UNDERGRADUATE DESIGN OF A PROPRIETARY, LOW-COST "QUBESAT"

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ABSTRACT

The "QUbeSat" project sought to create polymer additively manufactured components to replace off-the-shelf (OTS) CubeSat parts at a lower cost and weight as well as take temperature data of the proprietary frame while on orbit. An antenna deployment assembly, solar panel assembly, and frame assembly were successfully created for a prototype CubeSat that can perform the necessary functions of a post-deployment and orbital sequence.

1. INTRODUCTION

The purpose of this paper is to provide an overview of a mechanical engineering senior design project to design and build a CubeSat to satisfy the requirements of a future launch provider. The CubeSat will feature a unique, additively manufactured polymer frame, antenna deployment system, and solar panels with instrumentation measuring frame temperature while in orbit. CubeSats are small satellites belonging to a class called nanosatellites, which are determined by their standardized form factor and low weight. One CubeSat 'unit' is approximately 10x10x10 cm and weighs less than 2kg. Because of their small size and relatively low cost, CubeSats are ideal academic projects. They require the application and integration of knowledge and skills across many engineering disciplines.

1.1 Problem Statement

Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

The customer of the CubeSat is primarily the launch provider, which will ideally be NASA through the CubeSat Launch Initiative Program (CSLI). The requirements (dimensions, thermal and vibration resistance, etc.) are set by the launch provider and must be met for launch. Additionally, a formal application for acceptance is required by the CSLI and will cover the costs of the launch.

To attract the CSLI program described above, the CubeSat must be durable, innovative, compact, unique, lightweight, and inexpensive. The innovation aspect of the project is paramount as the CubeSat is experimental and must prove a hypothesis with evidence in a unique and viable fashion. Additionally, the CubeSat must be compact and lightweight to meet the dimensional and weight requirements for launch. Also, the durability is extremely significant because the purpose of the design is to test a new frame material and design to exemplify its effectiveness for space applications.

The CubeSat must meet requirements in several criteria: dimensions, weight, cost, innovativeness, and durability. The outer walls of the frame must fit within the dimensions specified in the Cal Poly handbook, which are generally 10x10x10 cm for a 1U CubeSat. Also, the weight must be under 2kg or 4.4lbs. The cost of a single CubeSat must be under $2000. The design must also be innovative and demonstrate a new technology, material, and its usefulness in space and future CubeSats. This could include a thermoplastic instead of aluminum, reducing weight and cost. It also can be a testing apparatus that takes valuable data on frame conditions in orbit. Lastly, the CubeSat must be durable and survive random vibration testing, shock testing, and a thermal vacuum bakeout to ensure orbit survival.

1.2 Recommended Design

Figure 1. Final "QUbeSat" Prototype

Many of the engineering characteristics chosen for this project were selected based on customer requirements, standards outlined by the California Polytechnic Institute, testing requirements established by The Aerospace Cooperation and NASA, and specifications needed to carry out this CubeSat's mission. It is important to note that the target for volume is derived for a cube with sides measuring 10 cm in length. This volume does not include the geometry outside of the cube such as the ends of the rails. Characteristics such as temperature requirements and vibration resistance were defined by testing procedures, however, the target values are often given by a launch provider and are subject to change. The mass, rail surface roughness, and axial distance from the center of mass to the CubeSat geometric center are standardized requirements across all 1U CubeSat's. The financial budget is determined by fund raising money and funds from the department. The priority and target values for the characteristics listed above can be found in Table 1. Actual values for these characteristics will be added once they have been determined.

Table 1. Design Specification List

Engineering Characteristic	**Priority**	**Target**	**Actual**
High Temperature Requirement [1]	1	> 100°C	In-Progress
Low Temperature Requirement	1	< -54°C	In-Progress
Vibration Resistance* [2]	2	> 2000 Hz	In-Progress
Mass [3]	2	< 1.33 kg	0.526 kg
Cost	3	< $2000	$1828.25
Rail Surface Roughness	4	< 1.6 µm	In-Progress
Volume	5	== 1000 cm^3	1000 cm^3
Frame Material Density	6	< 3 g/cm^3	1.27 g/cm^3
Axial Distance of Center of Mass to Geometric Center	7	< 2 cm	[0.39mm, 0.3mm, 1.48mm]

*Full specification listed in Appendix C

The prototype meets the targets. The mass, volume, frame material density, cost, and axial distance of center of mass to geometric center all met the targets, and the rest of the engineering characteristics tests are still in progress. For example, the high and low temperature requirements will not be tested until a flight ready CubeSat is produced. However, the frame material datasheet implies that these temperature requirements are met by the chosen frame material. Additionally, the rail surface roughness, and vibration resistance tests cannot be performed until a full CubeSat assembly is produced. Given the engineering design process has been followed throughout the project, each in-progress characteristic is expected to be met. Lastly, the mass and frame material density greatly exceeded the target values, which will help the CubeSat be much lighter and have lower launch costs.

2. BUSINESS CASE

The chosen material for the CubeSat frame, the Stratasys ULTEM™ 9085, weighs comparatively less than a standard aluminum frame that is used for many other CubeSat missions. Using the SolidWorks mass property measurement tool, the CubeSat frame was calculated to have a mass of 0.243 kg with the Stratasys ULTEM™ and a mass of 0.537 kg with standard Aluminum 7075. These measurements apply only to the 3D printable components of the design and are representative of only a portion of the total mass seen in Table 1.

3D printing the frame will also allow it to be readily assembled. The cost of the frame design is concluded to be significantly less expensive than other CubeSat manufacturers. For example, the total cost for only the CubeSat frame and solar panels, which makes up a portion of the total project cost in Table 1, was quoted via the manufacturer at about $1,220. Other manufacturers have been researched and shown to market a complete proprietary solar panel frame assembly (all six sides of a 1U CubeSat) for roughly 16 times the cost of this project's frame. Despite this large gap in cost, the "QUbeSat" frame still meets the requirements of structural integrity, a separation mechanism for deployment, and solar panels to supply power to the internal systems.

Component selection during the prototype and design process of the project was critical to minimizing the cost. Off the shelf, standard components were chosen to achieve proper system function if they proved useful and sufficient to carry out the project. Examples of these components are solar cells, microcontroller chips, and other structural hardware.

3. BACKGROUND RESEARCH

Information was gathered using several main techniques. First, the journal and conference papers were discovered from Google Scholar searches. A review paper was found and references in the paper were researched as well. The patents were searched using Google Patents and the United States Patent and Trademark Office Patent Search Website. Lastly, the standards were found within the NASA CSLI website and in government regulation documents.

From the review paper, current CubeSat technology was discussed and several CubeSats that tested unique frames were mentioned along with other technology demonstrations [4]. The Cal Poly CubeSat Design Specification provides the mechanical, electrical, and operational specifications for CubeSats along with CAD drawings of frame dimensions. It also includes testing requirements, which are referenced in the problem statement [5]. Lastly, another key resource is the NASA CSLI handbook, which describes the general process of designing and constructing a CubeSat along with a timeline and necessary resources [6].

After literature review was performed, the team created the customer requirements which were used in the Pareto chart, pairwise comparison, and the QFD. Details for the literature review and customer requirement discovery can be found in Appendix A.

Four similar CubeSats were found on the Nanosat Database [7]. They are as follows: GASPACS CubeSat [8], KRAKSAT [9], Oresat0 [10], and UVSQ-Sat [11]. The engineering characteristics of each item can be found in Appendix A's benchmarking section, as well as in the QFD. Please note that the mass, volume, and frame density of the CubeSats were found directly on the respective websites, but the testing requirements, including temperature resistance, vibration resistance, surface roughness, and center of mass were estimated based on the requirements for launch presented in the NASA documents. Additionally, the financial budget was estimated based on the costs of components listed on the websites. Lastly, the center of mass requirement is listed as being within a range of the absolute center of the CubeSat; 0 indicates the axial distance of the center of mass is at the geometric center.

3.1 STEP-GE Considerations

Social Considerations

The CubeSat requires input from multiple sources for a successful mission. The team reached out to local aerospace companies for input and assistance, but unfortunately received none. Additionally, the team sought additional funding for manufacturing processes, material, and launching from local researchers through crowdfunding. The CubeSat will also meet the needs of the launcher by fulfilling the pre-launch certification process.

Technical Considerations

The CubeSat must demonstrate an experimental and innovative technology that has not been tested before. There have been several CubeSats that use additively manufactured components or polymer frames as their technology demonstration. However, designing the solar panels and antenna deployment system for the unique frame design will be innovative and unique. Additionally, the CubeSat requires tracking technology to help fulfil considerations listed below. Finally, the CubeSat should resist malware, Denial of Service (DoS) attacks, and be able to recognize if a cyber-attack were to occur.

Political Considerations

The client requires that the CubeSat comply with regulations regarding communication, tracking, data sharing, and deorbiting. According to the Code of Federal Regulations, Title 47, Chapter I, Subchapter A, Part 15, communication should be operating within the amateur radio frequency (435-438 MHz) [12]. Because of this, one member of the group acquired an amateur radio operator's license. Per *White House: Space Policy Directive-3, National Space Traffic Management Policy*, CubeSat operators must be able to share their location data, utilize tracking software, and spend no more than 25 years in orbit [13].

Environmental Considerations

The Aerospace Corporation and NASA require that the CubeSat use materials which are rated to withstand the conditions in which it will operate. At 2022 IEEE Aerospace Conference 2022, the conditions were determined the CubeSat withstand temperatures between –100 and +100 degrees Celsius. Lastly, the outgassing properties of the material must be less than 1% total mass loss (TML) according to NASA standards.

Global Considerations

The client must minimize contribution to space debris. Space debris can impact the efforts of anyone launching anything into space around the globe. While in orbit, the CubeSat shall remain in-tact until reentry. Upon reentry, the CubeSat will burn up in the atmosphere. The CubeSat also must be tracked to avoid collisions with other satellites to prevent space debris creation. According to Ostrom, space debris poses a risk to all future space operations. Preventing space debris reduces risks that other missions are impacted by the CubeSat. Some considerations include reducing battery capacity to 30% while still holding up to 100 Wh of charge during launch. These specifications will prevent in-orbit burnup from the battery.

Economic Considerations

The CubeSat total costs must be less than $2000. The team used limited off-the-shelf products and inexpensive materials. A crowdfunding page was created for our team to spread awareness of the project and gain additional funds to alleviate material and prototyping costs.

3.2 Applicable Codes/Standards/Regulations

The first major code/standards document that applies to the CubeSat is the Cal Poly CubeSat Design Specification, which was discussed in the background research section. Next, the amateur radio regulations must be abided by to communicate safely and effectively with the CubeSat while in orbit [14]. Lastly, the regulations described in the NASA CubeSat handbooks must be included as they will be the most likely launch provider [15]. See Appendix A for more details.

4. RESULTS

The design process consists of conceptual design, embodiment design, and detailed design. Development of the prototype includes construction and assembly of components, risk management, and testing.

4.1 Conceptual Design

Using a Pareto chart, the most significant attributes to focus on during the design were found. The attributes were found from a survey of each team member where they individually ranked the attributes, and the results can be found in Appendix A. The most notable call for our design to be durable, innovative, compact, and unique. Less notable attributes were found to be communicative, experimental, and efficient. Even though some attributes received much more votes than others, it is still imperative for all of them to be included. Note that the "efficient" attribute was used as one of the major branches in the objective tree. This was done because "efficient" describes the attributes durable, compact, and lightweight. The pairwise comparison prioritizes customer requirements by comparing attributes two at a time and is also in Appendix B. Efficient and innovative had the equally greatest relative importance followed by inexpensive.

The Quality Function Deployment (QFD), found in Appendix C, displays the engineering characteristics (EC), problem statement, customer requirements (CR), technical assessment, and the design specification list. The ECs were developed by analyzing what the team believe are important factors in CubeSats, more specifically, the overall frame properties, which were derived from the previous tools, such as the pairwise comparison and Pareto chart. Simple factors, such as volume and mass were chosen as ECs, as well as more specific CubeSat parameters, like number of sensors and temperature resistance. The QFD compares the customer requirements with the engineering characteristics and assigns a relative importance to each EC depending on the correlation to the CR. The ECs correlated well with the CRs as there were only a few blank boxes (no correlation) in the QFD. After the QFD was completed, it was discovered that the temperature resistance (both high and low) was the most important factor. Further, the vibration resistance and mass were tied for second on the importance scale, and the financial budget was third. Factors such as the volume were not as important, more so because they must meet an exact value, as opposed to other characteristics, like the mass, which should be as low as possible. Lastly, the ECs were compared to the set target values by using the specification lists from some CubeSat project websites, which were found through "Nanosats Database." Further, in Appendix A, three CubeSats were found through the database and had general specifications as well as some links to software and hardware files. The target values were set by referencing the CubeSat specification documents from the literature review and comparing the values to those of the discovered CubeSats.

The functional decomposition was created by using outputs from the QFD, pairwise comparison, and Pareto chart. Next, the functional decomposition found in Appendix D was created by analyzing the EC's and the CR's, forming them into verb-noun combinations to describe the CubeSat's function. The functionality outcomes are dictated by the priority of each aspect as given by the previous tools. Certain features will be diminished in presence based on the selected order of pertinence. This lays out the functional decomposition. Some qualities are more exaggerated over others for the success of the CubeSat. Some key functions that define the design are providing data, telemetry, and demonstrating 3D printing material capabilities. These are the main purposes of the CubeSat, but it is also important that it endures space conditions, which will enable user interaction.

The design requirements list, found in Appendix E, is derived from the objectives tree and the engineering design specification list and allocates all the necessary requirements for the design. Critical requirements are labeled with an asterisk. The engineering design specification list was created from the official CubeSat specification documents; therefore, the design requirements list utilizes the same documents. Each of the requirements listed are not recommendations but must be met to qualify the CubeSat for launch. Additionally, the design requirements list feeds into the weighted decision matrix as they help determine the design criterion.

The morphological chart utilizes the functional decomposition to display with functions tree along with the means and physics. The means are the physical component used to achieve the functions. As seen in Appendix F, the functions are listed with several means that will achieve said function. Below that, physics, or the fundamentals that can be modeled, describe the forces, materials, etc. that play a role in the specific means. There are 3456 different combinations for the design.

The design alternatives chart in Appendix G also shows the functions and facilitates combinations of means from the morphological chart. An important feature of the design alternatives chart is how it ensures that the designer will not pick the worst possible design because of the volume of possible combinations. There are hundreds of different design alternatives that can be chosen from the morphological chart, but only four were selected. Each design alternative attempts to incorporate different means for each function to keep the alternatives unique.

The weighted decision matrix, as seen in Appendix H, is the final piece of the conceptual design section preceding the embodiment design section. The design alternatives chart created four possible versions of the final design by combining the different means and components into separate designs. The decision matrix inputs each design to help expose the highest rated combinations based on relative weight. Further, the design criterion and their respective weight factors (with units) are inputted into the decision matrix so each criterion can be given a magnitude, score, and rating. The scores of some design criteria are determined from utility curves, which can be viewed in Appendix H as well. Other design criteria were scored in a pass-fail fashion, demonstrated by the utility curve for financial budget, where they scored a one if they met the criteria and zero if they failed. The utility curves depict the usefulness of each design criterion as its numerical value changes, and the rating is the product of the weight and score. Lastly, the decision matrix outputs a total rating for each competing alternative so the designers can consider all the rated alternatives. The team has decided to pursue alternatives one and four because they had the highest rating. A single alternative was not chosen because the only difference between one and four is the frame material, both of which meet the requirements for launch. The process of DLP and FDM will be compared to analyze which method will prove to be the most effective financially, and in printing the geometries of the frame.

4.2 Detail Design

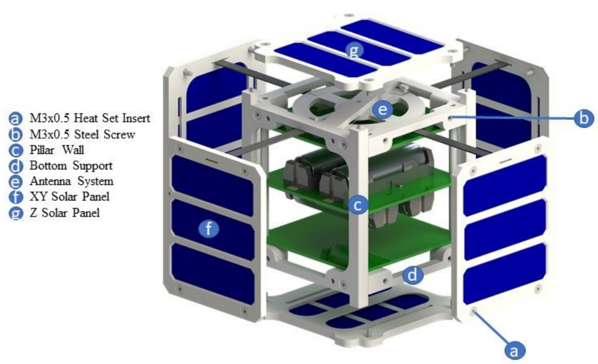

Figure 2. Exploded Isometric CAD Rendering of the "QUbeSat"

The CubeSat contains several components that will be made using additive manufacturing. Further, these components are the two pillar walls, the bottom support, the solar panel covers, the solar panel bases, and the antenna deployment system. The pillar walls and bottom support combine to create the main structure of the CubeSat, which is being made from a polymer material to decrease weight and experiment with new space worthy materials. The solar panel bases and covers are being made from the same material because the solar panel assembly is proprietary and requires complex geometries. Lastly, the antenna deployment system is being made from the same thermoplastic.

The other components will be purchased from suppliers, such as the fasteners and heat-set inserts, the circuit boards, the circuit spacers, the solar panels, and the batteries. The heat-set inserts are used to remove the need for thread geometry in the polymer parts, as they would not withstand a steel fastener. The separation mechanism uses an OTS spring and a small pin which is manufactured, the rest of the assembly is integrated into the frame. The antenna deployment mechanism was designed with crossed dipole antennas that will deploy 90 degrees from each other perpendicular to each of the four side faces of the cube. A screw and washer in the center of the disk holds the assembly together with a loaded spring. A nylon wire will be positioned to hold the spring in place. A resistor will also be positioned near the wire. Thirty minutes after the CubeSat is deployed from the dispenser aboard the launch providers auxiliary payload, a signal will be sent via the on-board data handling system which will heat the resistor, causing the nylon wire to burn and subsequently release the spring to activate the disk. The rotating disk will bring each antenna through a slot on each of the solar panel assembly until the disk reaches the bumper stop. This will lock each antenna in place once it is deployed.

In the center of Figure 2, battery holders along with four lithium-ion batteries can be seen as part of the electric power system board. The electric power system consists of solar panels, rechargeable batteries, and power controllers. Solar panels are assembled on every side of the CubeSat to power all systems and charge the li-ion batteries when sunlight is present in orbit. When sunlight is not present, the power regulating charge controllers will switch system power solely to the batteries. This cycle will repeat each orbit to keep the satellite powered during all stages of the mission.

The data handling system uses a Raspberry Pi Pico to control the subsystems. It also uses thermistors to take the temperature data and ADCs to convert the analog data to digital. There are also MicroSD cards to store the data in preparation for transmission.

The current CubeSat prototype meets the design specifications by having a volume of 1000 cubic centimeters, having a mass of 526 grams. Additionally, the tentative material for the frame is the Stratasys ULTEM^{TM} 9085, which has a glass transition temperature of 177.32 degrees Celsius and a melting temperature of 340. The material density is 1.27 grams per cubic centimeter, which is less than the target of 3. The latest

CAD model of the CubeSat was subject to a vibration testing simulation, but a complete test must be done at a testing facility when a flight ready model is completed. Also using SolidWorks, the center of mass was found to comply with project requirements, as it is less than two centimeters away from the geometric center in the three axial directions. The total project cost is also within the financial budget of the project, as it is less than the $2000 budget. These results can also be found in the design specification list in Table 1. Lastly, CAD renderings of the design can be found in Appendix P.

4.2.1 Design Drawings/Bill of Materials

The engineering drawings of the CubeSat components are as designed. The parts will be fabricated using additive manufacturing and can be found in Appendix I. The drawings were created in SolidWorks and provide a visual of the parts that cannot be misinterpreted.

All the necessary parts for the completed design can be found in the bill of materials (BOM). In Appendix J, the bill of materials is used to determine the materials and parts that are needed for the design. The BOM lists each component and identifies the responsible engineer as well. Before the design is constructed, the BOM is consulted to determine how each part will be manufactured and which parts will be purchased. The two pillar walls, the bottom support, the solar panel covers, and the solar panel bases will be 3D printed from a printing service, and the prototypes were made using in-house 3D printers with ABS plastic as the material. The circuit boards will be purchased through a PCB service. Lastly, the rest of the components were purchased from various vendors.

