	ROA	RABS	RRS
Powered	*Idle*	*Idle*	*Idle*	*Idle*
Flight Monitor: *Idle*	**Motor:** *Not burning* **E-Match:** *Safed*	**Flight Computer**: *Low power mode* **Sensors:** *Idle*	**Actuator:** *Idle* **Air Brakes:** *Stowed*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

3. Wake up for Ignition

Defining Mission Event: Wake command given by LBS (when go-ahead is given)

LBS	RPE	ROA	RABS	RRS
Active	*Armed*	*Active*	*Stowed*	*Stowed*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Not burning* **E-Match:** *Armed*	**Flight Computer**: *Powered* **Sensors:** *Polling*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

4. Ignition

Defining Mission Event: Power is sent to E-Match for activation

LBS	RPE	ROA	RABS	RRS
Active	*Active*	*Active*	*Powered*	*Idle*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Transient to Burning* **E-Match:** *Activated*	**Flight Computer**: *Performing all functions* **Sensors:** *Polling*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

5. Liftoff

Defining Mission Event: Rocket clears launch rail

LBS	RPE	ROA	RABS	RRS
Active	*Active*	*Active*	*Powered*	*Idle*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Burning* **E-Match:** *Depleted*	**Flight Computer**: *Performing all functions* **Sensors:** *Polling*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

6. Burnout

Defining Mission Event: Motor propellants are depleted

LBS	RPE	ROA	RABS	RRS
Active	*Depleted*	*Active*	*Active*	*Stowed*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Depleted* **E-Match:** *Depleted*	**Flight Computer**: *Performing all functions* **Sensors:** *Polling*	**Actuator:** *Active* **Air Brakes:** *Dynamically deployed via controller discretion*	**Parachute:** *Stowed* **Stage 1 Ejection**: *Installed* **Stage 2 Ejection**: *Installed*

7. Apogee

Defining Mission Event: Motor propellants are depleted

LBS	RPE	ROA	RABS	RRS
Active	*Depleted*	*Active*	*Powered*	*Active*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Depleted* **E-Match:** *Depleted*	**Flight Computer**: *Performing all functions* **Sensors:** *Polling*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Deployed in reefed configuration* **Stage 1 Ejection**: *Activated* **Stage 2 Ejection**: *Installed*

8. 1500 ft Crossing

Defining Mission Event: Motor propellants are depleted

LBS	RPE	ROA	RABS	RRS
Active	*Depleted*	*Active*	*Powered*	*Active*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Depleted* **E-Match:** *Depleted*	**Flight Computer**: *Performing all functions* **Sensors:** *Polling*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Deployed in full configuration* **Stage 1 Ejection**: *Depleted* **Stage 2 Ejection**: *Activated*

9. Landing

<u>Defining Mission Event:</u> Motor propellants are depleted

LBS	RPE	ROA	RABS	RRS
Active	*Depleted*	*Active*	*Powered*	*Idle*
Flight Monitor: *Receiving Data from vehicle*	**Motor:** *Depleted* **E-Match:** *Depleted*	**Flight Computer**: *Sending position data to LBS* **Sensors:** *Only polling GPS*	**Actuator:** *Powered* **Air Brakes:** *Stowed*	**Parachute:** *Deployed* **Stage 1 Ejection**: *Depleted* **Stage 2 Ejection**: *Depleted*

IV. Conclusions and Lessons Learned

Any team in its infancy faces many challenges. Over the past two years of operation, these challenges ranged from administrative and managerial to theoretical and practical. For many challenges, we do not yet have an answer for; the ones that we were able to overcome have resulted in the work presented in this report, and by induction has allowed for the team's participation in IREC 2018. The team will continue to follow the ideologies of experimentation to grow into different capabilities.

A. Technical Lessons

Back in May 2015, the team was formed with a mission to design and fly a sounding rocket with a hybrid rocket engine for IREC 2018. While the team is not able to present the hybrid engine this year, significant progress has been made on that project; including a functional prototype as well as an untested flight configuration. Many of the technical lessons that are presented here are a result of the work the team has put into the hybrid engine project. These lessons are also partially creditable for the quick development time of our competition rocket as presented in this report.

If any one statement can be made about the technical aspects the team has painfully learnt, it is that rigorous testing and validation efforts are the most important aspects of project realization. Designs will fail due to assumptions, fabrication errors can, and definitely will, affect results and the entire success or failure of a project cannot be theoretically analyzed. It is only through meticulous testing that deviations from desired results can be found and corrected. This lesson has led to many changes in the team's operations. A fair amount of thought is now put into how the component or system can be tested with high fidelity is included in all major design reviews. Additionally, frequent physical validation has also become a major goal for the team. This leads to an increase in data feedback in order to iteratively improve designs or concepts.

While testing and validation are considered the only true means of determining the functionality of any aspect of development, there are many other optimizations that the team has made to its design and high-level systems engineering efforts. Concepts such as DFM (Designed for Manufacturing) and agile development cycles are now implemented and have helped the team improve not only quality of technical work but also helped the team to reach milestones and deadlines on or closer to the initial schedule.