4.2.2 Analysis

The equations and analysis that are critical to the design of our CubeSat involve general properties of the entire CubeSat and equations related to specific systems. Programs such as SolidWorks can be used to calculate the mass, measured to be 526 grams, and location of the center of mass for the entire CubeSat assembly. A power table must be constructed to ensure the electrical power system can support the energy requirements of power consuming components. To properly construct this power table considerations such as the effects of orientation and location on charging cycles will be analyzed. The use of tools such as NI Multisim will be useful for ensuring every system on the CubeSat receives the correct amount of power. Heat transfer equations will be critical to the specifications of the thermal control system to ensure the temperatures of the CubeSat do not exceed the limits of different components. Equations related to the link budget and antenna length will be critical to the components of the communications system. Assuming a transmission frequency of 437 MHz, the length of the antenna should be 8.575 cm or 4.228 cm so it can rest inside the CubeSat before deployment. These calculations can be found within Appendix K.

4.3 Implementation

4.3.1 Construction/Assembly

Many of the integral components for the project were ordered from common circuitry and device component manufacturers such as Digi-Key, McMaster-Carr and Adafruit. They were then tested for proper functionality before being incorporated into the final design. The prototype frame pieces were 3D printed with the help of Mr. Dennis Hanlon using the Quinnipiac Maker Space. Rigorous testing and modification of the antenna slot geometry on each frame piece was performed, requiring the original design to be updated to allow smooth interaction between the antenna and frame each time it is deployed. Solar panels were connected on each face in parallel by soldering a connecting wire to each of the positive and negative terminals which were then soldered to plug connectors which will attach to the electric power board. The power, data-handling, and communication circuits are currently configured on breadboards which has made testing and troubleshooting very effective. These breadboards are sized to fit within the CubeSat and effectively mimic printed circuit boards (PCBs) before they are actually ordered.

4.3.2 Testing

The test plans for the CubeSat were used to assess how well the engineering characteristics were achieved. While some tests were completed, others remain in progress as they cannot be finished until a flight ready CubeSat is completed. Many of these tests can be completed by the CubeSat design team using Quinnipiac University’s facilities, however, tests such as the rail surface roughness will be completed by the CubeSat frame manufacturer. Other engineering specifications such as the frame material density and cost were set by the CubeSat design team and can also be tested using Quinnipiac University’s facilities.

The high temperature requirement can be completed by placing the assembled CubeSat in an oven set to 100°C. To test temperatures below -54°C a Styrofoam cooler can be used to house the assembled CubeSat and dry ice. Vibration resistance tests can be completed through simulations in SolidWorks and through another university’s CubeSat center for the physical model. The final mass of the assembled CubeSat can be measured on a scale. The volume is an engineering specification set to meet the 10x10x10 cm requirement for 1U CubeSats. These measurements can be obtained using calipers. SolidWorks was used to find the axial distance from the center of mass to the geometric center of the CubeSat assembly. It was also utilized to estimate the overall mass of the satellite as well as its ability to withstand a vibration test via a simulation. Since the frame material density does not include the mass of other components, this test will have to be completed prior to assembly. This will be completed by measuring the mass and volume of the frame to calculate the density. The cost of a complete CubeSat can be obtained from the bill of materials and was monitored throughout the duration of the project. Complete descriptions of the test plans and results can be found in Appendix L. Finally, other tests such as the radio range can be tested outdoors where the range can be obtained through external websites distance finders. It is important to maintain line-of-sight for this test to get an accurate reading of the radio range.

5. PROJECT MANAGEMENT

The most significant project management tools used were the schedule with Gantt chart, OneDrive, texting, and email. More specifically, assigning specific roles and tasks with due dates was integral to the success of the project. The schedule was used to organize the timeline of the semester and break down the tasks into smaller pieces with due dates and responsibilities. This tool allowed each team member to be held accountable for their specific roles and more effectively accomplish the problems that were faced. Given the project is very ambitious, the due dates were very important because struggling with a certain task for too long will set the entire project behind. If someone needed help or was struggling, the other team members could assist to make sure the task is completed on time. The schedule/Gantt Chart can be found in Appendix M.

The OneDrive folder was invaluable to the team as it was the hub for all the files. Everything was organized into subfolders for every assignment, design iteration, system, etc. Each team member knew where to find the files and had access to everyone else's work. Whenever files needed to be shared or opened simultaneously, Microsoft 365 and OneDrive were utilized, making the assignments and tasks seamless.

Lastly, the most used communication methods were email and texting. Texting was the most efficient and effective way to communicate throughout the project. Scheduling meetings, sending reminders, discussing new ideas, were usually done over text because of the simplicity. Formal meetings and messages were sent through email, as they usually involved the team advisor as well. The team was more connected with an established group chat, and the key to a well-functioning team is communication.

To be more efficient with time and resources, a better plan could have been created from the start of the semester. There should have been more detailed plans for the return to class because time at the beginning of the semester was used to do so. However, at the start of the spring semester, there was a set plan. Additionally, the team leader could have been stricter with due dates for tasks, which may have lowered team morale, but could have provided more accomplishments for the semester. The critical path was researching the different subsystems to create comprehensive designs. Each team member was working on a system and those are the most important aspects of the project. Without all the subsystems, the CubeSat cannot function. Additionally, once the individual subsystems are completed, they were combined to create the finished product.

5.1 Final Cost

The final cost for developing and manufacturing our single prototype was $865.19. The hardware category shown in Table 2 includes the costs of all parts that were purchased over the course of this project. The Overhead category includes the cost of sales taxes and tariffs. Shipping includes the costs of having every purchase order sent to the campus mail room. Finally, licensing fees include all costs associated with obtaining an amateur radio license. This table does not include the cost of having frame parts manufactured by Stratasys. A full breakdown of every expense over the course of this project can be found in Appendix N. The Stratasys quote for additively manufactured frame components in the Ultem 9085 material can also be found in Appendix N.

Table 2. Cost Breakdown

Catagory	Cost
Hardware	$672.10
Overhead	$59.49
Shipping	$53.94
Licensing Fees	$79.66
Total Cost	$865.19

5.2 Risk Management

Safety was designed for the CubeSat by following all the guidelines specified in the NASA and Cal Poly handbooks, as well as FCC orbital debris mitigation policies [16]. Additionally, the extensive testing process will ensure the CubeSat meets all the launch requirements and will mitigate the chance of failure. Many of the risk reduction efforts are built into the CubeSat standards and design process. In Appendix O, the FMEA worksheet and the Composite Risk Management Worksheet describe several key failure modes and their risk levels. The risk priority numbers were derived from tables found in the dissertation by Al-afnaan bin Mashal [16]. The FEMA Worksheet yields tied results for the highest risk priority numbers between Antenna Deployment Failure and Thermal Control System Failure. The hazards determined the most critical mode of failure to address. Parts are chosen based on their ability to withstand temperature conditions set by California Polytechnic Institute and NASA. When a hazard such as overheating or underheating presents itself, the temperature specifications of the materials should prevent risk. Therefore, antenna deployment failure is most critical to address because it cannot rely on engineering specifications in the event of failure.

6. LESSONS LEARNED

The most significant lesson learned over the course of this project was in regard to setting goals and research. CubeSats are very complex projects and require years of time and research to complete, along with usually having many diverse team members. This project was performed over the course of a single academic year, and the team consisted of four undergraduate mechanical engineering students. The initial objective the team set was to have a flight-ready CubeSat at the end of the academic year. The goal was aspirational and unrealistic given the circumstances. If preliminary research was performed prior to the start of the academic year, the goals could have been adjusted to accommodate the team's initial lack of CubeSat knowledge. However, if the expectations were lower for the project at the beginning, then it is possible less would have been achieved. Reaching out to an expert on satellite radio communications early in the project for recommendations on where to start learning about radios would have sped up the learning process. Information on satellite communications is spread across the internet but there are books with a lot of information that were not discovered until much further on in the project. Another lesson learned was on prototyping and using the prototypes to advance the design. For the antenna deployment, it was initially difficult to understanding how the 3D printing would work and what designs are more compatible with 3D printing. If In addition, more extensive research relating to all the components of a power system could have been done to grasp a more complete understanding of how the power system functions rather than focusing on just its primary function. Implementing a power management integrated circuit (PMIC) may have assisted with circuit prototyping.

7. SUMMARY

The final "QUbeSat" design featured proprietary frame, solar panels, and antenna deployment assemblies. A full launch sequence can be demonstrated by sending a signal to the device, deploying the antennas, taking temperature data, and then transmitting that data back to the ground station.

The project had very aspirational goals at the start, which included creating a flight-ready CubeSat. Given this was the first CubeSat project at Quinnipiac University, that objective was unrealistic, but allowed the team to set high expectations and strive to achieve them. In the short timeframe of 6 months, the objective of creating a proof of concept, experimental, CubeSat design that can perform post-deployment and orbital functions was achieved.

8. CONCLUSIONS

A proprietary frame, antenna deployment system, and solar panel assembly can be efficiently designed with complex geometries enabled by additive manufacturing at a lower weight and cost than OTS parts. This project has laid the foundation for future CubeSat project teams at Quinnipiac University and would be termed "QUbeSat 0." The design functions, but it must be finalized in a flight-ready model, which would be "QUbeSat 1." Future teams can continue this project by focusing on the circuitry and data systems.

9. ACKNOWLEDGMENTS

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APPENDICES

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APPENDIX A

LITERATURE REVIEW AND BACKGROUND RESEARCH

Literature Review

Journal Review Paper

Poghosyan, A., & Golkar, A. (2017). CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions. *Progress in Aerospace Sciences*, *88*, 59-83.

The paper reviews the current state of CubeSat technology before the year it was published, 2017. Most notably, the paper features a section on each major component of CubeSats and lists experimental technology, current challenges, and recent CubeSats that focused on that area. For example, it mentions the use of 3D printed frames and lists a few CubeSats: Tomsk-TPU-120, 1U PrintSat, and 2U QB50 UNSW EC0. Along with structure, it also includes the categories: Power, Propulsion, Guidance Navigation and Control, Communications, Command and Data Handling, and Thermal Control. The second half of the paper consists of payload capabilities, which are under the categories: Earth Science and spaceborne applications, Deep space exploration, Heliophysics: space weather, Astrophysics, Spaceborne in situ laboratory, and Technology demonstration. The appendixes list CubeSats in the previous categories, their size, organization, objectives, and launch date.

The information from the paper is relevant to the project as it provides a starting point for future literature review. The CubeSat examples that were given can be researched and built upon for this project. Further, the objective of the previous CubeSats can be expanded and made more innovative; the type of material or manufacturing process can be changed to something more recent and experimental. For example, the 1U PrintSat was very innovative for the time (2016), but it was destroyed when the rocket failed during launch. The instrumentation concepts used in that CubeSat can be a model for this project, and the material/printing method can be changed to a more modern counterpart. Lastly, because it is a review paper, there are hundreds of references which can be researched to find more information pertaining to the CubeSat project.

Patent

Patent Number: EP3431398A1

Official Name: Satellite Cover Panel

Author(s): Thomas Grubler & Martin Langer

Date of Publication: 01-23-2019

The device is simply a satellite cover panel and comprises an energy storage module, an energy generating module (e.g., Solar panels) and a logic board. The cover panel is modular and can create a simple cube shape, a hexagon, stack to create a multiple unit satellite, and use hinges to create walls that open to reveal the energy generating modules. The energy storage module is directly connected to the generating module and is within the confines of the cover panel, which helps increase the open area inside the satellite for instrumentation and other devices.

The information presented in the patent is very helpful for the CubeSat project as it demonstrates an innovative way to organize the walls while including the solar panels, energy storage device, and logic board. The walls for the CubeSat project will be additively manufactured, which allows for complex geometries to be created. Further, there is a possibility of integrating certain aspects of the CubeSat into the frame, whether that is circuit boards or simple wiring for power transmission. The patent could serve as inspiration for the integrated cover panel design, and additions could be made to work more efficiently with the CubeSat purpose. Lastly, the patented design introduces the concept of changing the classic CubeSat design while meeting the required specifications. A unique frame could be designed that is unorthodox and maximizes the space inside the CubeSat itself, which would be innovative and interesting to test.

Standard

CubeSat Design Specification (1U – 12U) REV 14.1 CP-CDS-R14.1

The CubeSat design standards document from Cal Poly includes the general, mechanical, electrical, and operational specifications for CubeSats, which are all key requirements. For example, the specifications of the frame are described using CAD drawings which depict the tolerances of every dimension. Additionally, it provides the testing requirements, which are random vibration, thermal vacuum bakeout, shock testing, and visual inspection. Lastly, it includes the specifications of the dispenser.

The CubeSat standards document is the most relevant and significant document in the entire project. It lays out every single piece of information, except from the launch provider, necessary to ensure the CubeSat will be at a launch-ready state. This will most likely become the most referenced document during the project because of how integral the information is to the overall success. Regarding the frame, the document describes how if the material is not an Aluminum alloy, it needs to be tested and approved by the launch provider which is extremely relevant to the CubeSat project. The purpose of the project will be to create an innovative frame design which will have to undergo extensive testing.

Journal Review Paper

Siemaszko, M., Piastowski, D., Namiotko, W., Dudenko, D., Krywko, J., & Lafont, U. (2022). 3D printing CubeSat parts with power and data transfer functionalities with two blends of Peek. *2022 IEEE Aerospace Conference (AERO)*.

This article describes an example of additive manufacturing being utilized to create a CubeSat frame. What sets this design apart, however, are data transfer paths integrated into the thermoplastic framework of the satellite. The developers made use of the Zortrax LPD Plus dual extrusion technology with standard and conductive polyetheretherketone (PEEK) material to fabricate this structure on the Zortrax Endureal 3D printer. The paper begins by summarizing traditional methods of printing the PEEK material, such as injection molding, and how such a process can unfavorably alter its physical properties, such as tensile strength. Comparatively, closed architecture 3D printers like the Endureal have proven to generate a material with an ultimate tensile strength in the upper range of 85 to 95 MPa (2022). The developers performed a thermal vacuum test on the fabricated frame between -100 ℃ and +100 ℃ and found it did not influence the interface or the conductive path (2022). These tests provide evidence to support the usage of this modified thermoplastic frame with internal conductive capabilities in structural applications of spacecraft.

The study results outlined in this article are an example of a potential benefit of incorporating a thermoplastic frame in a CubeSat opposed to the traditional aluminum structure. It also provides a key piece of information from a technological and economic perspective. Specifically, the paper describes the advantages of printing along a certain axis, as well as the significance of the orientation of the 3D printing nozzle (2022). This information is useful for the application of our team's goals as using a similar thermoplastic may require the same precautions and procedures be adhered to. With the evidence given by the authors to stick with a printer designed for high-temperature polymers for maximum material strength, the cost for any printing process carried out by our team will be a critical factor in the decision-making process of prototyping. Given the very limited budget and time for our project, a rudimentary fabrication could pose detrimental to our goals due to the great expense of operating a high-temperature polymer supported 3D printer.

Patent [18]

Patent Number: US9248924B2

Official Name: CUBESAT SYSTEM, METHOD AND APPARATUS

Author(s): Jordi Puig-Suari & Austin Williams

Date of Publication: 02-02-2016

The CubeSat device is a small, square shaped satellite with fixed dimensions and various electrical boards that can be modified to serve a multitude of functions. It includes boards for the battery, main system, payload apparatus, and at least one additional board for specific defined use. They are secured to each other via stackable connectors. The existence of this device allows the efforts of smaller groups or organizations outside of the government to brainstorm, design, test, and certify components of a real satellite that could be used to demonstrate a new technology and drive innovation in the astronautical industry.

This patent is particularly useful since it provides general CubeSat component information directly from its creators at Cal Poly Corporation. The drawings and diagrams are essential to comprehend the level of complexity required to create a baseline functioning CubeSat that can be modified for a unique purpose. Important features are also mentioned in the subsequent summary section, with the ability to take advantage of the small framework of such a device emphasized. For example, it is emphasized that the avionics can be programmed to reset periodically to avoid disruptions caused by radiation, rather than install shielding on the device. Along with the many technical and dimensional specifications the patent provides, the authors also provide a passage highlighting the implications of such a device framework being available to public developers. The simple and scaled-down satellite framework allows those with smaller budgets but creative minds to bring their aspirations to reality.

Standard [19]

NASA Launch Services Program Federal Requirements – Program Level Dispenser and CubeSat: Section 5 Programmatic Requirements

This section of the NASA Launch Services Program (LSP) requirements highlights requirements that will need to be adhered to for accommodation of the CubeSat as an additional payload on standard NASA Primary Payload Mission. The LSP will inform the Primary Mission directors about the presence of the CubeSat aboard the launch vehicle (LV) and provide additional resources to accommodate integration of CubeSats for the specified mission after approval. The requirements also state that the CubeSat cannot interfere with the mission success of other CubeSats belonging to the same dispenser. It is worth noting that the subsequent Section 6 of the requirements states the technical requirements for the CubeSat integration with the LV and dispenser.

These requirements are extremely important to ensure that the CubeSat will not generate any safety issues or problems with the dispenser or rest of the launch vehicle. Compliance will also ensure that our group's final design will be approved as an auxiliary payload about the LV without any technical issues or timeline delays which could also affect the mission as a whole. For example, adherence to the technical requirement 6.2.3., which states the overall dimensional requirements for the CubeSat, is of paramount importance since it is a major constraint in the design process. Failure to pay close attention to this requirement could result in wasted time, funds, failure of approval for the device aboard a LV, and iteration in design.

Journal Review Paper

Ostrom, Chris L, and John N Opiela., 2021, "ORBITAL DEBRIS MITIGATION AND CUBESATS." *ESA NEO and Debris Detection Conference, Houston, TX*

The article describes the increased interest in CubeSat and includes regulations to continue their missions while addressing orbital debris mitigation concerns. The concerns are addressed by the objectives proposed by the United States Government Orbital Debris Mitigation Standard Practices (ODMSP). This includes minimizing debris, preventing explosions during and after the mission, preventing a collision, and requiring a plan for after the mission is complete. Explosions are a great concern because they have the potential to cause space debris. The ODMSP sets regulations that the likelihood of something like an explosion is less than 1 in 1,000 during its life. Another point of concern the article addresses is maintaining the 25-year life span. CubeSats are reaching heights past 500km, which is out of the “Low Earth Orbit” altitude. Going past these heights increases the likelihood that a satellite will stay in orbit longer than 25 years. Thus, CubeSats should aim for below 550 km to avoid collisions and for deorbit purposes.

This article is useful as it summarizes important guidelines for CubeSats. Additionally, this article serves as a starting point for finding guidelines set out by NASA, the UN, and the Department of Transportation. For instance, a CubeSat can only have 100 Wh stored in its Li-ion batteries. The batteries should be charged at 30% capacity to prevent burnup in orbit. Other regulations discussed in the article are the 25 year-rule. CubeSats with a lower form factor are likely to go higher into orbit and will likely take longer than 25 years to exit orbit. This leads to the need for a tether or a mechanism to retract the CubeSat within 25 years. The article shows this in figure 1 where we can find the threshold and where the team would need to make changes. Since CubeSats are very likely to reach higher heights, it is important for us to model our location with DAS (Debris Assessment Software). Other regulations stated in this article are a human casualty risk no greater than 1:10,000 during reentry. The article discusses the benefits and drawbacks of design intents. “Design for demise” is one way, where safe materials will burn up upon reentry. The components are easily replaceable. The other is “design for minimum causality” where components cannot be easily replaced. This article covers ethical issues such as the prevention of casualties, and the prevention of space debris accumulation. Additionally, it explains how designers must make decisions for when a CubeSat reenters during the design process between those two options.

Code

White House: Space Policy Directive-3, National Space Traffic Management Policy

The key requirement of this policy is to reduce congestion in space, along with being to proceed with missions as planned. The Department of Defense now tracks over 20,00 objects in space. The high number of objects presents concerns about collisions and the safety of large-scale missions. Because of this, the DoD checks for potential collisions. The first principle addresses this: “Safety, stability, and operational sustainability are foundational to space activities, including commercial, civil, and national security activities. It is a shared interest and responsibility of all spacefaring nations to create the conditions for a safe, stable, and operationally sustainable space environment.” One way the principle is enforced is by requiring mitigation practices for the deorbit of Satellites. Additionally in this policy, The White House would also like satellites to follow a standard practice in handling data. The goal is for data to be protected, while still being able to share locations to prevent collisions. Additionally, it requires that constellation owners must have their own pre-launch certification that prevents conjunctions, orbit tracking, self-disposal, information service, data protection and encryption, and appropriate reliability.

This Policy proves helpful for the project because it describes all the considerations that are required for design. For instance, we could launch our CubeSat alongside others, which would impact our design choices and classify us with constellations. With this in mind, we need to prepare for Space Traffic Management (STM), and practice space situational awareness (SSA). These practices require sensors to track location, end-to-end encryption, and comply with data sharing for SSA data and STM (Sec. 5 Guidelines). Section 5 calls for a protocol to manage the data and encourages sharing it with other satellite operators. This is relevant as we are satellite operators. I think learning to keep the CubeSat data secure while still transmitting information to multiple parties will be challenging, but a necessary step in a successful and safe operation.