B. Non-technical Lessons

Team management and administration are incredibly difficult. These non-technical challenges can sometimes be downplayed due to the magnitude of technical challenges (which are many times much more interesting to engineering students) that the team faces. The team has slowly recognised these issues and reduced the risk of falling into the same situations again. This has mainly been done by better communication to all team members and enforcing certain organizational schemes be maintained by everyone. While the team is considered to be quite casual, all members are understanding of the fact that sometimes difficult decisions must be made. This understanding has flourished trust and even improved the means of feedback that the administrative members of the team are open to receiving.

C. Strategies for Knowledge Transfer

The efficient flow of knowledge has always been a focus for the team. There are certainly times where the documentation relaying information of some aspects of development may slip. However, in general the team has done a great job passing along knowledge to new members as well as potential recruits, either through mentorship by a veteran member or via documentation. The team will continue to improve documentation and teaching material as more events and projects are targeted.

Acknowledgements

The accomplishments of uOSTAR are possible only through the continued support of Dr. Bertrand Jodoin (Department of Mechanical Engineering, University of Ottawa), the Centre for Entrepreneurship and Engineering Design (CEED), industry sponsors, Dr. François Robitaille (Associate Professor, Department of Mechanical Engineering, University of Ottawa), Dr. Eric Lanteigne (Associate Professor, Department of Mechanical Engineering, University of Ottawa), Cat Czyrnyj (Ph.D. Candidate, University of Ottawa), other kind professors and academic personnel, skilled technicians and machinists, and all current and previous members of the team.

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Appendix

Appendix A. System Weights, Measurements, and Performance Data

Spaceport America Cup

Intercollegiate Rocket Engineering Competition

Entry Form & Progress Update

Color Key — SRAD = Student Researched and Designed — v18.1

Must be completed accurately at all time. These fields mostly pertain to team identifying information and the highest-level technical information.

Should always be completed "to the team's best knowledge", but is expected to vary with increasing accuracy / fidelity throughout the project.

May not be known until later in the project but should be completed ASAP, and must be completed accurately in the final progress report.

Date Submitted: 5/25/2018

Team ID: 55 — * You will receive your Team ID after you submit your 1st project entry form.

Country: Canada

State or Province: Ontario

State or Province is for US and Canada

Team Information

Rocket/Project Name:	Simple Latte
Student Organization Name	University of Ottawa Student Team of Aeronautics & Rocketry
College or University Name:	University of Ottawa Student Team of Aeronautics & Rocketry
Preferred Informal Name:	uOSTAR
Organization Type:	Club/Group
Project Start Date	6/1/2016 — *Projects are not limited on how many years they take*
Category:	10k – COTS – All Propulsion Types

Member	Name	Email	Phone
Student Lead	Manit Ginoya	mgino015@uottawa.ca	6479876706
Alt. Student Lead	Nikhil Peri	nperi104@uottawa.ca	-
Faculty Advisor	Jodoin Bertrand	Bertrand.Jodoin@uottawa.ca	-
Alt. Faculty Adviser	-	-	-

For Mailing Awards:

Payable To:	University of Ottawa Rocketry Team
Address Line 1:	161 LOUIS PASTEUR PVT
Address Line 2:	Ottawa
Address Line 3:	ON
Address Line 4:	K1N 6N5
Address Line 5:	Canada

Demographic Data

This is all members working with your project including those not attending the event. This will help ESRA and Spaceport America promote the event and get more sponsorships and grants to help the teams and improve the event.

Number of team members

High School	0	Male	12
Undergrad	15	Female	3
Masters	0	Veterans	0
PhD	0	NAR or Tripoli	0

Just a reminder the you are not required to have a NAR, Tripoli member on your team. If your country has an equivelant organization to NAR or Tripoli, you can cant them in the NAR or Tripoli box. CAR from Canada is an example.

STEM Outreach Events

We participate in all University of Ottawa engineering events open to the students as well as some other local conferences. We are looking to attend national and international events in the coming year.

Rocket Information

Overall rocket parameters:

	Measurement	Additional Comments (Optional)
Airframe Length (inches):	107.9	
Airframe Diameter (inches):	5.5	
Fin-span (inches):	18	
Vehicle weight (pounds):	28.72	
Propellent weight (pounds):	7.36	
Payload weight (pounds):	8.8	
Liftoff weight (pounds):	44.88	
Number of stages:	1	
Strap-on Booster Cluster:	No	
Propulsion Type:	Solid	
Propulsion Manufacturer:	Commercial	
Kinetic Energy Dart:	No	

Propulsion Systems: (Stage: Manufacturer, Motor, Letter Class, Total Impulse)

1st Stage: Cesaroni Pro 98, 7450 M2505-P, M Class, 7450 Ns

Total Impulse of all Motors: 7450 (Ns)

Predicted Flight Data and Analysis

The following stats should be calculated using rocket trajectory software or by hand.

Pro Tip: Reference the Barrowman Equations, know what they are, and know how to use them.