Patent [20]

Patent Number: US11423785B2

Official Name: Multi Satellite Detection and Tracking of Moving Objects

Publication Date: August 23, 2022

Author: ImageSat International (I.S.I) LTD

This patent describes a technology that is used to track small satellites in space. It covers technology that shows where current satellites are located and where they can end up. The technology measures the locations of multiple satellites at a time in relation to each other and determines the likelihood a satellite will track to a certain location by giving a probability score. The system works by collecting data from the vessel from the AIS (Automatic Identification System) and will produce movement graphs. The movement graphs make the predictions mentioned in the White House Policy while incorporating tracking entire constellations and preventing collisions within one.

The information from the patent is relevant to the regulations in that it is a technology that assesses current and future locations of a satellite, and its relative location to others in its constellation. By implementing this technology into our Cube Sat, we would be able to track our CubeSat and its future locations and implement any possible travel practices to avoid collisions with other CubeSats potentially in the same constellation. The software achieves this through analyzing movement paths during an observation window.

Technical Paper

Stenhaug, Beathe Hagen, 2011, "Antenna system for a ground station communicating with the NTNU Test Satellite (NUTS)," Norwegian University of Science and Technology Department of Electronics and Telecommunications, pp. 3-18

This technical paper describes the process of making a helical antenna to communicate with existing CubeSats in orbit and a CubeSat which had not been launched when the paper was written. My focus will be on section 1, which discusses the parameters of the ground station. This section includes information about the link budget, antenna system, interface between the antenna and ground station, and local environment. The link budget is only briefly summarized and lists only the most important parameters. The antenna system uses two antennas to broadcast at 145Mhz and 437Mhz which are used to broadcast or receive different information. Antenna movement parameters and different satellite tracking systems, such as WXtrack, are discussed in the interface between antenna and ground station section. Finally, the horizon outline and other environmental effects the antenna must be able to perform under are discussed in the local environment section.

This article is important to our projects because it discusses the requirements for a CubeSat ground station. Building a ground station is the most economically feasible solution to communicating with a satellite in orbit. Since the budget is very limited, economic feasibility is a very important factor in our designs. The likelihood of launching the satellite seems very slim at this point in our project, however, it is good to understand how satellite communication works. The parameters of the ground station are also determined by the frequencies our satellite works with, and vice versa. Our CubeSat communications system should be designed with these parameters in mind.

Patent

The patent number for the "Parabolic antenna with self-structured reflector" is 20170162946. It can be found on https://patft.uspto.gov/ using document identifier, US 20170162946 A1. This version of a parabolic antenna was published on December 10th, 2015. There were two inventors for this antenna, Joao do Espirito Santo Abreu and Joao Alexandre de Abreu.

This device was designed mainly for communicating with satellite antennas. This antenna is different from previous iterations of the parabolic antenna because the reflector is made of a metal screen. Some advantages of this design are being lighter weight and having less air resistance. The main disadvantage it has compared to previous iterations of the parabolic antenna is the accuracy the screen can be manufactured to a parabolic shape compared to solid metal reflectors.

This invention is relevant to our senior projects because it is one of the potential types of antennas that could be used when constructing the ground station. Parabolic antennas are better at capturing radio waves when the exact location of a satellite cannot be determined. Another form of antenna that has a similar function is a Yagi antenna which has a significantly different structure. During the construction phase of our senior project, a decision on the type of antenna that should be used based on information regarding cost, market availability, and shipping time will help determine what we purchase. This antenna patent was reviewed because a screen reflector may be cheaper to manufacture compared to a solid metal reflector.

Code

Code of Federal Regulations, Title 47, Chapter I, Subchapter A, Part 15 Radio Frequency Devices.

Focusing more specifically on part 15.221 Operation in the band 525-1705 kHz, this section covers what is acceptable for unlicensed radio transmitters on a college or university campus. It covers information such as the strength of the transmitter, allowable frequencies, and power limits. Another notable section of this code is subpart D, unlicensed personal communications service devices. This subpart covers all the regulations that must be followed for personal communications services devices operating in the 1920-1930 MHz band.

This information is relevant to the project because it tells us what types of radio transmitters are acceptable to operate without a license. We would ideally have a license to operate a radio transmitter in the amateur frequency band because we would use those frequencies to communicate with the CubeSat if it were launched into orbit. For testing purposes on the ground, it may be acceptable to use a radio transmitter operating under these codes if attaining an amateur radio license is infeasible. To further research this topic, communication with the club or group that operates the radio station next to the upstairs bookstore in the student center would be beneficial.

Information Gathering Raw Compiled Data

Initial survey data was taken from each member of the team after the literature review was complete. Based on the basic CubeSat information discovered by the team, each team member ranked the 10 possible customer requirements by importance. The initial customer requirements were brainstormed by the team. A scale of 1-10 was used with 1 being the most important characteristic. Data analysis was conducted using cumulative percent and overall importance to create a Pareto chart found in Appendix (B). Any attribute not exceeding the cumulative percent was disregarded.

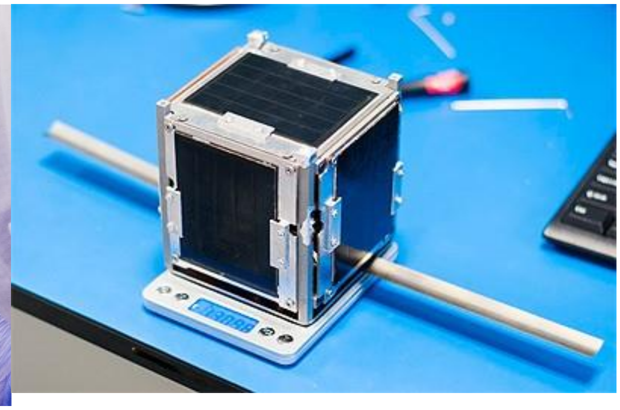
Attribute	Scores				Total Score	Cumulative Percent
Durable	5	2	1	1	35	15.91%
Innovative	3	1	3	3	34	31.36%
Compact	1	3	6	4	30	45.00%
Unique	4	5	5	2	28	57.73%
Lightweight	2	4	7	6	25	69.09%
Inexpensive	6	6	8	5	19	77.73%
Safe	10	7	2	10	15	84.55%
Communicative	9	8	4	9	14	90.91%
Efficient	7	10	9	8	10	95.45%
Experimental	8	9	10	7	10	100.00%

Benchmarking Information

CubeSat	cm^3	kg	μm	°C	°C	Hz	g/cm^3	cm	$
GASPACS	1000	1.17	1.6	100	-54	2000	2.71	0	~50000
KRAKSAT	1000	1.37	1.6	100	-54	2000	2.81	0	>10000
Oresat0	1000	1	1.6	100	-54	2000	2.70	0	>10000
UVSQ-Sat	1398	1.6	3	60	-38	2000	2.73	0	>10000

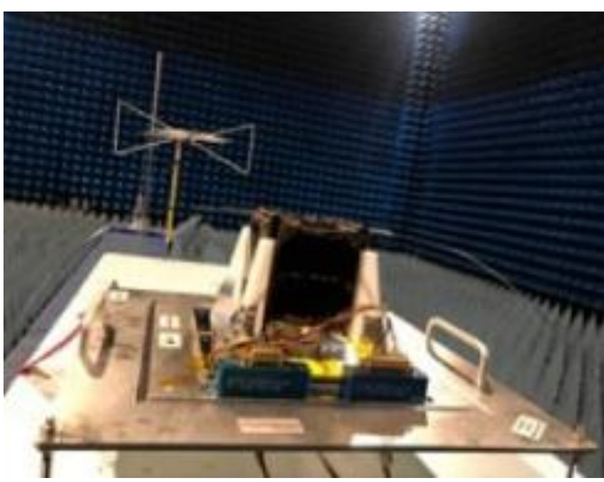
Competitor A, GASPACS:

Competitor B, KRAKSAT:



Competitor C, Oresat0:

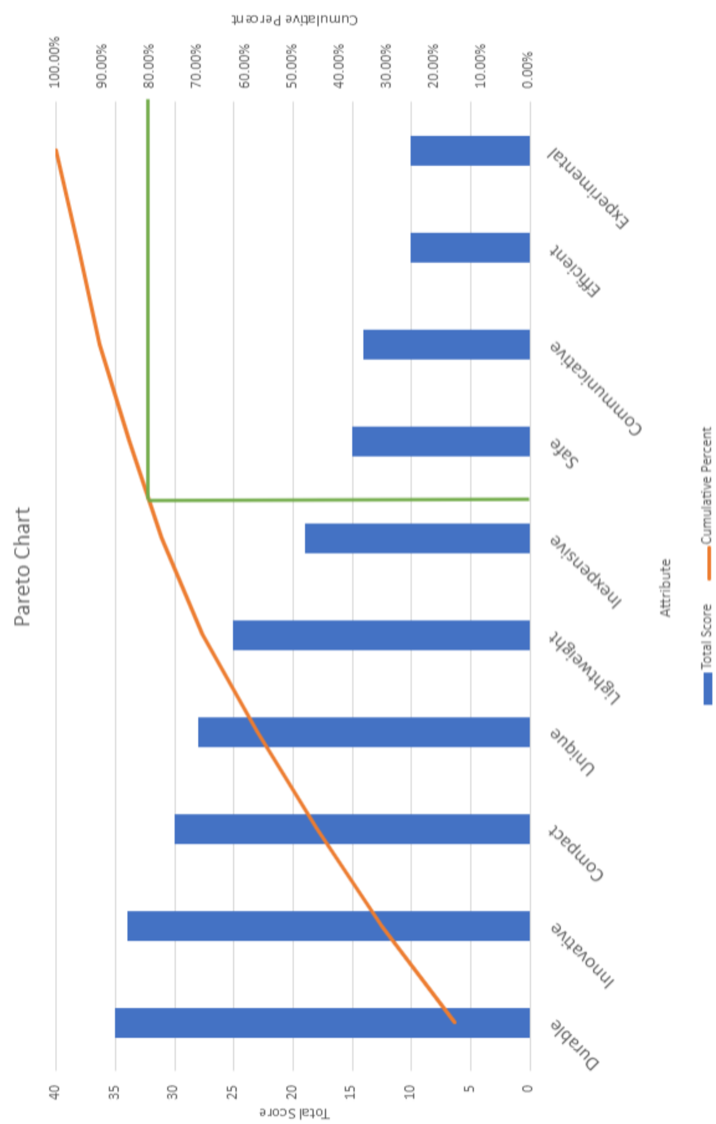
Competitor D, UVSQ-sat:



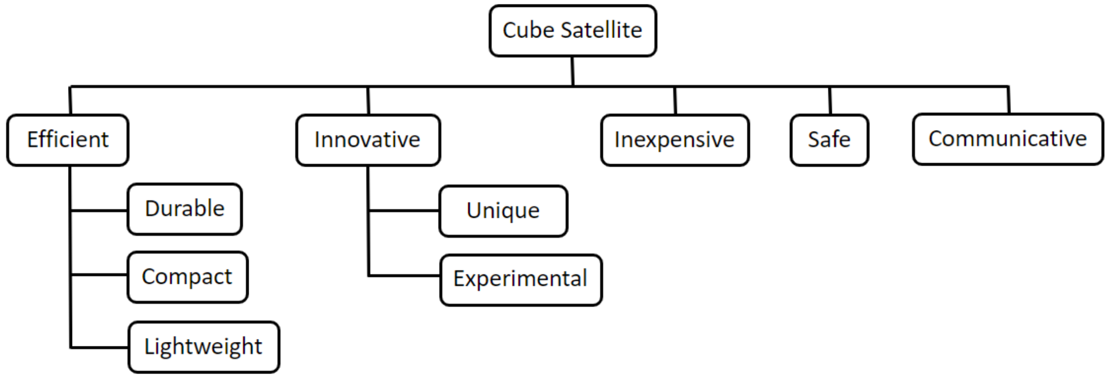
APPENDIX B

CUSTOMER REQUIREMENT TOOLS

APPENDIX B-1: Pareto Chart



APPENDIX B-2: Objectives Tree



APPENDIX B-3: Pairwise Comparison

	Efficient	Innovative	Inexpensive	Safe	Communicative	Sum	Relative Importance
Efficient		0.5	0.5	1	1	3	0.3
Innovative	0.5		0.5	1	1	3	0.3
Inexpensive	0.5	0.5		0.5	1	2.5	0.25
Safe	0	0	0.5		0.5	1	0.1
Communicative	0	0	0	0.5		0.5	0.05

APPENDIX C

QUALITY FUNCTION DEPLOYMENT

Problem Statement: Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

		Engineering Characteristics									Competitor Rankings 1 - Poor, 3 - OK, 5 - Excellent			
Improvement Direction		↓	↓	↓	↑	↓	↑	↓	↓	↓				
Units		cm^3	kg	μm	°C	°C	Hz	g/cm^3	cm	$				
Customer Requirements	Importance Weight Factor	Volume	Mass	Rail Surface Roughness	High Temperature Requirement	Low Temperature Requirement	Vibration Resistance	Frame Material Density	Axial Distance from Center of Mass to Geometric Center	Cost	A	B	C	D
Efficient	0.3	9	9	9	9	9	9	3	3	3	3	5	5	4
Innovative	0.3		3	1	9	9	3	3	1	3	5	5	3	4
Inexpensive	0.25	3	3	1				3	1	9	1	3	3	3
Safe	0.1		1	9	3	3	9	3	1	1	5	5	5	5
Communicative	0.05		1						3	3	5	5	5	5
Raw Score		3.45	4.5	4.15	5.7	5.7	4.5	2.85	1.7	4.3				
Relative Importance		0.094	0.122	0.113	0.155	0.155	0.122	0.077	0.046	0.117				
Rank Order		4	2	4	1	1	2	5	6	3				
Technical Assessment: GASPACS CubeSat		1000	1.17	1.6	100	-54	2000	2.71	0	~50000				
KRAKSAT		1000	1.37	1.6	100	-54	2000	2.81	0	>10000				
Oresat0		1000	1	1.6	100	-54	2000	2.70	0	>10000				
USQV-sat		1398	1.6	3.0	60	-38	2000	2.73	0	>10000				
Target Values		1000	2	1.6	100	-54	2000*	2.70	2	2000				
Units		cm^3	kg	μm	°C	°C	Hz	g/cm^3	cm	$				

↓	↑

A = GASPACS CubeSat
B = KRAKSAT
C = Oresat
D = UVSQ-

Design Specification List

Engineering Characteristics	Target (with units)	Relative Importance
High Temperature Requirement	> 100 °C	0.155
Low Temperature Requirement	< -54 °C	0.155
Vibration Resistance	> 2000 Hz	0.122
Mass	< 1.33 kg	0.122
Cost	< $2000	0.117
Rail Surface Roughness	< 1.6 μm	0.113
Volume	== 1000 cm^3	0.094
Frame Material Density	< 3 g/cm^3	0.077
Axial Distance from Center of Mass to Geometric Center	< 2 cm	0.046

*Full table for the vibration requirement

20 Hz	@	0.01 g^2/Hz
20 to 80 Hz	@	+3 dB/oct
80 to 500 Hz	@	0.04 g^2/Hz
500 to 2000 Hz	@	-3 dB/oct
2000 Hz	@	0.01 g^2/Hz
Overall Level	=	6.8 grms

APPENDIX D

FUNCTIONAL DECOMPOSITION

Problem Statement: Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

1.0 Interact with the User

- 1.1 Provide data and telemetry
  - 1.1.1 Utilize temperature sensors
  - 1.1.1 Process and convert data
  - 1.1.2 Communicate data
- 1.2 Demonstrate 3D printing material capabilities (methods)

2.0 Interact with the Internal Environment

- 2.1 Maximize available internal volume
- 2.2 Protect components
  - 2.2.1 Regulate thermal conditions
  - 2.2.2 Prevent electrical malfunction

3.0 Interact with the External Environment

- 3.1 Generate solar energy
- 3.2 Endure space conditions (material)

APPENDIX E

DESIGN REQUIREMENTS LIST

Quinnipiac University School of Engineering	**Requirements List** Device Name: CubeSat	Composed on: 10-31-22

Geometry

- Must be less than 133.5mm tall and the base must be 100x100mm
- The pillars must be 8.5mm thick and have a 1mm or greater fillet on the edges
- No components can protrude farther than 6.5mm normal to the sides

Kinematics

- Freely tumbling CubeSat must be able to charge and send/receive communications regardless of orientation

Forces

- The weight must be under 2.00kg
- Center of gravity must be within + or – 2 cm from the geometric center
- A separation spring shall be used to provide separation between the neighboring CubeSats when exiting the dispenser (Max force less than 6.7N (1.5lbf) and a stroke length greater than 2.5mm (0.1in))
- Random vibration testing shall be performed to the levels and duration as defined by the Launch Provider

Energy

- Solar panels should supply an ample amount of charge to battery
- Circuits should utilize correct voltage and use voltage regulator as needed to provide proper voltage and current to hardware

Material

- The frame material should be unique and fabricated by additive manufacturing
- Surface roughness of rails must be less than 1.6 micrometers
- Surfaces in contact with the rails should be hard anodized to avoid cold-welding
- Must satisfy NASA low outgassing criteria (http://outgassing.nasa.gov)

Signals

- A deployment switch shall be used to indicate to the electronic system the CubeSat has been deployed. Minimum of one switch

- If the CubeSat deployment switch toggles from the actuated state and back, the satellite shall reset to a pre-launch state, including reset of transmission and deployable timers

Safety*

- All parts must remain attached to the CubeSat during launch, ejection, and operation
- The CubeSat shall include an remove before flight (RBF) pin, which cuts all power to the satellite once it is inserted into the satellite
- The RBF pin shall protrude no more than 6.5 mm from the CubeSat rail surface when it is fully inserted into the satellite
- CubeSats shall incorporate battery circuit protection for charging/discharging to avoid unbalanced cell conditions. Additional manufacturer documentation and/or testing will be required for modified, customized, or non-UL-listed cells
- CubeSat shall have at least three independent RF inhibits to prohibit inadvertent RF transmission
- CubeSat mission design and hardware shall be in accordance with NPR 8715.6 to limit orbital debris
- Thermal vacuum bakeout shall be performed to ensure proper outgassing of components

Quality Control

- Visual inspection of the CubeSat and measurement of critical areas will be performed per the CIFP (cubesat.org) or as defined by the Launch Provider

Transport

- Power system shall be in a power off state from delivery to deployment

Operation

- Operators shall obtain and provide documentation of proper licenses for use of radio frequencies
- CubeSats shall comply with their country's radio license agreements and restrictions
- All deployables such as booms, antennas, and solar panels shall wait to deploy a minimum of 30 minutes after the CubeSat's deployment switch(es) are activated during dispenser ejection
- CubeSats shall not generate or transmit a signal earlier than 45 minutes after on-orbit deployment

Costs*

- Must be under $2000

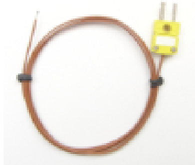
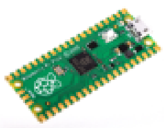
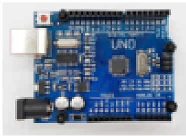
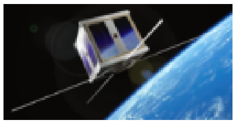
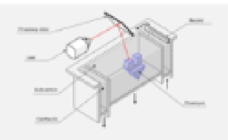
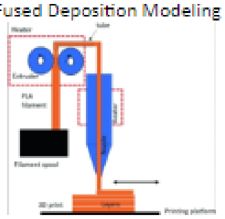
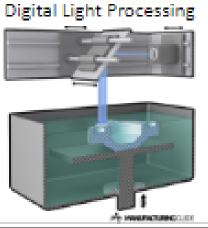
Schedules • Primary purchase order and BOM must be completed before Thanksgiving, 2022 • The CubeSat project must be completed by the end of the spring semester, May 2023

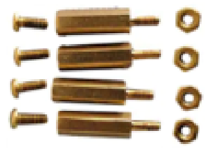
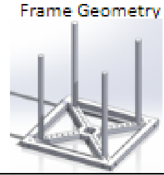
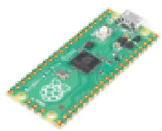
*Critical Requirements

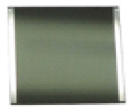
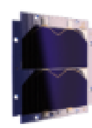
APPENDIX F