	Measurement	Additional Comments (Optional)
Launch Rail:	ESRA Provide Rail	
Rail Length (feet):	17	
Liftoff Thrust-Weight Ratio:	3.6	
Launch Rail Departure Velocity (feet/second):	116.47	
Minimum Static Margin During Boost:	1.55	*Between rail departure and burnout
Maximum Acceleration (G):	14.3	
Maximum Velocity (feet/second):		
Target Apogee (feet AGL):	10K	
Predicted Apogee (feet AGL):	10292	

Payload Information

Payload Description:

Due to time contraints, the payload will not be functional. The payload will still be attached to the main rocket body for the entire duration of the flight and will be at least 8.8 lbs. If some time remains before the competition final report deadline and the time we are done all other components and integration, then some payload functionality may be implemented.

Recovery Information

The recovery system for our project will include a reefed parachute. The changing shape of the parachute will allow for different drag coefficients, eventually resulting in different descent speeds (these parachute configurations will be determined experimentally via windtunnel testing). The initial deployment of the parachute (into the reefed stage) will be completed via the COTS CD3 CO2 system. At 1500 ft during descent the reefing lines will be detached by activating the COTS Tender Descender Level 2 system. The control of these events will occur primarily through a SRAD avionics stack. The backup system to ensure the release of the recovery stages will be the COTS RRC3 altimeter and dual deployment system. Some tests have been completed and more are planned for the near future when the SRAD parachute is complete.

Planned Tests

* Please keep brief

Date	Type	Description	Status	Comments
12/4/17	Ground	Parachute Lines - tensile strength test	Successful	erified the listed tensile strength for shroud lin
12/4/17	Ground	Internal Structures - Breakpoint Test	Successful	material properties of multiple components of
1/10/18	Ground	Initial Communications Test	Minor Issues	Some software issues with GPS sensor
2/10/18	Ground	SRAD Electrical Components Test	Successful	tom avionics hardware is functioning as expec
3/25/18	Ground	Second Communications Test	Successful	Test all communication functionality
4/8/18	Ground	SRAD Aerobrake Test	Successful	Test aerobrake functionality
4/10/18	Ground	Electrical Systems Integration Test	Successful	ctionality in flight configuration (i.e on battery
4/10/18	Ground	Parachute Reefing Test	Successful	nctionality and experimentally determine reef
4/23/18	Ground	Parachute Deployment Test	Successful	Test deployment sequence functionality
4/27/18	Ground	All Systems Integration Test	Minor Issues	onents and communications after rocket is ful

Any other pertinent information:

Due to regulations in Canada, we will not be able to flight test before the competition and therefore we will be proving out flightworthyness but performing several rounds of testing (some of which has yet to be determined). Please let us know if there is anything in particular that would aid us in our validation.

End of File

Appendix B. Hazard/Risk Assessment Matrix

Team 55	*<Rocket Name>*	*Date: 5/01/2018*		
Hazard	**Possible Causes**	**Risk of Mishap Rational**	**Mitigation Approach**	**Risk of Injury after Mitigation**
Uncontrolled thermal runaway of Solid Rocket Motor including potential flying debris	- Fractures in propellant grain - Nozzle obstruction - Motor casing manufacturing defects	Low: COTS component, verified by experienced professionals	- Visual inspection of motor casing - Visual inspection of nozzle - Visual inspection of propellant grain - Only essential crew during operations	Low
Uncontrolled Rocket Trajectory with potential impact with personal or Equipment	- Fin Failure - Nozzle manufacturing defects - Blue Tube structural failure - Air brake mechanical stall - Nose cone structural failure	Medium: Student built aerostructures with limited testing opportunities	- Visually inspect fins for manufacturing defects likely to affect aerodynamics - Visually inspect nozzle and nose cone - Visually inspect blue tube (especially near cuts) - Enforce safe distance and barriers during launch operations	Low to medium (due to consequences being potentially catastrophic)
Failure to actuate and deploy any outlined stage of recovery system. Rocket undergoes terminal velocity descent	- Failure of electronics - Severing of wires - Energy Storage System failure (battery) - Parachute tethers get obstructed during ejection - Parachute material failure	Medium: Student built parachute with limited testing of inverted reefing concept.	- Inspect parachute for tears or disassembly of stitches - Inspect all COTS components for signs of fatigue - Inspect parachute chamber and recovery mount for any potential obstructions - Implement all wiring and redundancy guidelines (including a fully separated recovery deployment system)	Low to Medium (due to consequences being potentially catastrophic)
Loss of vehicle due to communications failures	- SRAD avionics failure (software or hardware) - Severing or wires	Medium: SRAD avionics dictate the transmission of data to ground station	- Implement all wiring guidelines - Perform communication checks prior to launch	Low

	- Failure or Energy Storage System			
Rocket does not ignite when commanded, but potentially when approached by crew for troubleshooting	- E-match fell out of position - Faulty E-match - Main power to ignition system not provided	Low: SRM and ignitor are all COTS components	- Visually inspect vehicle for any signs of smoke or ignition - Ensure main power to ignition system is turned OFF - limited crew approach vehicle with appropriate PPE and barriers	Low
Vehicle experiences loss of mechanical support on pad, prior to launch	- Rail lugs fail structurally - Launch rail fails structurally	Medium: SRAD launch lugs	- Inspect rail and lugs prior to installation of vehicle onto pad - Watch for signs of rail or lug failure after vehicle installation	Low

Appendix C. Assembly, Pre-flight and Launch Checklists

The checklists provided under this section have no predefined sequence. Some must happen before others, but others can be done anytime. Therefore, the lists are written sequentially in the order that is expected to occur but the true order will be determined during launch. The 'Step' column is to record the actual sequence of events during mission. Additionally, it is implied that during all operations, the safety procedures and inspections are performed. Furthermore, it is also implied that media equipment is setup as desired.

Assumptions: Motor mount and fins are already installed. Air Brakes are already installed. Recovery Mount is not installed onto rocket outer body tubes (but has the eyebolt installed onto it).

Assembly		
Step	**Description**	**Notes and Completion Sign Off**
	Install payload into assembled bottom section	
	Prepare and install CD3 CO_2 system onto the recovery mount	
	Wire the E-matches for the recovery system	
	Attach parachute reefing line to Tender Descender	
	Prepare and install Tender Descender onto recovery mount	
	Slide recovery mount into top tube section.	
	Route and mate E-match wiring to both SRAD and COTS avionics systems.	
	Install both SRAD and COTS avionics systems	
	Pack and install parachute	
	Install nose cone	
	Mate top and bottom body sections by fastening recovery mount into place	

Assumptions: Rocket is fully assembled in flight configuration with the exception of the Solid Rocket Motor and Ignition system

Pre-Flight		
Step	**Description**	**Notes and Completion Sign Off**
	Install Rocket onto Pad	
	Power the vehicle's avionics	
	Perform pre-flight telemetry test	
	Perform manual actuation test of air brakes	
	Perform pre-flight sensor tests	
	Perform pre-flight software tests	
	Install Solid Rocket Motor and ignition system as instructed by Tripoli certified member (likely just prior to launch)	

Launch		
Step	**Description**	**Notes and Completion Sign Off**
	Ensure all systems Powered and in appropriate state for launch	
	Countdown	
	Send ignition signal via provided COTS ignition control box as instructed by the Tripoli certified member	

Recovery		
Step	**Description**	**Notes and Completion Sign Off**
	Send command to ask for GPS data	
	Locate rocket on a map	
	Travel to landing site when cleared for recovery by officials	
	De-power all onboard systems	
	Load rocket into appropriate carrying structure back to main camp	
	Disassemble rocket for analysis and data collection	

Appendix D. Project Test Reports

The following are excerpts from verbose test reports that were generated to document the results of testing efforts. For the sake of brevity, some non-essential tests are omitted.

1. Recovery Ejection and Communications Test

Test Item: Analog parachute, shroud lines, COTS CO_2 ejection system, analog rocket body, recovery mounting plate

Test Objectives:

1 - Demonstrate telemetry command over Xbee radios
2 - Demonstrate ability to puncture CO_2 canister using COTS system
3 - Demonstrate proper separation of nose cone and ejection of analog parachute
4 - Collect media on tests as a means of proof of completion and data collection

Success Criteria

1 - Completing all test objectives
2 - Sustaining no significant damage to the test item

Test Description

The test will consist of sending a control signal (via telemetry) to test item electronics. The electronics onboard the test item will then send the appropriate signal to the COTS CO_2 ejection system which will result in ignition of a small gunpowder charge. After ignition, the COTS CO_2 ejection system will release pressurized CO_2 into the recovery chamber which will result in the separation of the nose cone and ejection of the analog parachute.

Test Execution - Radio Communication			
Step	**Description**	**Test Dir. Initials**	**ANSWER [YES, NO, NA, Value, etc.)**
1	Send onboard electronics a test signal and record response	MG	SUCCESS
-	If no response is received or response is not as expected, do not continue with test	MG	-
2	If response is received as expected, the ejection test can be executed	MG	SUCCESS

Test Execution - Ejection			
Step	**Description**	**Test Dir. Initials**	**ANSWER [YES, NO, NA, Value, etc.)**
1	Send onboard electronics ejection signal	MG	SUCCESS
2	Record approximate time (if discernible) between signal being sent and ejection	MG	SUCCESS [less than 1 second]
4	Send signal for De-reefing event	MG	SUCCESS [Proper release as observed]
-	If no ejection occurs after signal is sent, wait at least 5 minutes before approaching	MG	-
-	In the case of emergency approach - two persons should approach. All appropriate PPE must be worn and a fire extinguisher must be in hand.	MG	-
3	Note qualitative irregularities (if any)	MG	Marginal loss of pressure in parachute chamber due to unpopulated fastener holes

Test Outcome: SUCCESS, with note to ensure all fastener holes are populated during mission

2. Recovery Parachute Drag Characterization

Test Item: parachute

Test Objectives

1 - Determine configuration of reefing line and main line lengths to achieve proper drag
2 - Determine Cd of parachute in reefed and fully deployed configurations
3 - Demonstrate overall functionality of the parachute

Success Criteria

1 - Completing all test objectives
2 - Sustaining no significant damage to the test item

Test Description

The test will be performed in multiple stages.