MORPHOLOGICAL CHART

Problem Statement: Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

Functions		Means			
		1	2	3	4
1.0	**Interact with the User**				
1.1	Provide data and telemetry				
1.1.1	Utilize temperature sensors	Thermistor 	Thermocouple 		
	(Underlying Physics)	(measures temperature dependant voltage across component)	(measures temperature dependant voltage across dissimlar wires)		
1.1.2	Process and convert data	Raspberry Pi Pico 	Arduino 		
	(Underlying Physics)	(converts analog to digital, processes and stores data)	(converts analog to digital, processes and stores data)		
1.1.3	Communicate data	One tape measure antenna and attitude control 	Four Tape Measure Dipole Antenna 		
	(Underlying Physics)	(Communicate data via radio waves. Utilize Earth's magnetic feild to correct cubesat into position)	(Communicate data via radio waves regardless of CubeSat Orientation)		
1.2	Demonstrate 3D printing material capabilities	Selective Laser Sintering 	Fused Deposition Modeling 	Stereolithography 	Digital Light Processing 
	(Underlying Physics)	(Powder and a laser sinters the powder)	(Filament is heated and extruded from nozzel to layer material)	(UV laser cures each layer of resin)	(Flashes of UV light that cures resin layer by layer)

Functions (Cont.)		Means (Cont.) 1	2	3	4
2.0	**Interact with the Internal Environment**				
2.1	Maximize available internal volume	Standoffs 	Rod & Spacers 	Frame Geometry 	
	(Underlying Physics)	(standoffs hold circuit board positions)	(slide circuit boards over rod and use spacers to separate boards)	(circuit board supports are incorporated into the frame geometry)	
2.2	Protect components				
2.2.1	Regulate thermal conditions	Mylar Wall Sheets 	Heat Blanket 	Mylar Radiation Shield 	
	(Underlying Physics)	(isolates internal thermal environemnt)	(controls thermal radiation)	(control thermal radiation via deployable shield)	
2.2.2	Prevent electrical malfunction	Voltage Regulator 	Power Allocation 		
	(Underlying Physics)	(ensure components recieve a constant voltage)	(computer regulates power given to each component or system)		

Functions (Cont.)		Means (Cont.) 1	2	3	4
3.0	**Interact with the External Environment**				
3.1	Generate solar energy	ANYSOLAR Cells 	Spectrolab Cells 	EnduroSat Solar Array 	
	(Underlying Physics)	(Monocrystalline cells with 25% efficiency)	(Ga-As cells with 30% efficiency)	(Ga-As cell assembly with 30% efficiency)	
3.2	Endure space conditions	Somos PerFORM 	CE221 	Ultrasint PA6 MF 	PEKK 
	(Underlying Physics)	(High melting temperature, rigidity, low coefficient of thermal expansion)	(High melting temperature, strong, lightweight, UV aging resistant)	(High melting temperature, strong, lightweight)	(relatively strong, good temperature resistance, very lightweight)

APPENDIX G

DESIGN ALTERNATIVES

Problem Statement: Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

Functions		Alternatives			
		1	2	3	4
1.0	**Interact with User**				
1.1	Provide data and telemetry				
1.1.1	Utilize temperature sensors	Thermistor	Thermistor	Thermocouple	Thermistor
1.1.2	Process and convert data	Raspberry Pi Pico	Raspberry Pi Pico	Arduino	Raspberry Pi Pico
1.1.3	Communicate data	Four Tape Measure Dipole Antennas	Four Tape Measure Dipole Antennas	One tape meaure antenna and attitude control	Four Tape Measure Dipole Antennas
1.2	Demonstrate 3D printing material capabilities	DLP	Fused Deposition Modeling	SLS	Fused Deposition Modeling
2.0	**Interact with the Internal Environment**				
2.1	Maximize available internal volume	Standoffs	Frame Geometry	Frame Geometry	Standoffs
2.2	Protect components				
2.2.1	Regulate thermal conditions	Mylar Wall Sheets	Mylar Wall Sheets	Mylar Radiation Shield	Mylar Wall Sheets
2.2.2	Prevent electrical malfunction	Voltage Regulator	Power Allocation	Voltage Regulator	Voltage Regulators
3.0	**Interact with the External Environment**				
3.1	Generate Solar Energy	ANYSOLAR Cells	Spectrolab Cell	EnduroSat Solar Array	ANYSOLAR Cells
3.2	Endure Space Conditions	CE221	PEKK	Ultrasint PA6	PEKK

APPENDIX H

DECISION MATRIX

Problem Statement: Design a CubeSat that will test an additively manufactured frame material. The CubeSat should be high-quality, durable, meet the requirements for launch laid out in the Cal Poly and NASA handbooks, and must not exceed $2000. The project should be completed by the end of the spring semester (May 2023).

Alternative 1:
Thermistor, Raspberry Pi Pico, four tape measure dipole antennas, DLP, standoffs, mylar wall sheets, voltage regulator, ANYSOLAR cells, CE221

Alternative 2:
Thermistor, Raspberry Pi Pico, four tape measure dipole antennas, fused deposition modeling, frame geometry, mylar wall sheets, power allocation, spectrolab cell, PEKK

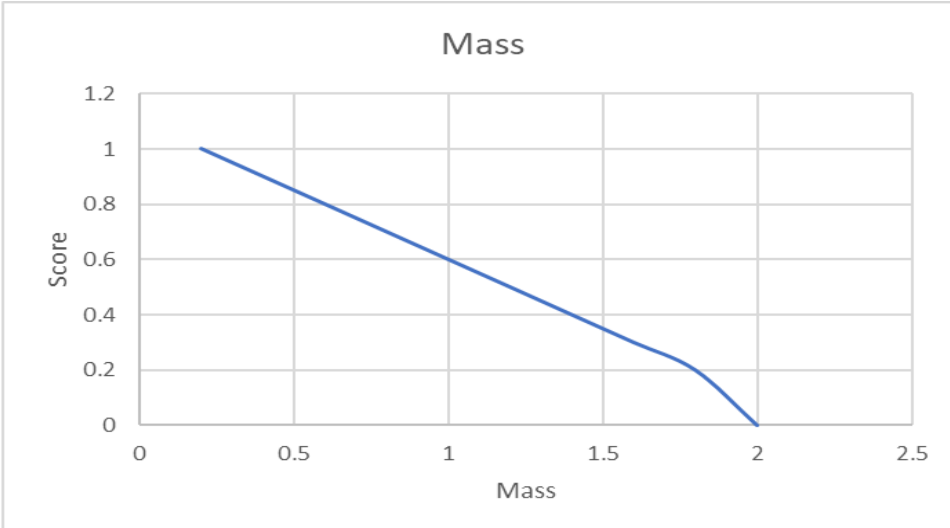
Alternative 3:
Thermocouple, Arduino, One tape measure antenna and attitude control, Selective Laser Sintering, Frame Geometry, mylar radiation sheild, voltage regulator, EnduroSat Solar Array, Ultrasint PA6 MF

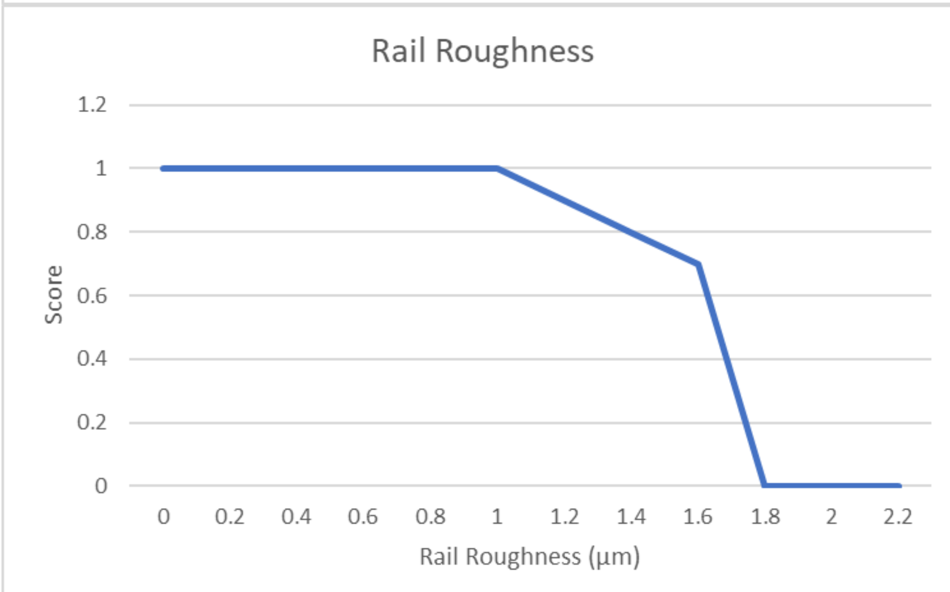
Alternative 4:
Thermistor, Raspberry Pi Pico, four tape measure antennas, fused deposition modeling, standoffs, mylar wall sheets, voltage regulator, ANYSOLAR cells, PEKK

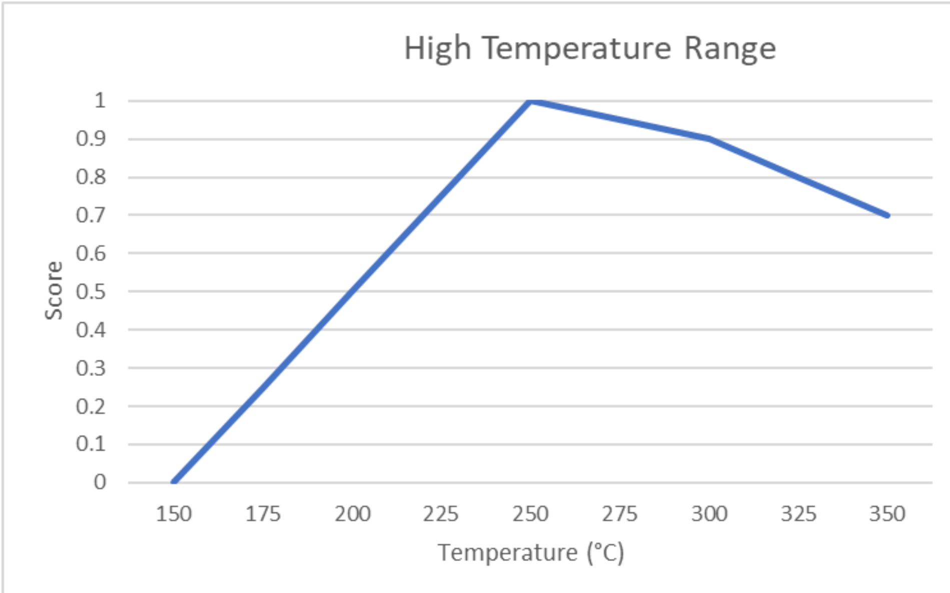
			Alternative 1			Alternative 2			Alternative 3			Alternative 4		
Design Criterion	Weight Factor	Units	Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating	Magnitude	Score	Rating
Volume	0.094	cm^3	1000	1	0.094	1000.0	1	0.094	1000	1	0.094	1000	1	0.094
Mass	0.123	kg	0.09	0.65	0.08	0.098	0.6	0.0738	0.108	0.59	0.0726	0.098	0.6	0.0738
Rail Surface Roughness	0.113	um	2.4	0	0	0.667	0.58	0.0655	3.9	0	0	0.667	0.58	0.0655
High Temperature Requirement	0.155	C	230	0.8	0.124	200	0.5	0.0775	209	0.58	0.0899	200	0.5	0.0775
Low Temperature Requirement	0.155	C	-90	0.8	0.124	-70	0.9	0.1395	-75	0.775	0.1201	-70	0.9	0.1395
Vibration Resistance	0.123	Hz	2000	1	0.123	2000	1	0.123	2000	1	0.123	2000	1	0.123
Frame Material Density	0.078	g/cm^3	1.20	0.8	0.0624	1.14	0.9	0.0702	1.44	0.35	0.0273	1.14	0.9	0.0702
Center of Mass to Geometric Center	0.042	cm	0.00	1	0.042	0.00	1	0.042	0.00	1	0.042	0.00	1	0.042
Financial Budget	0.117	$	700	1	0.117	2950	0	0	5000	0	0	550	1	0.117
				Total Rating	**0.766**		Total Rating	**0.686**		Total Rating	**0.569**		Total Rating	**0.803**

Recommendation: Pursue further consideration and development of Alternatives 1 and 4 because they had the hghest rating.

UTILITY CURVES






High Temperature Range
Score
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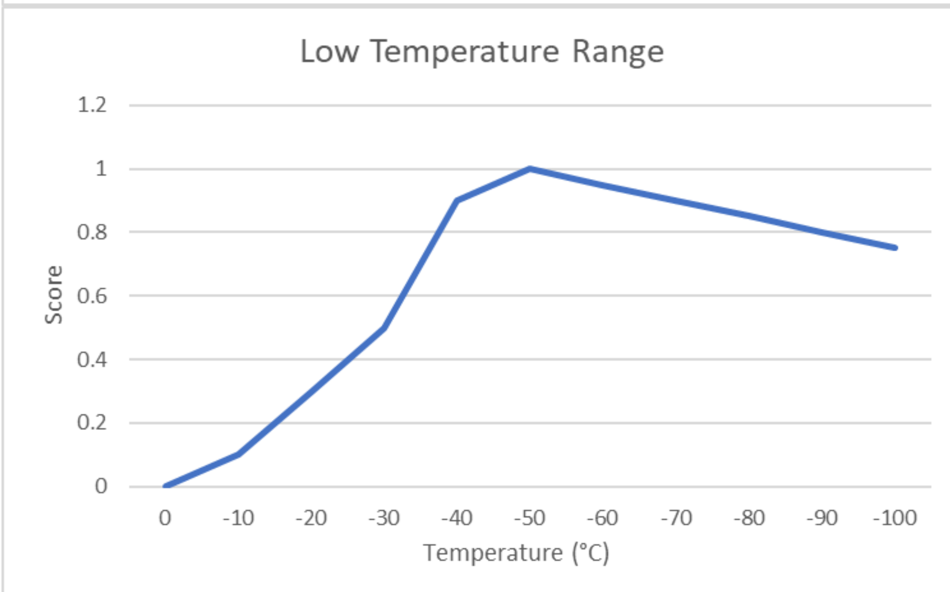
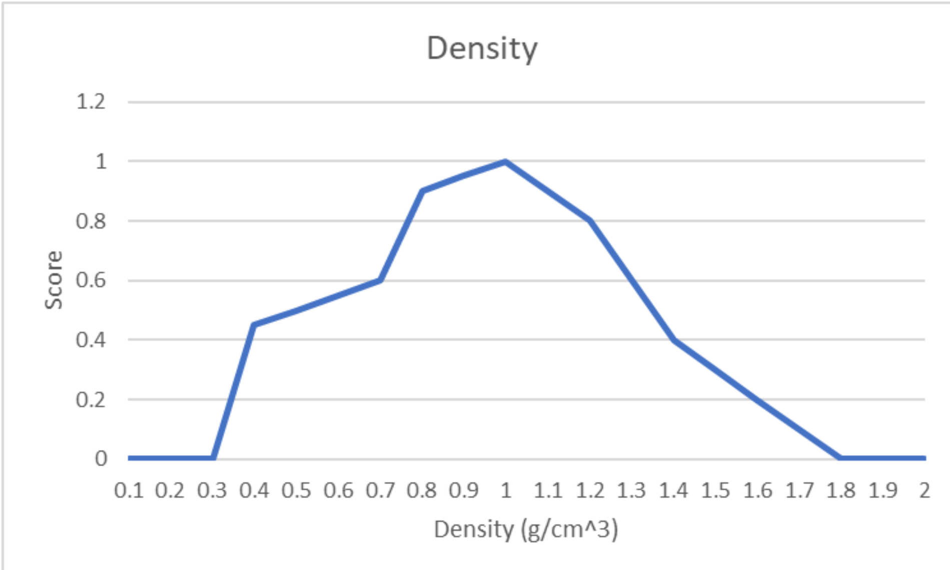
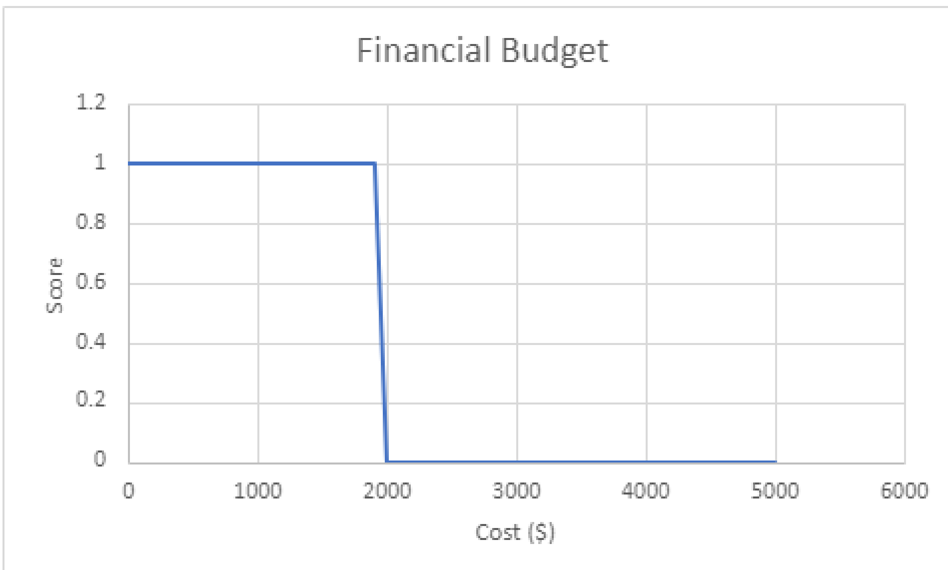
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
150
175
200
225
250
275
300
325
350
Temperature (°C)


Low Temperature Range
Score
1.2
1
0.8
0.6
0.4
0.2
0
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
Temperature (°C)


Density
Score
1.2
1
0.8
0.6
0.4
0.2
0
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2
Density (g/cm^3)


Financial Budget
Score
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1
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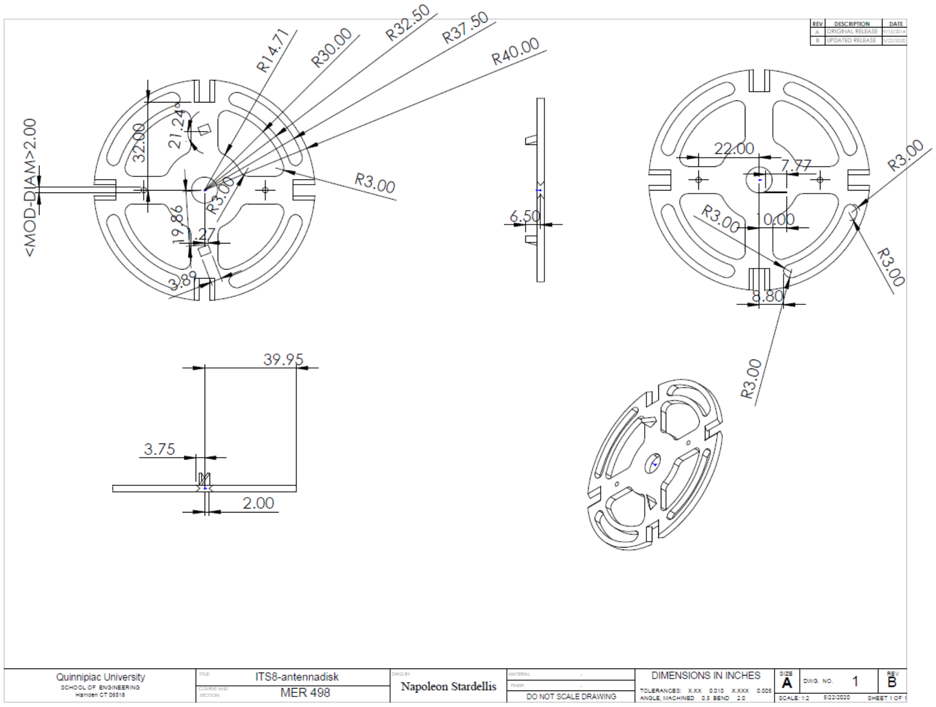
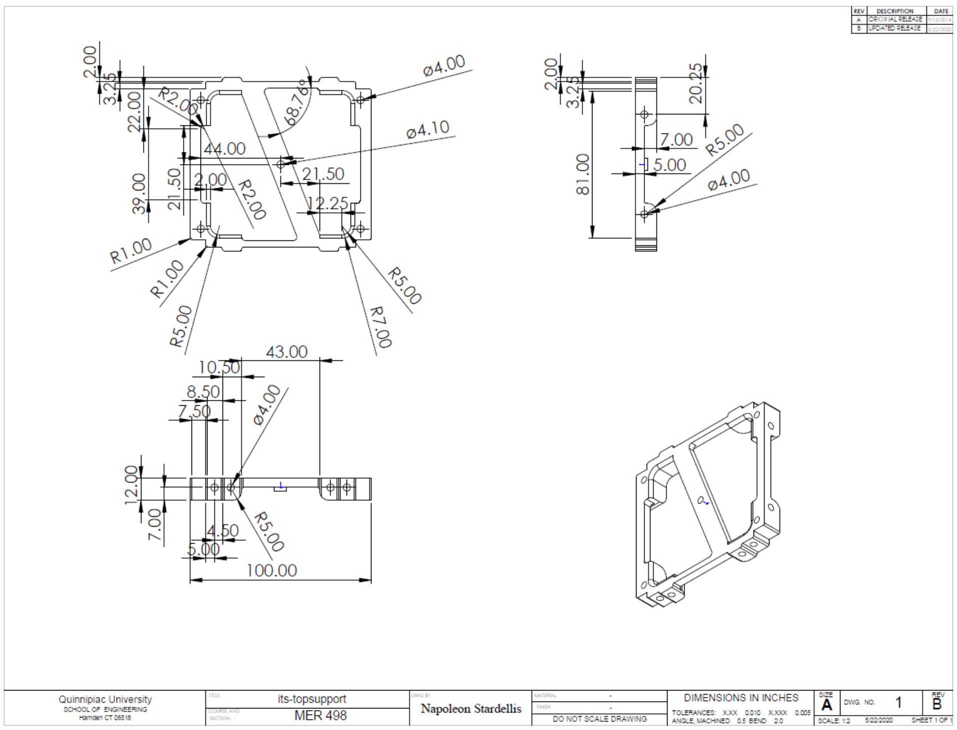
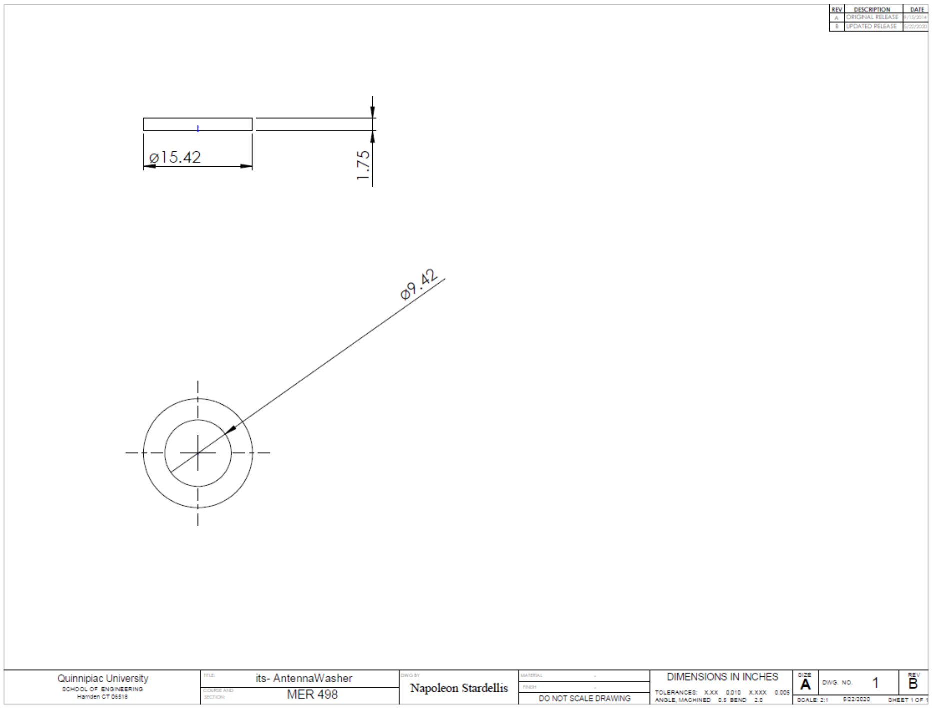
0.6
0.4
0.2
0
0 1000 2000 3000 4000 5000 6000
Cost ($)

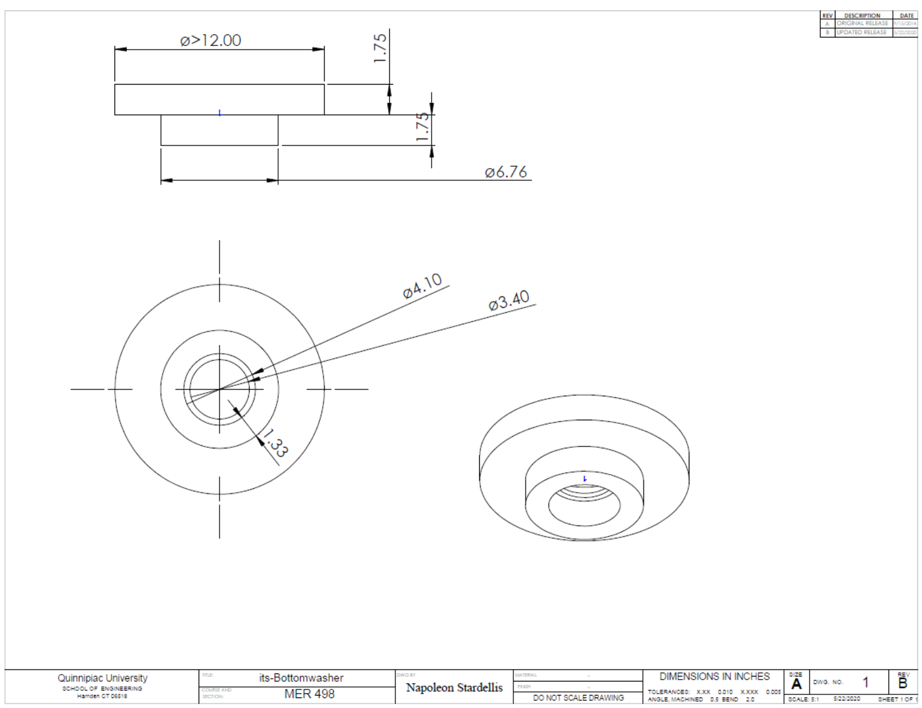
APPENDIX I

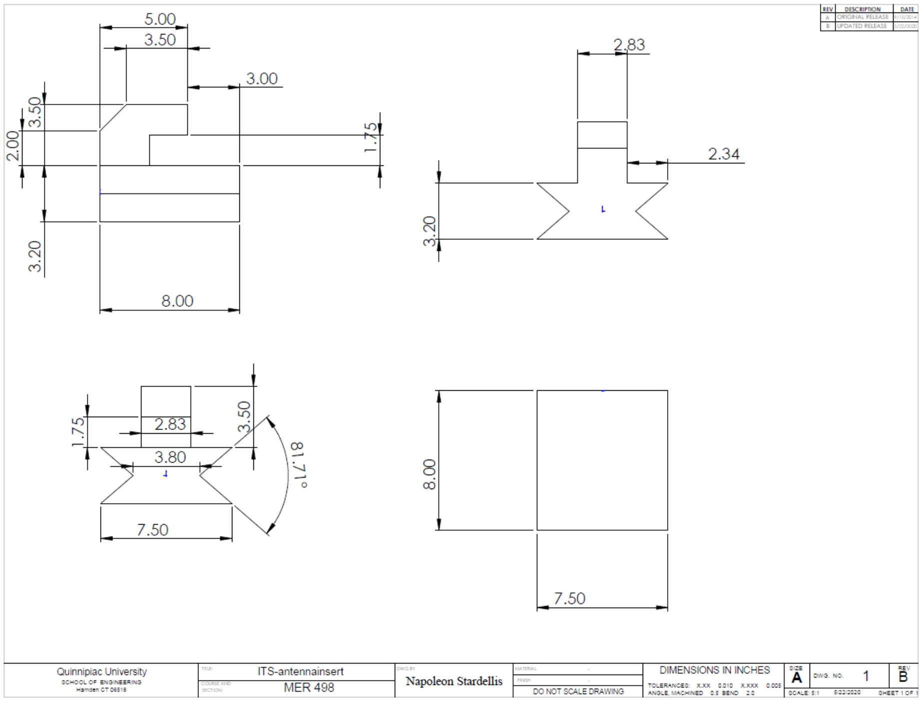
ENGINEERING DRAWINGS



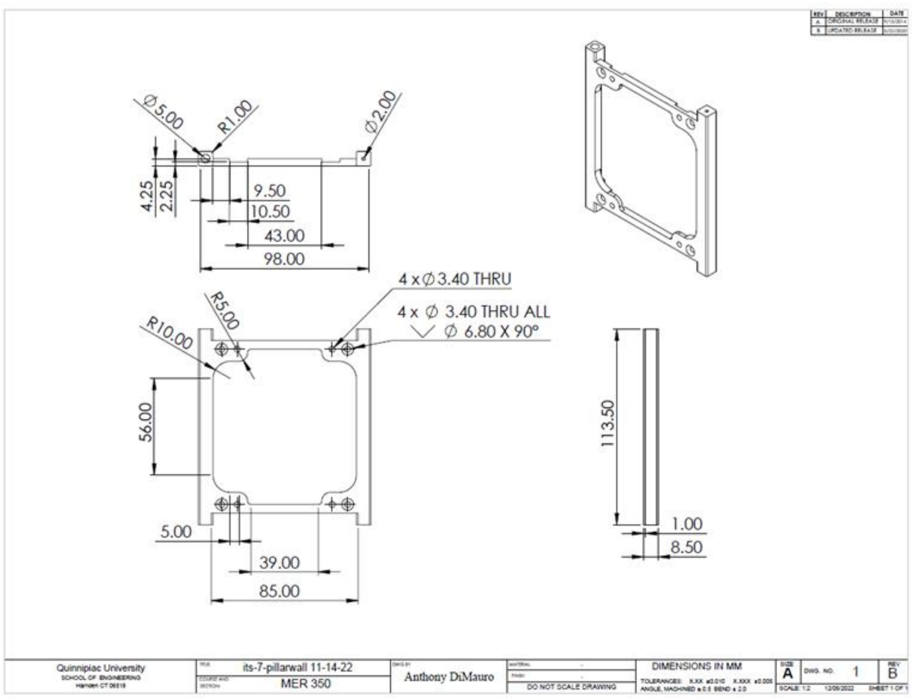



⌀15.42
1.75
⌀9.42
Quinnipiac University
its- AntennaWasher
MER 498
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN INCHES
A
1
B

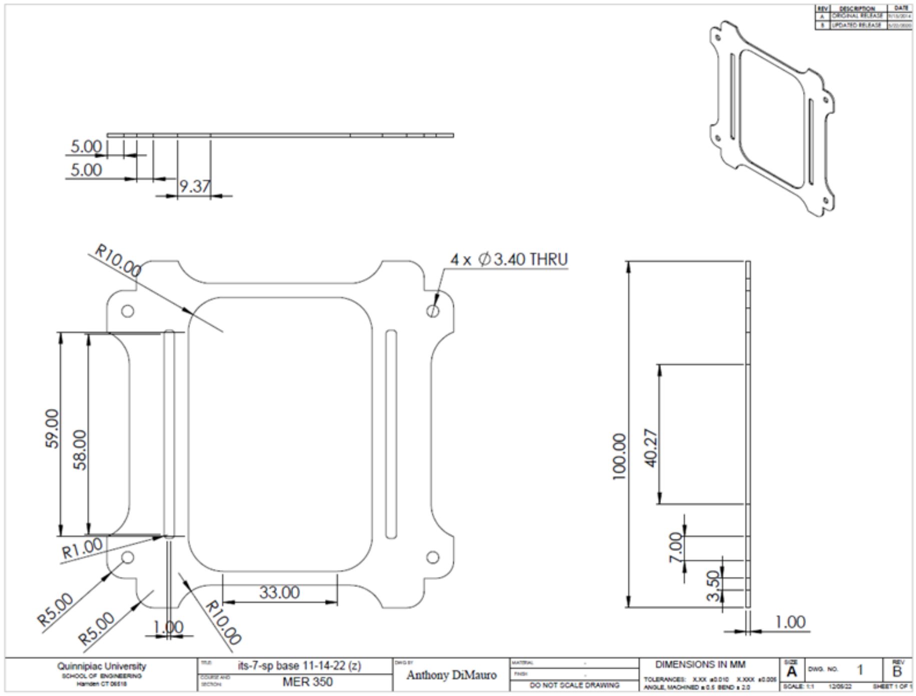

⌀>12.00
1.75
1.75
⌀6.76
⌀4.10
⌀3.40
1.33
Quinnipiac University
its-Bottomwasher
MER 498
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN INCHES
A
1
B



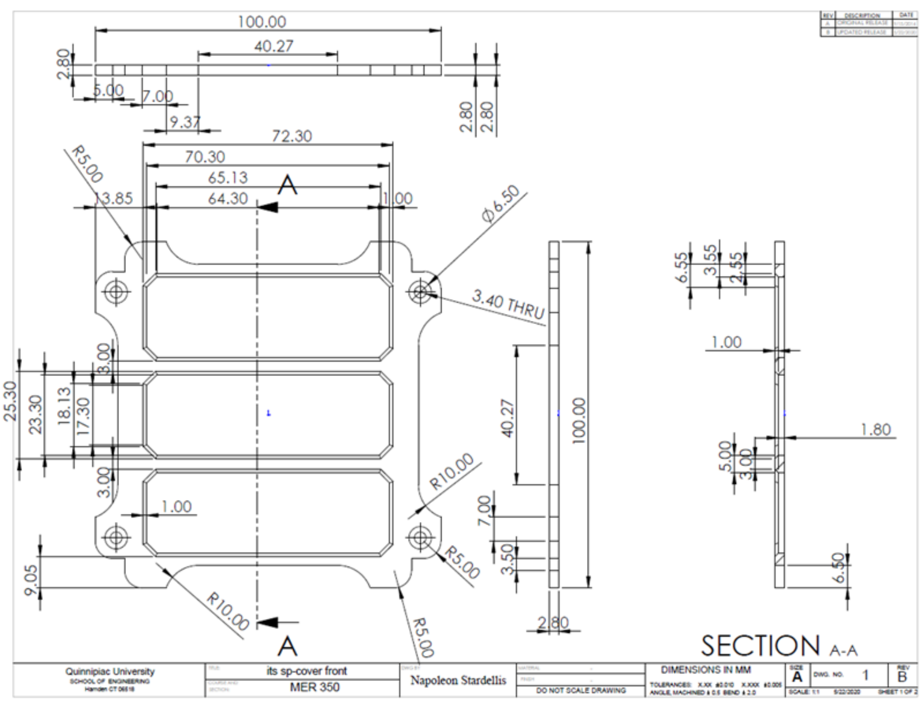
Quinnipiac University
SCHOOL OF ENGINEERING
ITS-antennainsert
MER 498
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN INCHES
A
1
B



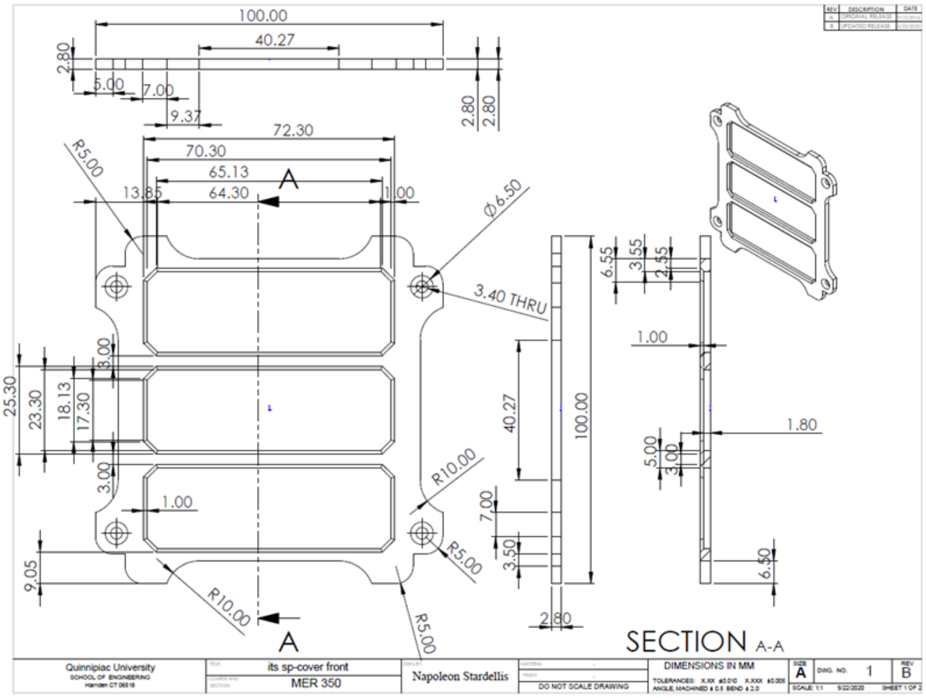
4 x Ø 3.40 THRU
4 x Ø 3.40 THRU ALL
Ø 6.80 X 90°
Quinnipiac University
SCHOOL OF ENGINEERING
its-7-pillarwall 11-14-22
MER 350
Anthony DiMauro
DO NOT SCALE DRAWING
DIMENSIONS IN MM
A
1
B

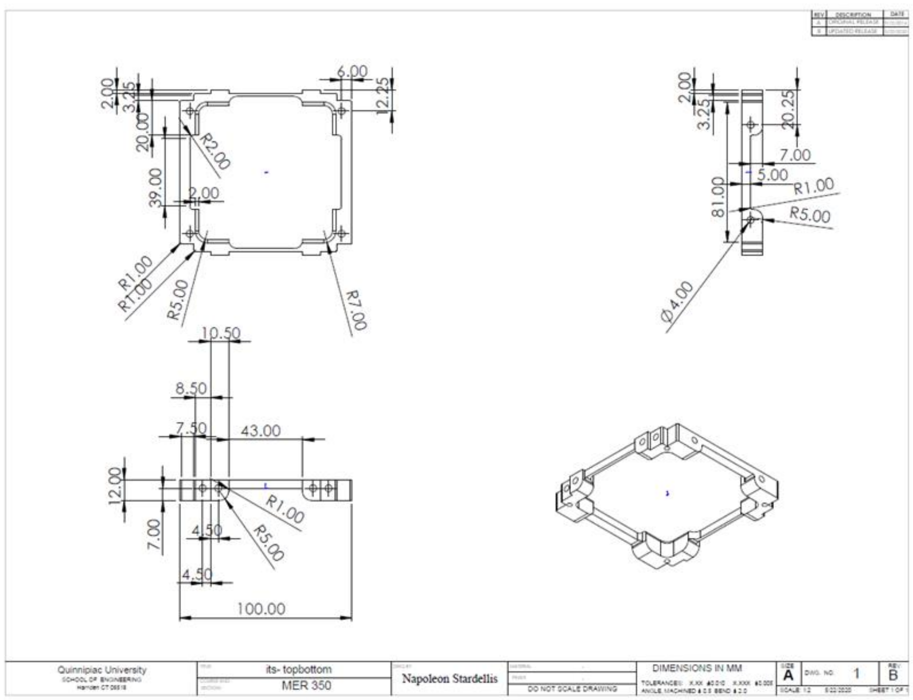


4 x ∅3.40 THRU
R10.00
59.00
58.00
R1.00
R5.00
R5.00
1.00
R10.00
33.00
100.00
40.27
7.00
3.50
1.00
5.00
5.00
9.37
Quinnipiac University
SCHOOL OF ENGINEERING
its-7-sp base 11-14-22 (z)
MER 350
Anthony DiMauro
DO NOT SCALE DRAWING
DIMENSIONS IN MM
A
1
B



100.00
40.27
2.80
5.00
7.00
9.37
2.80
2.80
72.30
70.30
65.13
64.30
13.85
1.00
R5.00
A
∅6.50
3.40 THRU
3.00
25.30
23.30
18.13
17.30
3.00
1.00
R10.00
R5.00
9.05
R10.00
R5.00
40.27
100.00
7.00
3.50
2.80
6.55
3.55
2.55
1.00
1.80
5.00
3.00
6.50
SECTION A-A
Quinnipiac University
SCHOOL OF ENGINEERING
its sp-cover front
MER 350
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN MM
A
1
B