The first stage is to measure the drag in fully deployed configuration. By driving at 35 km/h (~9m/s), the drag (for below 1500ft descent) can be determined via measuring force applied through a load cell. If the drag is not the expected amount, the length of the fully deployed lines can be varied to achieve the proper drag amount.

The second stage is to measure the drag in reefed configuration. By driving at 90 k/m (25m/s), the drag (for above 1500ft descent) can be determined via measuring force applied through a load cell. If the drag is not the expected amount, the length of the reefed lines can be varied to achieve the proper drag amount.

In the above-mentioned way, the correct lengths of the parachute can be determined. Additionally, the overall functionality of the parachute can be demonstrated.

Test Execution - Fully Deployed Drag Characterization			
Step	**Description**	**Test Dir. Initials**	**ANSWER [YES, NO, NA, Value, etc.)**
1	Disconnect reefing lines from test rig (tie them so they are not dragging on the ground)	MG	SUCCESS
2	Start recording force from load cell	MG	SUCCESS
3	Get truck up to 9 m/s (35 km/h). Record time when truck has reached that speed	MG	SUCCESS
4	Deploy parachute and sustain truck speed for about 10s	MG	SUCCESS
5	Record average drag during 10s and compare with desired drag - if not desirable, change main line length and repeat test	MG	SUCCESS [Values ranging from 180 N to 230 N] [Wind was 5 mph north east and contributed to some additional drag]

Test Execution - Reefed Drag Characterization			
Step	**Description**	**Test Dir. Initials**	**ANSWER [YES, NO, NA, Value, etc.)**
1	Connect reefing lines from test rig	MG	Configured so that the reefing lines are the same length as main lines
2	Start recording force from load cell	MG	DONE
3	Get truck up to 25 m/s (90 km/h). Record time when truck has reached that speed	MG	SUCCESS
4	Deploy parachute and sustain truck speed for about 10s	MG	SUCCESS

5	Record average drag during 10s and compare with desired drag - if not desirable, change reefing line length and repeat test	MG	SUCCESS [Values ranging from 190 N to 240 N] [Some mild oscillations were noticed, a marginal change in vent hole and rings should attenuate these]

Test Outcome: SUCCESS, with note to marginally increase venting interfaces on parachute. Length of lines was determined to be optimized at 3.5 m in length.

4. SRAD Avionics Software Test

Test Item: SRAD avionics system

Test Objectives

1 - Observe the proper polling and logging of sensor values
2 - Observe the proper transitioning of all programmed states given simulated inputs

Success Criteria

1 - Completing all test objectives
2 - Sustaining no significant damage to the test item

Test Description

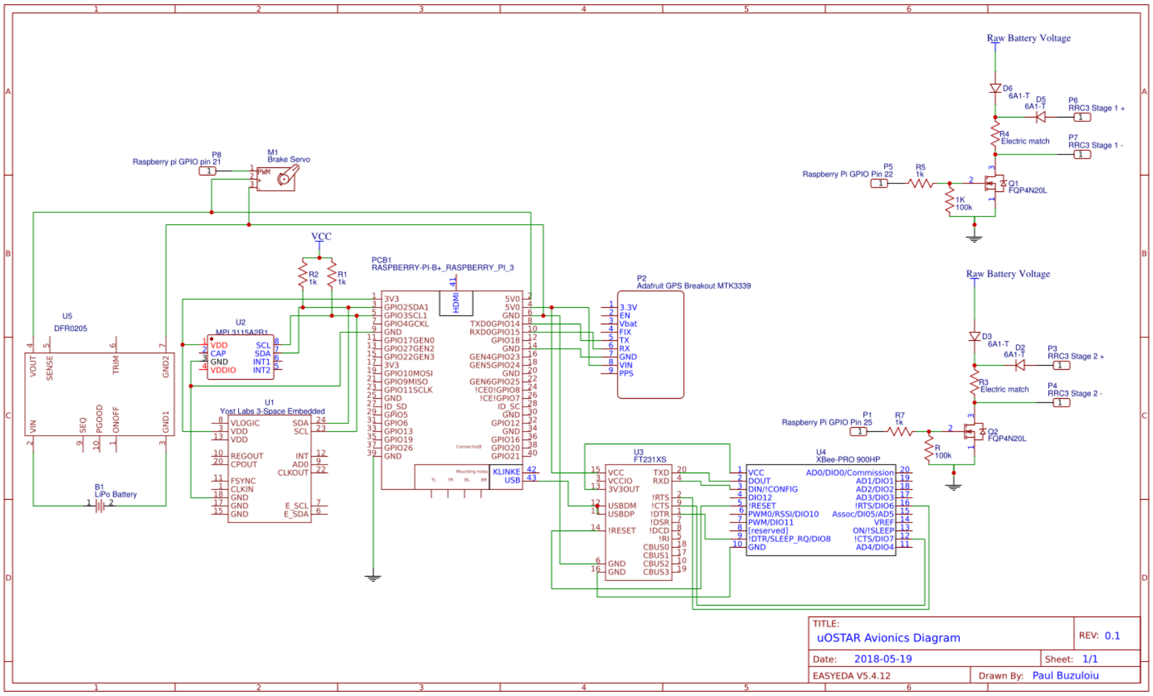
The purpose of this test is to primarily validate that the software behaves as desired. Additionally, it is important for the airbrake control schema to have accurate state estimation. Therefore, the sensor values were measured and examined. This aided in validation of filtering and digital signal processing techniques.