100.00
40.27
72.30
70.30
65.13
64.30
A
SECTION A-A
3.40 THRU
Quinnipiac University
SCHOOL OF ENGINEERING
its sp-cover front
MER 350
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN MM


100.00
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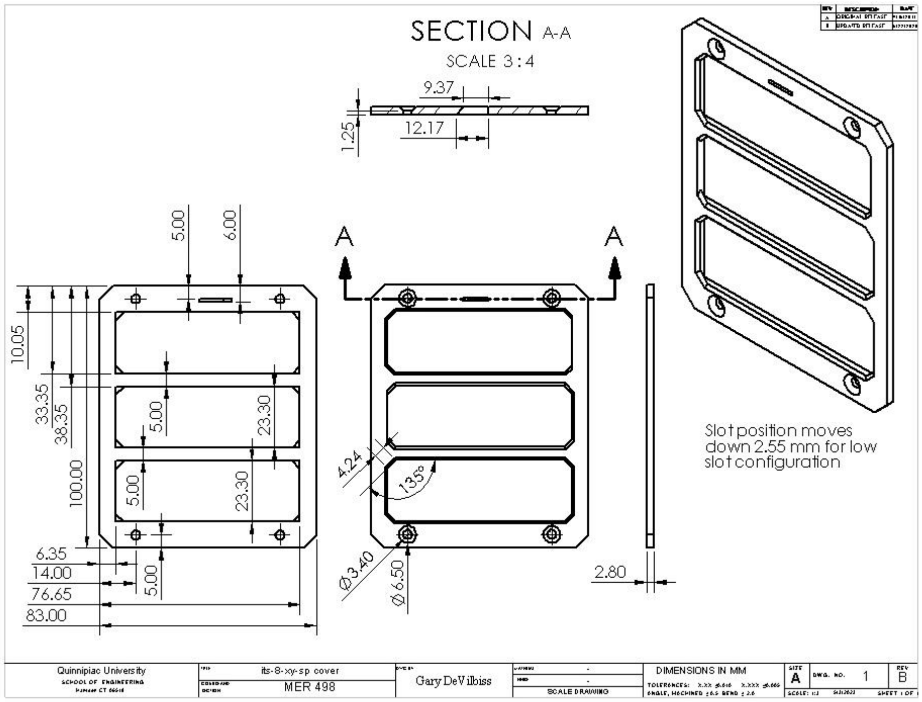
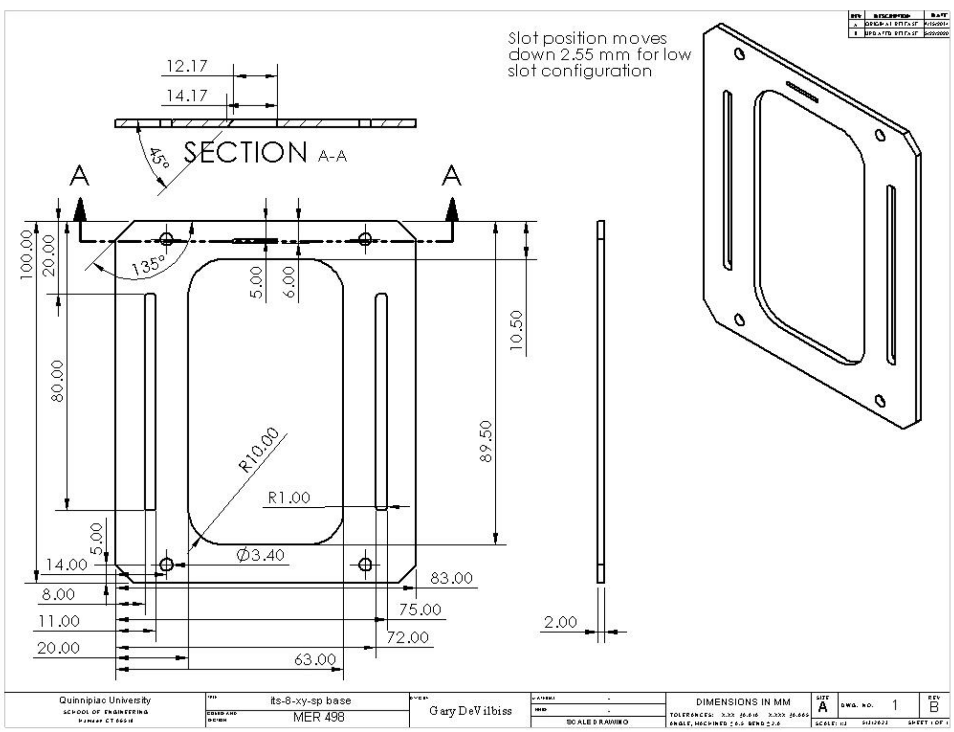
Quinnipiac University
SCHOOL OF ENGINEERING
its- topbottom
MER 350
Napoleon Stardellis
DO NOT SCALE DRAWING
DIMENSIONS IN MM


SECTION A-A
SCALE 3 : 4
9.37
12.17
1.25
A
A
10.05
33.35
38.35
100.00
5.00
6.00
23.30
4.24
135°
6.35
14.00
76.65
83.00
Ø3.40
Ø6.50
2.80
Slot position moves down 2.55 mm for low slot configuration
Quinnipiac University
SCHOOL OF ENGINEERING
its-8-xy-sp cover
MER 498
Gary DeVilbiss
SCALE DRAWING
DIMENSIONS IN MM
A
1
B


Slot position moves down 2.55 mm for low slot configuration
12.17
14.17
45°
SECTION A-A
A
A
100.00
20.00
135°
5.00
6.00
10.50
80.00
89.50
R10.00
R1.00
Ø3.40
14.00
8.00
11.00
20.00
63.00
83.00
75.00
72.00
2.00
Quinnipiac University
SCHOOL OF ENGINEERING
its-8-xy-sp base
MER 498
Gary DeVilbiss
SCALE DRAWING
DIMENSIONS IN MM
A
1
B

APPENDIX J

BILL OF MATERIALS

Purchase

Qty	Part/Material Description	Part Number	Unit Cost	Total Cost	Vendor	Delevery Date	Date Required	Responsible
2	Raspberry Pi Pico H	DEV-17829	$6.00	$12.00	PiShop	11/15/2023	5/5/2023	Rocco
20	THERMISTOR NTC 10KOHM 3887K BEAD	480-3158-ND	$6.40	$128.00	Digi-key	4/28/2023	5/5/2023	Rocco
3	Analog to digital converter MCP3008	856	$4.50	$13.50	Adafruit	2/20/2023	5/5/2023	Rocco
1	Micro SD card (2-pack)	N/A	$25.00	$25.00	Amazon	2/20/2023	5/5/2023	Rocco
2	MicroSD card breakout board+	254	$7.50	$15.00	Adafruit	2/20/2023	5/5/2023	Rocco
50	RES 10K OHM 1% 1/4W AXIAL	RNF14FTD10K0CT-ND	$0.05	$2.50	Digikey	4/28/2023	5/5/2023	Rocco
2	Heat-Set Inserts for Plastic, Aluminum, M3 x 0.5 mm, 5.9 mm Installed Length	94459A421	$7.55	$15.10	McMaster	11/4/2022	5/5/2023	Rocco
1	18-8 Stainless Steel Hex Drive Flat Head Screw, M3 x 0.5 mm Thread, 10 mm Long	92125A130	$7.31	$7.31	McMaster	11/4/2022	5/5/2023	Rocco
1	Corrosion-Resistant Compression Springs	2006N105	$15.96	$15.96	McMaster	3/20/2023	5/5/2023	Rocco
4	BREADBOARD TERM STRIP 3.40X3.20"	377-2091-ND	$9.00	$36.00	Digikey	4/28/2023	5/5/2023	Rocco
2	Adafruit RFM96W LoRa Radio Transceiver Breakout - 433 MHz - RadioFruit	1528-1668-ND	$19.95	$39.90	Digikey	4/6/2023	5/5/2023	Gary
1	Stanley 39-130 3 x 1/4-Inch PowerLock Key Tape	B00002X2HB	$6.99	$6.99	Amazon	3/27/2023	5/5/2023	Gary
1	Clear Nylon line	9442T5	$7.00	$7.00	Amazon	3/27/2023	5/5/2023	Napoleon
1	TRANS NPN 400V 0.3A TO92-3	KSP44BU	$0.48	$0.48	Digi-key	4/28/2023	5/5/2023	Napoleon
1	Torsion Spring 90 Degree Left-Hand Wound, 0.309" OD	9287K205	$2.91	$2.91	McMaster	3/20/2023	5/5/2023	Napoleon
10	Tenergy Li-ion 18650 Cylindrical 3.7V 2600mAh Flat Top Rechargeable Battery-UL listed	MH48285	$5.99	$59.90	Tenergy Power	3/21/2023	5/5/2023	Anthony
21	ANYSOLAR MONOCRYST SOLAR CELL G3 THIN 6.91V 307MW	2994-SM141K10L-ND	$9.96	$209.16	Digikey	4/6/2023	5/5/2023	Anthony
4	IC BATT MFUNC LI-ION 1CELL 24QFN	LTC4066EUF#PBF-ND	$7.11	$28.44	Digikey	4/6/2023	5/5/2023	Anthony
8	DEANS CONNECTOR - M/F PAIR	1568-1659-ND	$1.05	$8.40	Digikey	4/6/2023	5/5/2023	Anthony
5	IC OR CTRLR SRC SELECT 16DFN	LTC4415EDHC#PBF-ND	$9.74	$48.70	Digikey	4/6/2023	5/5/2023	Anthony
1	Frame Pillar Walls (its-8-pillarwall)	N/A	$117.00	$117.00	Stratasys	N/A	N/A	Rocco
2	Frame Bottom Support (its-8-bottomsupport)	N/A	$74.00	$148.00	Stratasys	N/A	N/A	Rocco
1	Frame Top Support (its-8-topsupport)	N/A	$133.00	$133.00	Stratasys	N/A	N/A	Rocco
2	XY Solar Panel Base High (its-8-xy-sp base high)	N/A	$64.00	$128.00	Stratasys	N/A	N/A	Rocco
2	XY Solar Panel Base Low (its-8-xy-sp base low)	N/A	$64.00	$128.00	Stratasys	N/A	N/A	Rocco
2	XY Solar Panel Cover High (its-8-sp cover high)	N/A	$60.00	$120.00	Stratasys	N/A	N/A	Rocco
2	XY Solar Panel Cover Low (its-8-sp cover low)	N/A	$60.00	$120.00	Stratasys	N/A	N/A	Rocco
2	Z Solar Panel Base (its-8-z-sp base)	N/A	$66.00	$132.00	Stratasys	N/A	N/A	Rocco
2	Z Solar Panel Cover (its-8-z-sp cover)	N/A	$60.00	$120.00	Stratasys	N/A	N/A	Rocco
			Total:	$1,828.25				

APPENDIX K

SUPPORTING CALCULATIONS

Antenna Length Calculation

assume:

$c = 2.9979 \times 10^8$ m/s (speed of light) $\quad f = 437$ MHz $= 4.37 \times 10^8$ Hz (frequency) $\quad n \equiv$ Natural #

$c = f\lambda$ $\quad \lambda \equiv$ wavelength

$$\lambda = c/f = \frac{2.9979 \times 10^8}{4.37 \times 10^8} = 0.68602 \text{ m}$$

$L \equiv$ antenna length

$$L = \frac{\lambda}{2^n}$$

n	L(m)
1	0.34301
2	0.17151
3	0.08575
4	0.04288

Choose $L = 8.575$ cm or $L = 4.228$ cm to fit inside CubeSat

APPENDIX L

TEST PLAN

This section of the appendix contains test plans and results that were used to determine the properties of the CubeSat and how well they meet the engineering specifications as well as vibration simulation results. See next page for test plans.

Test Title: High Temperature Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: High Temperature Requirement **Test Director:** Gary DeVilbiss	**Date Test Conducted** Untested **Conditions** • Location (Eastview 410) • Time required to conduct test (90 minutes)

Test Abstract

Target/Goal: > 100°C
Target Achieved (Y/N): Untested, In-Progress
If not, Plan of Action: Analyze possible causes for failure and redesign thermal control system or reselect necessary components.
Note: Untested because a complete CubeSat assembly has not been achieved.

Resources Required

Personnel	**Supplies/Equipment**	**Facilities**
Gary DeVilbiss Marcus Rocco Fratarcangeli	Assembled CubeSat Oven Oven Mitts	N/A

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) **Likeliness to Occur and Severity if it Occurs**	**Mitigation Measures**
Burns (Low Risk)	Wear PPE

Test Procedure

Description (with pictures and/or standards if applicable)
1. Preheat Oven to 100°C 2. Wear oven mitts and place battery powered CubeSat inside oven for 45 minutes 3. Remove CubeSat from oven while wearing oven mitts 4. Ensure CubeSat is still functioning after cooling back down to room temperature

Test Title: Low Temperature Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Low Temperature Requirement **Test Director:** Gary DeVilbiss	**Date Test Conducted** Untested **Conditions** • Location (CCE038) • Time required to conduct test (90 minutes)

Test Abstract

Target/Goal: < -54°C
Target Achieved (Y/N): Untested, In-Progress
If not, Plan of Action: Analyze possible causes for failure and redesign thermal control system or reselect necessary components.
Note: Untested because a complete CubeSat assembly has not been achieved.

Resources Required

Personnel	**Supplies/Equipment**	**Facilities**
Gary DeVilbiss Marcus Rocco Fratarcangeli Anthony DiMauro Napoleon Stardellis	Styrofoam Cooler Dry Ice Tongs Thermostat Safety Glasses	CCE038

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	**Mitigation Measures**
Burns (Low)	Use tongs while handling dry ice and CubeSat
Explosion (Low)	Poke holes in cooler to vent evaporating CO_2 Wear Safety Glasses

Test Procedure

Description (with pictures and/or standards if applicable)
1. Place dry ice and thermostat inside Styrofoam cooler and close the cooler
2. Check thermostat to ensure the cooler has reached a temperature below 54°C
3. Use tongs to place the battery powered CubeSat inside the cooler
4. Leave CubeSat inside cooler for 45 minutes
5. Use tongs to remove CubeSat and allow it to warm up to room temperature
6. Ensure CubeSat still functions

Test Title: Random Vibrations Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Vibration Resistance **Test Director: Facility Operator**	**Date Test Conducted** Untested **Conditions** • Location (Princeton University CubeSat Center) • Time required to conduct test (120 minutes)

Test Abstract

Target/Goal: 2000 Hz @ 0.01g^2/Hz
Target Achieved (Y/N): Untested, In-Progress
If not, Plan of Action: Adjust frame design in high stress/displacement areas before reconstructing and repeating test.
Note: Untested because a complete CubeSat assembly has not been achieved. Test would be conducted using NASA testing facility operator.

Resources Required

Personnel	**Supplies/Equipment**	**Facilities**
Final Frontier team members Testing facility personnel	PPE Vibration Table	(Princeton University CubeSat Center)

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) **Likeliness to Occur and Severity if it Occurs**	**Mitigation Measures**
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Follow chosen facility protocols and procedures to complete random vibration testing adhering to the NASA Vibroacoustic testing standards **(Table 1):**

20 Hz	@	0.01 g^2/Hz
20 to 80 Hz	@	+3 dB/oct
80 to 500 Hz	@	0.04 g^2/Hz
500 to 2000 Hz	@	-3 dB/oct
2000 Hz	@	0.01 g^2/Hz
Overall Level	=	6.8 grms

Table 1: NASA Payload Vibroacoustic Test Criteria

Test Title: Random Vibrations Simulation Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Vibration Resistance **Test Director:** Anthony DiMauro	**Date Test Conducted** 4/5/2023 **Conditions** • Location (CCE-032) • Time required to conduct test (~90 minutes depending on program runtime)

Test Abstract

Target/Goal: 2000 Hz @ 0.01 g^2/Hz
Target Achieved (Y/N): Yes, however battery holders failed to mesh in simulation. Holders are expected to increase displacement of PCB. No significant displacement or stress of thermoplastic frame identified.

If not, Plan of Action: Adjust frame design in high stress/displacement areas.

Resources Required

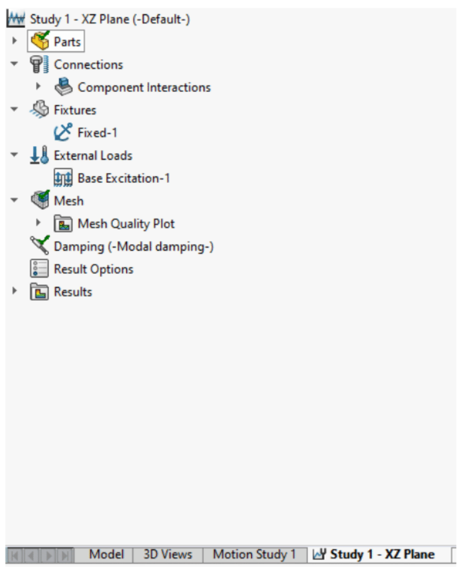
Personnel	**Supplies/Equipment**	**Facilities**
Student	SolidWorks (Simulation Software)	CCE-032 (Engineering Lab)

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)

1. Open the SolidWorks assembly file for the latest cube satellite design
 	
2. Click on the **Simulation** tab and then click **New Study**
    a. Give the study a name
    b. Under **Advanced Simulation**, select **Linear Dynamic,** then select **Random Vibration**
    c. Click OK
 	

 	
Figure 1: Simulation Study Tree
 	
3. In the Simulation Study Tree, set the following study options and controls (compare settings with **Figure 1**):
    a. Right-click on the top-level study name and select **Properties**…
        i. Under **Frequency Options**, set solver to FFEPlus.
        ii. Under **Random Vibration Options**, set the following values for Operating Frequency Limits:
            1. Units: Cycles/sec (Hz)
            2. Lower Limit: 20
            3. Upper Limit: 2000
        iii. Click OK
    b. Open the **Parts** tab and ensure that each part has a selected material
        i. Right click on each part and select **Apply/Edit Material…**
        ii. After the correct material is selected, click **Apply** then close

c. Right-click on the **Connections** tab and create a new **component interaction**
    i. Check the global interaction box and select the assembly in the bodies window
    ii. Under properties, set the gap range for bonding to .1 mm
    iii. Click OK
d. Right-click on the **Fixtures** tab and select **Fixed Geometry**
    i. Under **Faces, Edges, Vertices for Fixture** select all eight of the corner rail top and bottom faces of the cube satellite assembly in the graphics window and click OK.
e. Right-click on the **External Loads** tab and select **Selected Base Excitation**
    i. Under **Type**, select **Acceleration**
    ii. Under **PSD Acceleration,** select **g^2/Hz** and then select the plane for the load to be applied by entering a value of 1 in its value window.

        NOTE: For 1U cube satellites, the load will most likely be applied along Plane Dir. 2 (Bottom to Top).

        NOTE: Multiple tests can be simulated in each direction if required.

    iii. Under **Variation with Frequency**, select Curve and then click **Edit…**
        1. Enter a name for the curve and then next to **Shape** select User defined.
        2. In **Curve Data**, select Hz for Units in the X column and N/A for units in the Y Column (units in this column will be set to those previously selected in the acceleration section)
        3. Enter data points to test according to the vibration requirements (See **Table 1** and **Figure 2**).
        4. NOTE: Click on the last point number to add new points.

Table 1: NASA Payload Vibroacoustic Test Criteria

20 Hz	@	0.01 g^2/Hz
20 to 80 Hz	@	+3 dB/oct
80 to 500 Hz	@	0.04 g^2/Hz
500 to 2000 Hz	@	-3 dB/oct
2000 Hz	@	0.01 g^2/Hz
Overall Level	=	6.8 grms

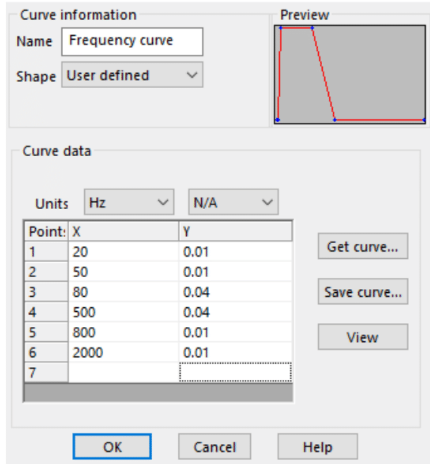


Figure 2: Frequency Curve Window Example

5. Once the desired frequency curve is set, click OK to exit the window, then click OK again

f. Right-click on **Damping** and select **Edit/Define…**
   i. Under Options, select Modal damping and uncheck **Compute from material damping** *unless* you are confidant in the complete accuracy of material properties selected in the model
   ii. If you unchecked **Compute from material damping** in the previous step, set the damping Ratios value under the **Damping Ratios** column header to an estimated 1/40.
   iii. Click OK

4. Right-click on **Mesh**
   a. Set the initial **Mesh Density** to a lower (coarse) value by using the slider. If necessary, set **Mesh Parameters** to Blended curvature-based and alter number of elements and element sizes.
   b. Click OK, and wait for the mesh to complete. If any errors or distorted elements appear, open the **Mesh Advisor** by right-clicking on **Mesh** again and follow the steps to remove any issues.
   c. Repeat the steps **a.** and **b.** if necessary, gradually making the mesh density finer.