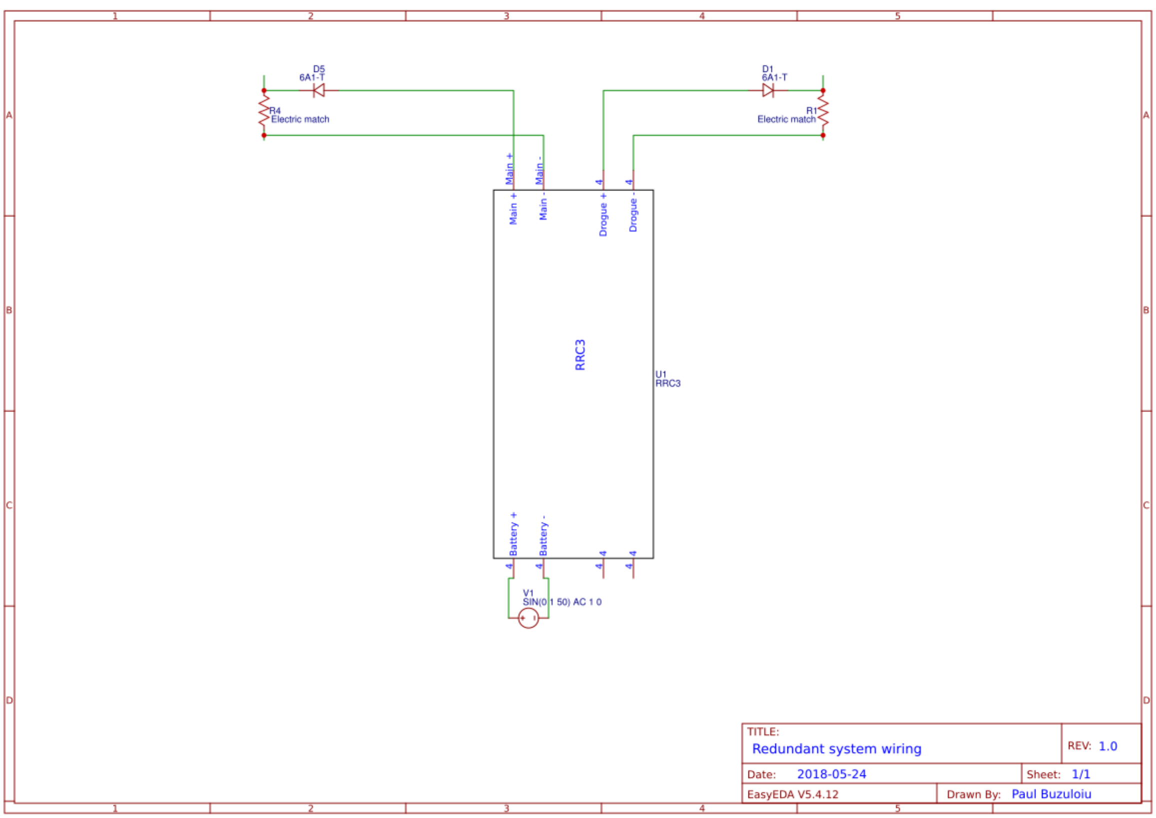
Test Execution -			
Step	**Description**	**Test Dir. Initials**	**ANSWER [YES, NO, NA, Value, etc.)**
4	Disconnect all sensors and attached flight computer to simulated sensors	PB	DONE
5	Run the simulation suite and validate all state transitions	PB	SUCCESS [All transitions behaved as expected]
1	Re-configure system in flight configuration	PB	DONE
2	Power on avionics and validate initialization sequence	PB	SUCCESS [System enters pre-launch state]
3	Observe values from sensors and confirm accuracy	PB	SUCCESS [GPS doesn’t work indoors]