   NOTE: Time to mesh will depend greatly on system hardware.

5. Check to make sure each part under the **Parts** tab each has an assigned material and is properly meshed. Each part should have a green mesh and check mark.

6. Right click on the study name and select **Run**. The solver will generate contact points and then begin running the analysis. After it is complete, plots will appear in the **Results** folder. These can be modified and additional plots can be generated based on desired data of stress and strain in the model.

7. Export graphical data and results of the test design decision making based on high stress and displacement areas in the plots.

Test Title: Assembled CubeSat Mass Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Mass **Test Director:** Gary DeVilbiss	**Date Test Conducted** 04/04/2023 **Conditions** • Location (CCE038) • Time required to conduct test (15 minutes)

Test Abstract

Target/Goal: < 1.33 kg
Target Achieved (Y/N): Y, 0.526 kg
If not, Plan of Action: If mass is less than 2.00 kg mass requirement set by Cal Poly, discuss with CubeSat design team if measured mass is acceptable before making redesign decisions.
Note: Test was conducted using SolidWorks instead of the listed procedure because a complete CubeSat assembly has not been achieved. Further testing required.

Resources Required

Personnel	Supplies/Equipment	Facilities
Gary DeVilbiss	Assembled CubeSat Scientech Scale	CCE038

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Zero Scale with enclosure closed 2. Open enclosure and place assembled CubeSat inside 3. Close enclosure and record the mass 4. Open enclosure and remove CubeSat 5. Repeat Steps 1 – 4 five times 6. Calculate average mass and error

Test Title: Cost Analysis **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Cost **Test Director: Project Team**	**Date Test Conducted** 5/3/2023 **Conditions** • Location (CCE-038) • Time required to conduct test (project duration)

Test Abstract

Target/Goal: < $2000
Target Achieved (Y/N): Y, $1828.25
If not, Plan of Action: Consult with all team members and advisor to discuss cost mitigation.

Note: This cost includes the quoted price from Stratasys for 3D printing the frame but does not include the cost of PCBs because breadboards are being used in the prototype final design.

Resources Required

Personnel	**Supplies/Equipment**	**Facilities**
All project members	Excel (Data handling program)	CCE-038

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Consult project bill of material (BOM) and identify manufacturing costs when ordering parts to track total expenses.

Test Title: Rail Surface Roughness Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Engineering Characteristic: Rail Surface Roughness **Test Director:** Fratarcangeli	**Date Test Conducted:** Untested **Conditions** • Location (3D Printing Facility) • Time required (TBD)

Test Abstract

Target/Goal: <= 1.6um
Target Achieved (Y/N): Untested, in progress
If not, Plan of Action: Find out whether the surface roughness requirement is necessary for non-metal materials
NOTE: Untested because the final frame has not been printed by the manufacturer yet

Resources Required

Personnel	**Supplies/Equipment**	**Facilities**
Representative from the 3D printing facility	Surface roughness measuring tool	

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) **Likeliness to Occur and Severity if it Occurs**	**Mitigation Measures**
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Speak with the representative from the 3D printing facility that is printing the final frame design to ask for the surface roughness tests to be performed 2. After they perform the test, request and official document with the testing results

Test Title: Assembled CubeSat Volume Test	Date Test Conducted
Purpose - Engineering Characteristic/Proof of Concept Tested: Volume	04/04/2023
Test Director: Napoleon Stardellis	**Conditions** • Location (CCE-038) • Time required to conduct test (15 minutes)

Test Abstract

Target/Goal: <= 1000 cm^3 (10 x 10 x 10) cm
Target Achieved (Y/N): Y, 1000 cm^3
If not, Plan of Action: If volume is greater than 1000 cm^3 and the dimensions are greater than 10 x 10 x 10 cm, discuss with CubeSat design team on ways to reduce total satellite volume by reducing dimensions to meet Cal Poly requirements.
Note: Test was conducted using SolidWorks instead of listed procedure because a complete CubeSat assembly has not been achieved. Further Testing is required

Resources Required

Personnel	Supplies/Equipment	Facilities
Napoleon Stardellis Anthony DiMauro Rocco Fratarcangeli Gary DeVilbiss	Calipers Calculator	CCE-038

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Measure the height of the CubeSat with calipers (+/- .001 cm) from the top of a corner pillar to the bottom of a corner pillar 2. Measure the width of the CubeSat with calipers (+/- .001 cm) 3. Measure the length of the CubeSat with calipers (+/- .001 cm) 4. Multiply dimensions 5. Compute averages from measured dimensions 6. Repeat steps 1-4 five times and compare the results.

Test Title: CubeSat frame Density Test

Purpose - Engineering Characteristic/Proof of Concept Tested: Frame Density

Test Director: Napoleon Stardellis

Date Test Conducted
04/04/2023

Conditions

- Location (CCE-038)
- Time required to conduct test (15 minutes)

Test Abstract

Target/Goal: < 2.70 g/cm^3
Target Achieved (Y/N): Y, 1.27 g/cm^3
If not, Plan of Action: If density is greater than 2.70 g/cm^3 the design team will discuss if changes to the design and material choice are necessary to achieving the goals outlined in the problem statement.
Note: Test was conducted using the datasheet provided by the manufacturer instead of listed procedure because a complete CubeSat assembly has not been achieved. Further Testing required.

Resources Required

Personnel	Supplies/Equipment	Facilities
Napoleon Stardellis Anthony DiMauro Rocco Fratarcangeli Gary DeVilbiss	Calculator Scientech Scale CubeSat Frame components Graduated Cylinder	CCE-038

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Use Scientech Scale to obtain Mass of assembled CubeSat frame and record mass 2. Fill graduated cylinder where the water is 10 cm above the 3. Record starting volume of water 4. Submerge all components in the water 5. Record new volume with all components submerged 6. Subtract new volume from starting volume 7. Compute density from measured mass and volume values 8. Repeat steps 1-7 five times and compare the results. 9. Compute averages from measured denity, volumes and mass

Test Title: Center of Mass **Purpose - Engineering Characteristic/Proof of Concept Tested:** **Engineering Characteristic:** Center of mass in relation to the geometric center **Test Director:** Fratarcangeli	**Date Test Conducted:** April 5, 2023 **Conditions** • Location (CCE-032 or TH-105) • Time required (10 minutes)

Test Abstract

Target/Goal: Center of mass within 2cm of the geometric center
Target Achieved (Y/N): Y, (0.39mm, 0.3mm, 1.48mm) (X,Y,Z)
If not, Plan of Action: Adjust the circuit board heights and positions to move the center of mass, then retest

Resources Required

Personnel	Supplies/Equipment	Facilities
Fratarcangeli	Computer/SolidWorks	CCE-032 or TH-105

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Open SolidWorks on a computer in one of the engineering labs 2. Ensure the CubeSat model is fully assembled and the materials are correct 3. See where the origin is on the model 4. Use the mass properties tool to see the center of mass in relation to the origin 5. If the origin is not the geometric center, calculate the actual geometric center and compare the center of mass 6. If the center of mass is not within 2cm of the geometric center, move around the circuit boards and change the spacer heights until it is within the tolerance

Test Title: Radio Range Test **Purpose - Engineering Characteristic/Proof of Concept Tested:** Proof of Concept: Adafruit RFM69HCW Transceiver Radio Breakout Board Connection Range **Test Director:** Gary	**Date Test Conducted** 03/24/2023 **Conditions** • Location (Outdoor, York Hill) • Weather Requirements (Clear) • Time Total Duration (10 minutes)

Test Abstract

Target/Goal: 400 meters
Target Achieved (Y/N): N, 200 meters
If not, Plan of Action: Analyze possible causes for failure, such as antenna length, power, and line-of-sight.
Note: Further testing required.

Resources Required

Personnel	Supplies/Equipment	Facilities
Gary DeVilbiss Marcus Rocco Fratarcangeli	- 6x AA Batteries - Communications Transmitter Circuit - Communication Receiver (CubeSat) Circuit	None

Risk Management (If any risk greater than low, must have advisor approval and presence at test)

Hazard/Risk (after mitigation) Likeliness to Occur and Severity if it Occurs	Mitigation Measures
None Identified	

Test Procedure

Description (with pictures and/or standards if applicable)
1. Connect three AA Batteries to Raspberry Pi power supply pins on transmitter and receiver 2. Leave receiver in safe location with one of the personnel (Person A) 3. Other person (Person B) will take the transmitter and press the “signal test” every few seconds button while walking away from the receiver 4. Person A will wait until “signal received” light no longer blinks and notify person B 5. Person B will begin to walk back slowly towards the receiver while pressing the signal test button 6. Person A will notify person B to stop moving when a signal is received 7. Take note of the location of the receiver and new location of the transmitter. 8. Use a website (ex. https://www.calculator.net/distance-calculator.html) to measure the distance between the receiver and transmitter

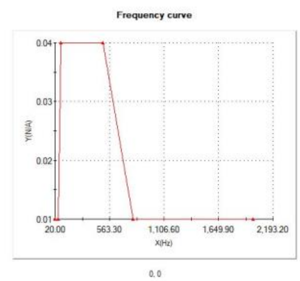
Vibration Simulation Results

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		**Entities:** 8 face(s) **Type:** Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	2.90772e-06	8.21629e-06	2.16655e-06	8.98088e-06
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details	Function Curve
Selected Base Excitation-1		**Type:** Acceleration **Fixture:** Fixed-1 **Translation:** ---, 1, --- **Units:** in **Phase Angle:** 0 **Units:** deg	 **Frequency curve**

Mesh information

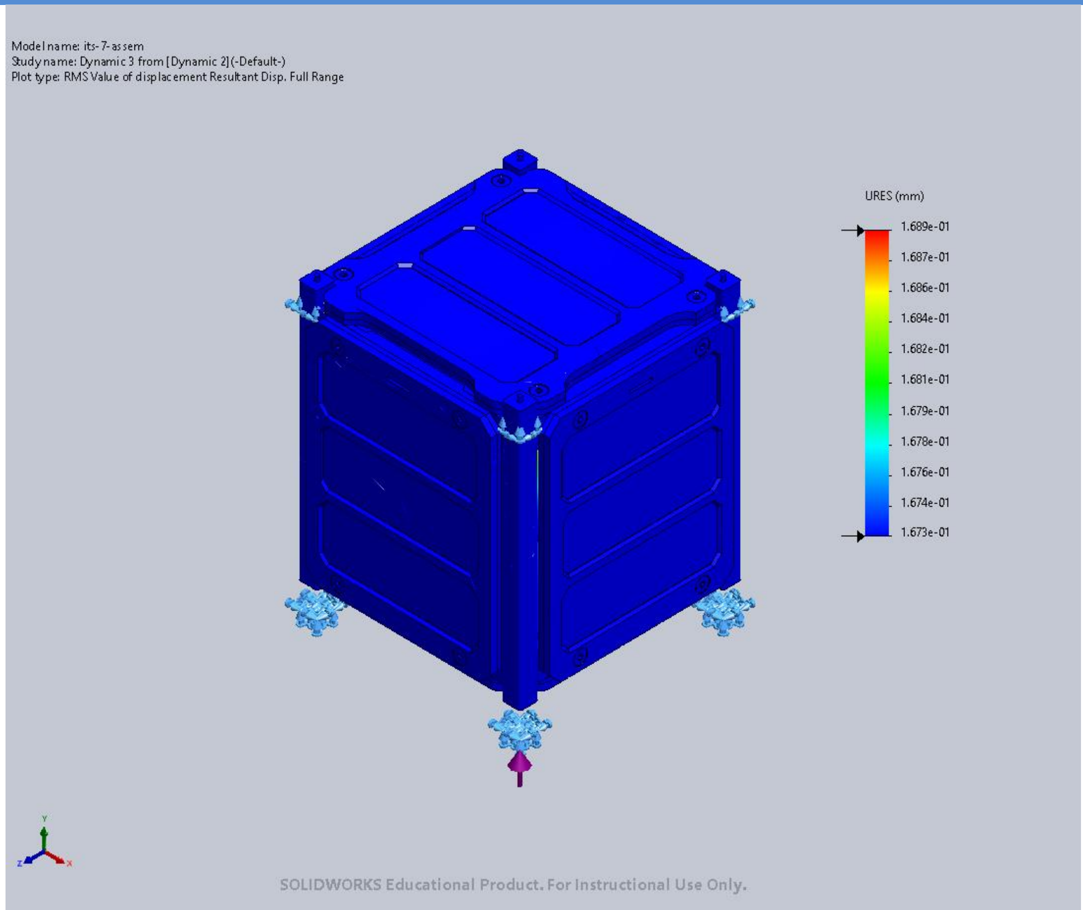
Mesh type	Solid Mesh
Mesher Used:	Blended curvature-based mesh
Jacobian points for High quality mesh	16 Points
Maximum element size	37.8566 mm
Minimum element size	1.89283 mm
Mesh Quality	High
Remesh failed parts independently	Off

Mesh information - Details

Total Nodes	250683
Total Elements	128429
Maximum Aspect Ratio	1,132.6
% of elements with Aspect Ratio < 3	62.5
Percentage of elements with Aspect Ratio > 10	13
Percentage of distorted elements	0
Time to complete mesh(hh;mm;ss):	00:02:24
Computer name:	CCE40-15

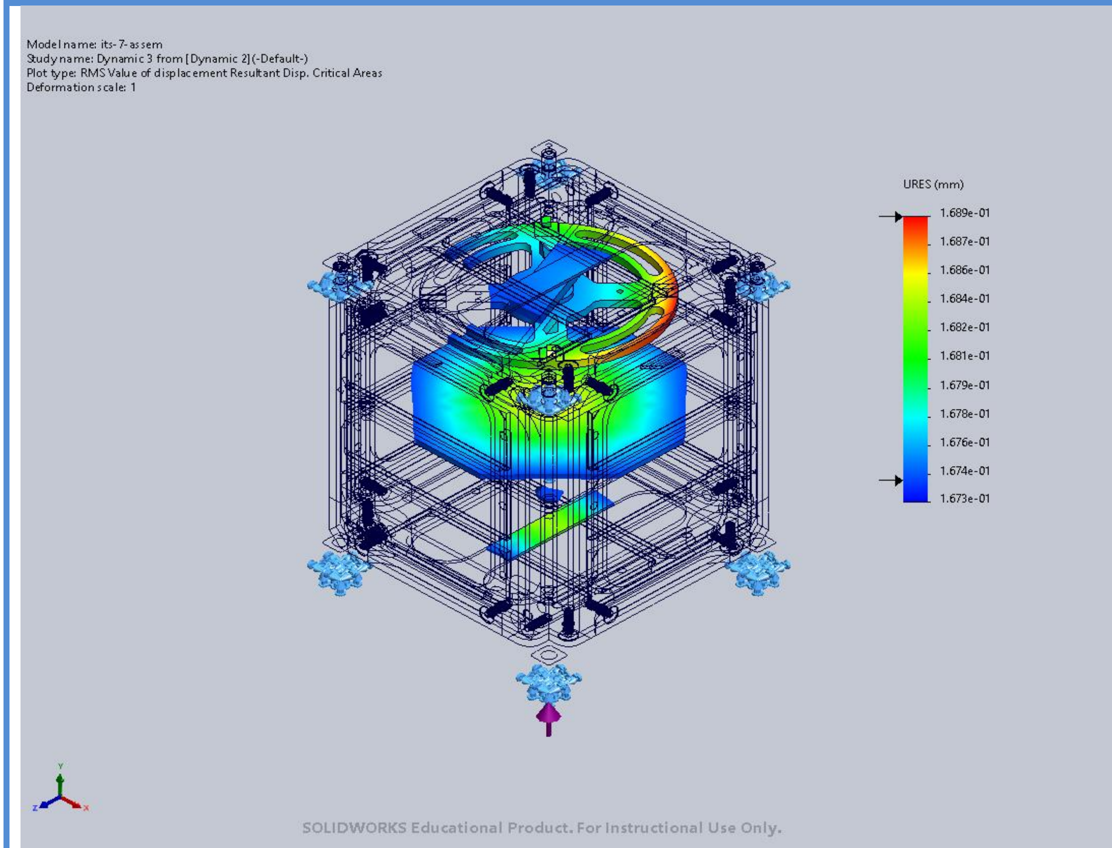
Study Results

Name	Type	Min	Max
Resultant Disp. Full Range	URES: Resultant Displacement	1.673e-01mm Node: 52231	1.689e-01mm Node: 227728



its-7-assem-Dynamic 3 from [Dynamic 2]-Displacement-Resultant Disp. Full Range

Name	Type	Min	Max
Resultant Disp. Critical Areas	URES: Resultant Displacement	1.673e-01mm Node: 52231	1.689e-01mm Node: 227728



its-7-assem-Dynamic 3 from [Dynamic 2]-Displacement-Resultant Disp. Critical Areas

APPENDIX M

PROJECT SCHEDULE

FALL 2022

PROJECT TITLE	CubeSat	GROUP NAME	Final Frontier
PROJECT ADVISOR	Professor Crawford	PERIOD	August 2022 - October 2022

TASK ID	TASK TITLE	TASK RESPONSIBILITY	START DATE	DUE DATE	DURATION IN DAYS
1	Team Charter	Group	09/02/22	09/07/22	5
1.1	Advisor Meeting 1		09/07/22	09/07/22	
2	Literature Review	Group	09/02/22	09/12/22	10
2.1	CCAT Inc. Tour & Discussion		09/14/22	09/14/22	
3	Initial Project Schedule	A & N	09/15/22	09/19/22	4
4	Info Gather / Customer Req. Report	R & G	09/15/22	09/19/22	4
4.1	Advisor Meeting 2	Group	09/21/22	09/21/22	
5	Preliminary Design Review (PDR)	Group	09/19/22	09/26/22	7
5.1	Lithoz Meeting	Group	09/26/22	09/26/22	
5.2	Modeling & Simulation (Class)	Group	09/28/22	09/28/22	
6	Idea & Purpose Consensus	Group	09/07/22	09/30/22	23
7	Lithoz STL Model	Group	09/26/22	10/03/22	7
8	Systems Summary	Group	09/30/22	10/07/22	7
8.1	Advisor Meeting 3	Group	10/05/22	10/05/22	
9	QFD/Engineering Design Specifications	Group	09/23/22	10/10/22	17
10	Risk Analysis	Group	10/10/22	10/19/22	9
10.1	Advisor Meeting 4	Group	10/12/22	10/12/22	
11	Alternative Generation/Decision Matrix	Group	10/19/22	10/28/22	9
11.1	Advisor Meeting 5	Group	10/19/22	10/19/22	
11.2	Advisor Meeting 6	Group	10/26/22	10/26/22	

TASK ID	TASK TITLE	TASK RESPONSIBILITY	START DATE	DUE DATE	DURATION IN DAYS
11.3	Advisor Meeting 7	Group	11/02/22	11/02/22	
11.4	Advisor Meeting 8	Group	11/09/22	11/09/22	
12	Preliminary BOM	Group	10/19/22	11/16/22	28
13	Initial Bill of Materials/Orders	Group	10/28/22	11/16/22	19
14	Critical Design Review 1 (CDR1)	Group	10/28/22	11/18/22	21
15	Interim Design Report	Group	11/16/22	12/07/22	21
15.1	Advisor Meeting 9		11/16/22	11/16/22	
16	Peer Rating	Group	12/09/22	12/09/22	
17	Final Exam Presentation	Group	11/16/22	12/16/22	30
18	Safety Class	Group	11/28/22	11/28/22	
18.1	Advisor Meeting 10		11/30/22	11/30/22	
19	Energy Budget				
19.1	Advisor Meeting 11	Group	12/07/22	12/07/22	
19.2	Power System (EPS)	Anthony	11/18/22	01/23/23	66
19.3	Onboard Data Handling (OBDH)	Rocco	11/18/22	01/23/23	66
19.4	Communications	Gary	11/18/22	01/23/23	66
19.5	Telemetry, Tracking & Controls (TTC)	Napoleon	11/18/22	01/23/23	66