Test Outcome: SUCCESS

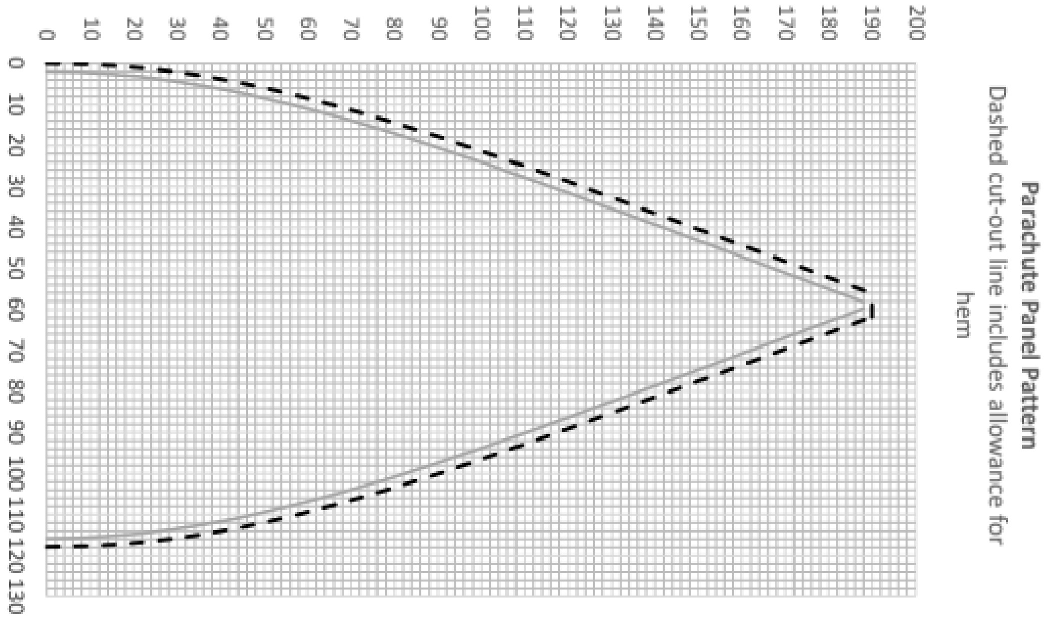
Appendix E. Engineering Drawings

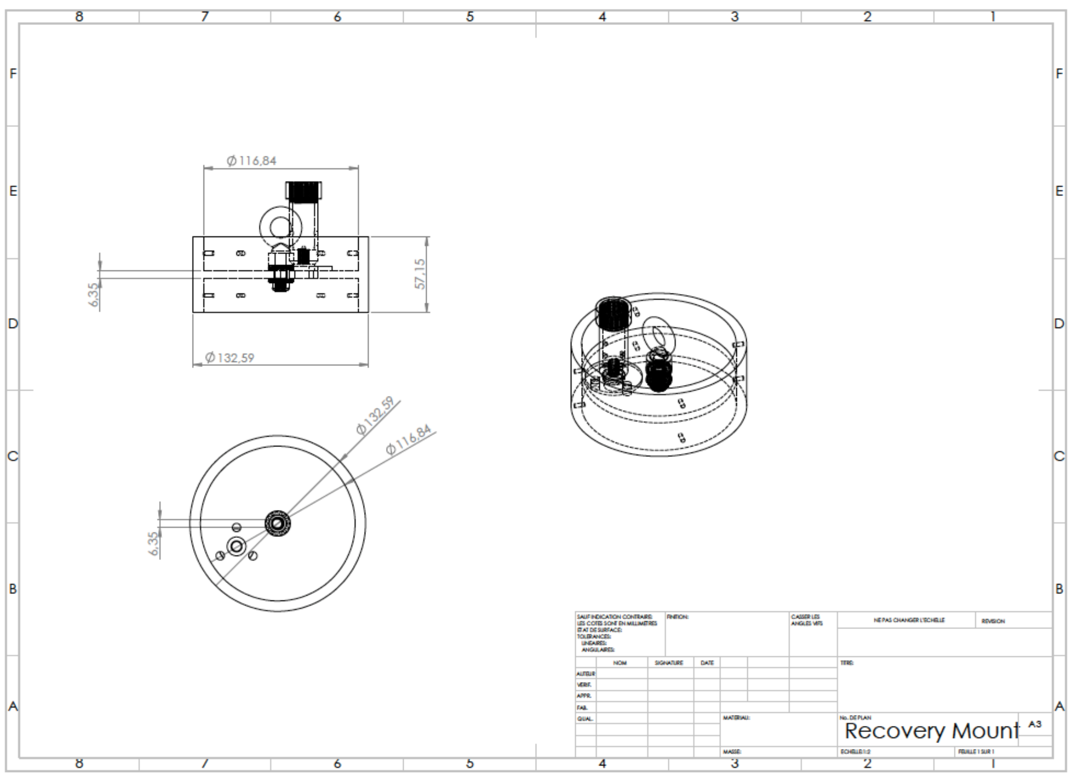
1. Avinoics Circuit Diagrams



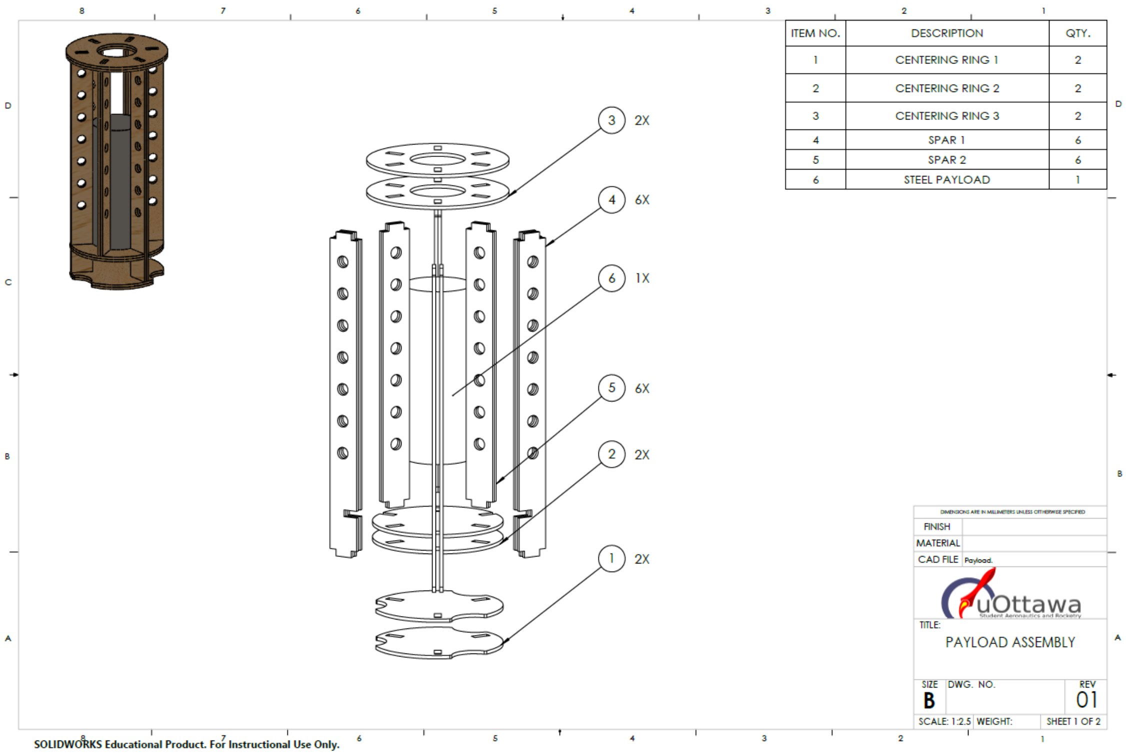


2. Recovery Drawings

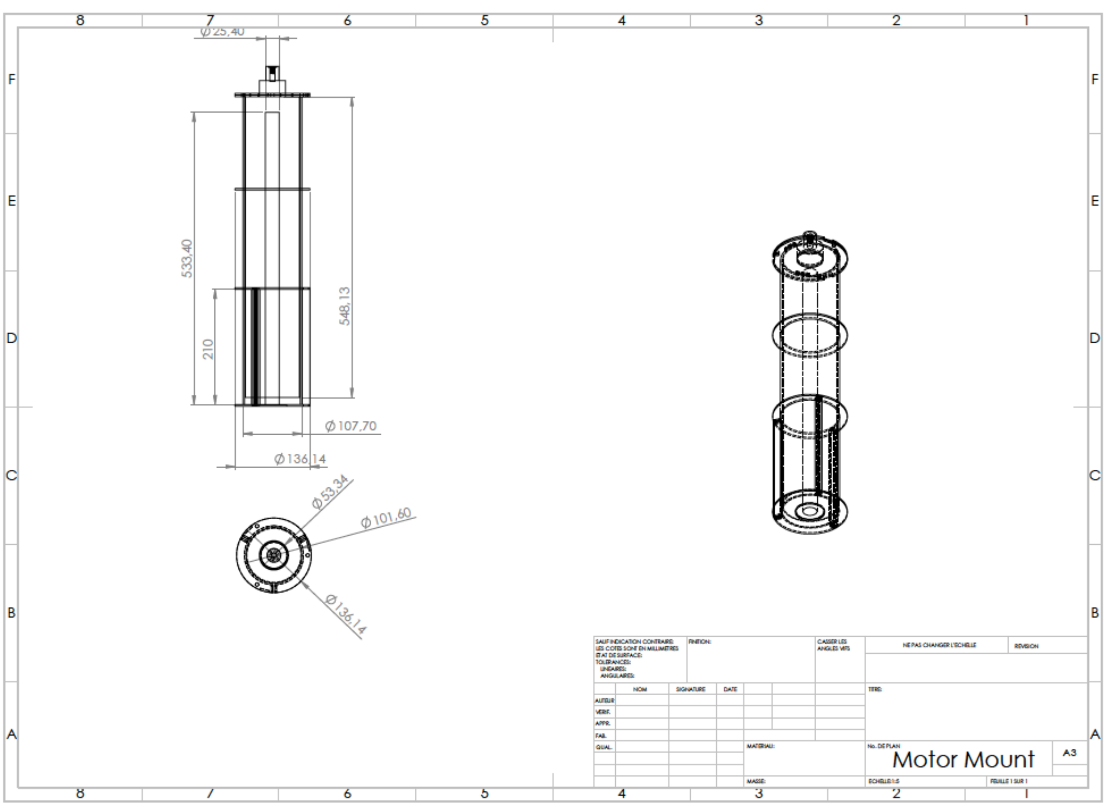




3. Payload Drawing



4. Motor Mount Drawing



5. Cesaroni M2505 Rocket Motor with protruding ignition head