SPRING 2023

TASK ID	TASK TITLE	TASK RESPONSIBILITY	START DATE	DUE DATE	DURATION IN DAYS
1	CDR 2	Group	02/08/23	02/13/23	5
2	Test Plan	Group	02/13/23	02/24/23	11
3	Impact Assessment	Group	02/24/23	03/03/23	7

TASK ID	TASK TITLE	TASK RESPONSIBILITY	START DATE	DUE DATE	DURATION IN DAYS
4	Testing Results	Group	03/03/23	04/05/23	33
5	One-Slide Project Summary	Group	04/05/23	04/19/23	14
6	Project Poster (Assignment)	Group	02/13/23	04/24/23	70
7	Final Design Review	Group	04/17/23	05/01/23	14
8	Final Design Report	Group	04/17/23	05/01/23	14
13	Projects Day Poster Session	Group	05/08/23	05/08/23	

APPENDIX N

COST BREAKDOWN

FINAL COST TABLE

Part Number	Description	Quantity	Unit Cost	Total	Source
Hardware					
377-2091-ND	BREADBOARD TERM STRIP 3.40X3.20"	4	$9.00	$36.00	Digi-Key
480-3158-ND	THERMISTOR NTC 10KOHM 3887K BEAD	20	$6.41	$128.16	Digi-Key
1568-1565-ND	HOOK-UP SOLID 22AWG WHITE 25'	1	$2.81	$2.81	Digi-Key
KSP44BU-ND	TRANS NPN 400V 0.3A TO92-3	10	$0.39	$3.87	Digi-Key
RNF14FTD10K0CT-ND	RES 10K OHM 1% 1/4W AXIAL	50	$0.05	$2.47	Digi-Key
438-1049-ND	JUMPER KIT VARIOUS 140PCS	3	$6.99	$20.97	Digi-Key
1528-1668-ND	RFM96W LORA RADIO TRANSCEIVER BR	2	$19.95	$39.90	Digi-Key
2994-SM141K10TF-ND	SOLAR CELL G3 THIN 6.91V 307MW	21	$8.43	$177.10	Digi-Key
1568-1659-ND	DEANS CONNECTOR - M/F PAIR	8	$1.05	$8.40	Digi-Key
2994-SM141K10L-ND	MONOCRYST SOLAR CELL 307MW 6.91V	4	$9.39	$37.56	Digi-Key
235-1012-ND	THERMISTOR NTC 3KOHM 3969K BEAD	2	$8.05	$16.10	Digi-Key
2648-SC0917-ND	RASPBERRY PI PICO H	2	$5.00	$10.00	Digi-Key
92125A130	18-8 Stainless Steel Hex Drive Flat Head Screw, M3 x 0.5 mm Thread, 10 mm Long, Packs of 100	1	$7.31	$7.31	McMASTER-CARR
94459A421	Heat-Set Inserts for Plastic, Aluminum, M3 x 0.5 mm, 5.9 mm Installed Length, Packs of 25	5	$7.55	$37.75	McMASTER-CARR
2006N105	302 Stainless Steel Corrosion-Resistant Compression Springs, 11 mm Long, 4.39 mm OD, Packs of 5	2	$15.96	$31.92	McMASTER-CARR
9287K205	302 Stainless Steel Torsion Spring, 360 Degree Right-Hand Wound, 0.371" OD	3	$2.91	$8.73	McMASTER-CARR
N/A	Adafruit MCP3008	2	$8.00	$16.00	Amazon
N/A	Stanley Powerlock Tape Measure	1	$9.75	$9.75	Amazon
N/A	Adafruit MicroSD Breakout Board	2	$9.23	$18.46	Amazon
N/A	Fishing Line	1	$6.99	$6.99	Amazon
N/A	Copper Foil	1	$7.99	$7.99	Amazon
485-3070	Adafruit RFM69HCW Transceiver Radio Breakout - 868 or 915 MHz - RadioFruit	2	$9.95	$19.90	Mauser Electronics
MH48285	Tenergy Li-ion 18650 Cylindrical 3.7V 2600mAh Flat Top Rechargeable Battery-UL listed	4	$5.99	$23.96	Tenergy Power
SUBTOTAL				**$672.10**	

Overhead					
480-3158-ND	THERMISTOR NTC 10KOHM 3887K BEAD	1	$12.82	$12.82	Section 301 Tariff
KSP44BU-ND	TRANS NPN 400V 0.3A TO92-3	1	$0.39	$0.39	Section 301 Tariff
RNF14FTD10K0CT-ND	RES 10K OHM 1% 1/4W AXIAL	1	$0.25	$0.25	Section 301 Tariff
N/A	Sales Tax	1	$14.02	$14.02	Tax
N/A	Sales Tax	1	$14.76	$14.76	Tax
235-1012-ND	THERMISTOR NTC 3KOHM 3969K BEAD	1	$1.61	$1.61	Section 301 Tariff
N/A	Sales Tax	1	$4.59	$4.59	Tax
N/A	Sales Tax	1	$3.39	$3.39	Tax
N/A	Sales Tax	1	$7.66	$7.66	Tax
SUBTOTAL				**$59.49**	
Shipping					
N/A	Shipping	1	$12.99	$12.99	Digi-Key
N/A	Shipping	1	$6.99	$6.99	Digi-Key
N/A	Shipping	1	$6.99	$6.99	Digi-Key
N/A	Shipping	1	$9.99	$9.99	McMASTER-CARR
N/A	Shipping	1	$9.99	$9.99	McMASTER-CARR
N/A	Shipping	1	$6.99	$6.99	Mauser Electronics
SUBTOTAL				**$53.94**	
Licensing Fees					
N/A	Amateur Radio Technician Licensing	1	$35.00	$35.00	FCC
N/A	Amateur Radio Technician Test	1	$15.00	$15.00	ARRL
N/A	ARRL Ham Radio License Manual 5th Edition	1	$29.66	$29.66	Amazon
SUBTOTAL				**$79.66**	
TOTAL		**85**		**$865.19**	

STRATASYS 3-D PRINTING QUOTE

stratasys
DIRECT MANUFACTURING

Rapid Prototyping
Low-Volume Production Parts
Tooling and Molding
3D Viewing & Markup Software

Stratasys Direct Manufacturing Quote for Production Parts

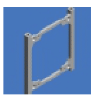
AS9100 & ISO 9001 Certified (Valencia CA, Poway CA, Austin TX, Belton TX, Eden Prairie MN) | ISO 9001 Certified (Phoenix AZ, Tucson AZ)

PREPARED FOR

Anthony DiMauro
Quinnipiac University
1260 sherman avenue
Hamden, Connecticut 06457
Phone: (860) 999-4857
Email: anthonyndimauro@gmail.com

QUOTATION INFORMATION

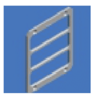
Quote Number: 2958226-5
Quoted On: 4/24/2023 2:56:18 PM
Reference: RFQ - 813289
Project Engineer: Steve Exner | (952) 906-2735 steve.exner@stratasys.com
Account Manager: Scott St John | (256) 975-5423 scott.stjohn@stratasys.com

Item	Description	Quantity	Unit	Total
1	 **its-8-bottomsupport** x | y | z extents: 3.76 | 0.47 | 3.94 inches volume | s. area: 1.22 | 18.53 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	1	$117.00	$117.00
2	 **its-8-pillarwall** x | y | z extents: 3.94 | 0.33 | 4.47 inches volume | s. area: 0.93 | 22.53 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	2	$74.00	$148.00
3	 **its-8-topsupport** x | y | z extents: 3.76 | 0.47 | 3.94 inches volume | s. area: 1.50 | 23.48 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	1	$133.00	$133.00
4	 **its-8-xy-sp base high** x | y | z extents: 3.27 | 0.08 | 3.94 inches volume | s. area: 0.55 | 16.84 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	2	$64.00	$128.00
5	 **its-8-xy-sp base low** x | y | z extents: 3.27 | 0.08 | 3.94 inches volume | s. area: 0.55 | 16.84 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	2	$64.00	$128.00

28309 Avenue Crocker • Valencia, CA 91355 • Phone (661) 295.4400 • Fax (661) 257.9311
www.stratasysdirect.com | quotes@stratasysdirect.com

Stratasys Direct Manufacturing Quote for Production Parts

AS9100 & ISO 9001 Certified (Valencia CA, Poway CA, Austin TX, Belton TX, Eden Prairie MN) | ISO 9001 Certified (Phoenix AZ, Tucson AZ)

Item	Description	Quantity	Unit	Total
6	 **its-8-xy-sp cover high** x | y | z extents: 3.27 | 0.11 | 3.94 inches volume | s. area: 0.55 | 14.10 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard Note: Knife edge features of geometry will be a best effort. Minimum feature size: 0.040". .	2	$60.00	$120.00
7	 **its-8-xy-sp cover low** x | y | z extents: 3.27 | 0.11 | 3.94 inches volume | s. area: 0.55 | 14.10 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard Note: Knife edge features of geometry will be a best effort. Minimum feature size: 0.040". .	2	$60.00	$120.00
8	 **its-8-z-sp base** x | y | z extents: 3.94 | 3.94 | 0.08 inches volume | s. area: 0.55 | 18.49 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard	2	$66.00	$132.00
9	 **its-8-z-sp cover(fixed)** x | y | z extents: 3.94 | 3.94 | 0.11 inches volume | s. area: 0.61 | 15.27 FDM Solid 10: Material=ULTEM™ 9085 resin Black, Finish=Standard Note: Knife edge features of geometry will be a best effort. Minimum feature size: 0.040". .	2	$60.00	$120.00

Delivery: Estimated shipment in 8 working days A.R.O. Actual schedule to be determined after receipt of order.

Terms: EXW (ExWorks). Net 30 on approved Credit, 1.5% per month late charge.

Notes: Stratasys Direct Manufacturing standard terms and conditions apply.
Other Product Information:
FDM Solid 10: Technology = FDM; Resolution = 0.010" Z, 0.040" XY; Tolerance = ± 0.010” or 0.0015” per inch, whichever is greater; Minimum feature size = 0.040”.
Parts that exceed the build envelope capacity for a particular Additive Manufacturing process/machine will be built in segments and bonded together, as will parts with hollow/void areas that require support removal.
Items quoted will be manufactured using Stratasys Direct Manufacturing's (SDM) standard processes using materials listed above and inspected per SDM standard acceptance criteria.

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Stratasys Direct Manufacturing Quote for Production Parts

AS9100 & ISO 9001 Certified (Valencia CA, Poway CA, Austin TX, Belton TX, Eden Prairie MN) | ISO 9001 Certified (Phoenix AZ, Tucson AZ)

AUTHORIZATION TO PROCEED

Company: ______________________

Name: ______________________

Signature: ______________________

Date: __________ P.O. __________

OFFERED BY STRATASYS DIRECT MANUFACTURING

Steve Exner

Per: ______________________

Steve Exner, Project Engineering

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APPENDIX O

RISK REDUCTION TOOLS

FMEA WORKSHEET

Failure Mode	**Severity (SR)**	**Occurrence (OR)**	**Detection (DR)**	**Risk Priority Number (RPN)** **(SR×OR×DR)**
Frame fracture during launch	9	2	3	54
Frame fracture during orbit	6	2	3	36
Antenna Deployment Failure	7	6	3	126
Thermal control system failure	6	3	7	126
Electrical power system failure (generation, storage, or transfer)	7	4	4	112
Inability to disintegrate upon atmospheric reentry	10	2	2	40
High outgassing of material contaminates	6	3	1	18
Attitude Adjustment System failure	3	4	4	48

Tracking system software bugs	4	3	2	24

Most critical failure mode to address is Antenna Deployment Failure.

Table 1. Severity Rating

Rating	Severity Description
1	Unnoticeable Effect
2	Very Slight Effect Noticed by Users
3	Slight Effect, Annoyance May Occur
4	Slight Effect, Users May Return Product
5	Moderate Effect
6	Significant Effect
7	Major Effect
8	Extreme Effect
9	Critical Effect
10	Hazardous

Table 2. Occurrence Rating

Rating	Approximate Probability of Failure	Description of Occurrence
1	$\leq 1x10^{-6}$	Very Remote
2	$1x10^{-5}$	Remote
3	$1x10^{-5}$	Very slight chance
4	$4x10^{-4}$	Slight chance
5	$2x10^{-3}$	Occasional
6	$1x10^{-2}$	Moderate
7	$4x10^{-2}$	Frequent
8	0.20	High
9	0.33	Very High
10	≥ 0.50	Extremely High

Table 3. Detection Rating

Rating	Description of Detection
1	Almost Certain to detect
2	Very High Chance of detection
3	High Chance of detection
4	Moderately High Chance of detection
5	Medium Chance of detection
6	Low Chance of detection
7	Slight Chance of detection
8	Remote Chance of detection
9	Very Remote Chance of detection
10	No Chance of detection of detection

COMPOSITE RISK MANAGEMENT WORKSHEET

COMPOSITE RISK MANAGEMENT WORKSHEET
For use of this form, see FM 5-19; the proponent agency is TRADOC.

1. MSN/TASK: **Final Frontier CubeSat In-Orbit Operation**	2a. DTG BEGIN	2b. DTG END	3. DATE PREPARED *(YYYYMMDD)* **20221017**

4. PREPARED BY

a. LAST NAME Fratarcangeli, DeVilbiss, DiMauro, Stardellis	b. RANK N/A	c. POSITION

5. SUBTASK	6. HAZARDS	7. INITIAL RISK LEVEL	8. CONTROLS	9. RESIDUAL RISK LEVEL	10. HOW TO IMPLEMENT	11. HOW TO SUPERVISE (WHO)	12. WAS CONTROL EFFEC-TIVE?
Antenna Deployment	Deployment failure results in equipment loss and mission termination	H	- Extensively test deployment method/mechanism - Once a solution is determined and tested, no further adjustments will be made that could affect performance.	M	-Careful selection of materials and parts during the design phase - Test deployment in LEO environmental conditions simulated by vibration tests	- Team Members - Team Advisor - Testing Personnel - Ground Station Operator	
Thermal control system maintaining operational temperature of components	Overheating/Underheating	H	-Identify temperature sensitive components -Simulate the temperature conditions to find the proper heating level -Ensure temperature requirements are met during testing	M	-Take note of temperature requirements in all SDS -Using heat transfer software to simulate the TCS and components -Ensure accurate and realistic testing apparatus	-Two of the team members will separately verify each requirement	
Electrical power generation, storage, and transfer	No power generation or storage results in no component functionality No transfer could cause certain systems to be offline	H	-Identify electrical components and minimum power requirements, generation, and maximum power storage. Use a power budget table. -Simulate the power consumption and generation of the system and each component individually -Test the power consumption and generation to ensure the simulation was accurate	M	-Ensure the power budget table is correct -Make the simulation and testing apparatus as realistic as possible	-Each team member will verify all the power budget tables, simulations, and testing	
	Unscheduled deployment	H	- Extensively test deployment method/mechanism - Ensure antenna are secure during before, during, and after transportation	L	- Inspection of deployment mechanism when transporting	- Team Members - Testing Personnel	
Disintegration of device upon atmospheric re entry	Space debris posing potential risk threat to property, the environment, or fatal injury	M	-Adhere design considerations to NASA and FCC space debris mitigation policies. -Ensure material properties of design do not hinder burn up of device upon atmospheric reentry	L	-Ensure compliance documents are of latest revision -Refer to CubeSat specification sheet and NASA procedural requirements for limiting space debris when altering a material aboard the device	- Team Members - Testing Personnel	
Frame successfully supports components	Frame fractures during launch from vibrational or gravity forces	H	-Simulate the forces and vibration with the correct material and design -Test the frame by the NASA standards to ensure effectiveness and resistance to vibration and heat	M	-Take note of all material properties from TDS -Ensure the simulation and testing apparatus are as realistic as possible	-Two team members will verify the designs and simulations -Testing officials will oversee the testing process	

Additional space for entries in Items 5 through 11 is provided on Page 2.

13. OVERALL RISK LEVEL AFTER CONTROLS ARE IMPLEMENTED *(Check one)*

☐ LOW ☐ MODERATE ☐ HIGH ☐ EXTREMELY HIGH

14. RISK DECISION AUTHORITY

a. LAST NAME	b. RANK	c. DUTY POSITION	d. SIGNATURE

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ITEMS 5 THROUGH 12 CONTINUED

5. SUBTASK	6. HAZARDS	7. INITIAL RISK LEVEL	8. CONTROLS	9. RESIDUAL RISK LEVEL	10. HOW TO IMPLEMENT	11. HOW TO SUPERVISE (WHO)	12. WAS CONTROL EFFECTIVE?
	Frame fractures during orbit from the temperature cycling	M	-Simulate the temperature cycling and effect on the frame structure/material from the sun and the internal components	L	-Take note of all material properties from TDS -Ensure simulation is as realistic as possible	-Two team members will verify the simulation	
Low outgassing	Contaminant matter released from device as air pressure decreases to vacuum	M	-Adhere to the ICD (interface control document) pertaining to the thermal vacuum (TVAC) bakeout testing -Successfully completed the TVAC bakeout test -Choose materials that naturally have low outgassing properties	L	-Send testing procedures to mission integrator before testing for feedback -Review the testing summary report	-Team members will verify TVAC testing results with testing personnel	
Attitude adjustment	Failure to maintain proper position in orbit will result in charging issues, communication issues, and possible premature deorbit	L	-Simulate and model CubeSat position in LEO -Utilize magnetorquer and reaction wheel to achieve desired position -Monitor proper orientation for charging, and communication	L	-Utilize the Earth's magnetic field and onboard parts to orient the CubeSat - Continuously monitor CubeSat position	Team will verify system success in simulation Team will monitor CubeSat orientation in orbit	
Track CubeSat	Failure to track CubeSat may result in legal consequences and impractical data collection	L	-Onboard system hardware -Compatible coding programs will control NASA GMAT along with onboard hardware	L	-Debug software and calibrate CubeSat dimensions	-Two Team members will verify specifications for accurate predictions	

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Page 2 of 2
APD V 2.00

APPENDIX P

CAD RENDERINGS

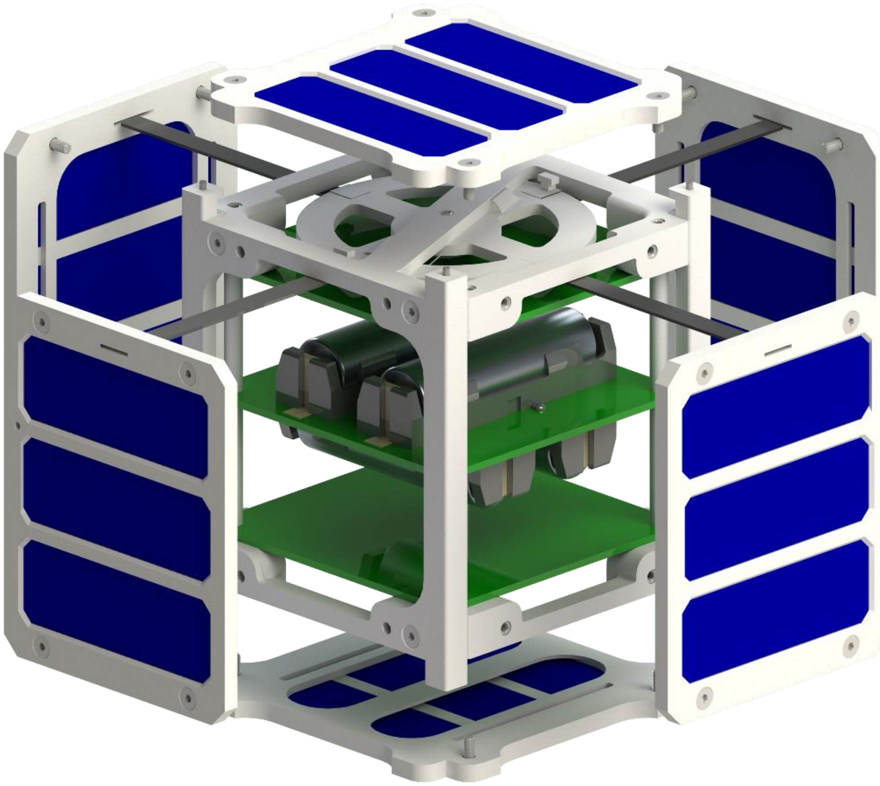

Figure 1: Isometric Exploded View

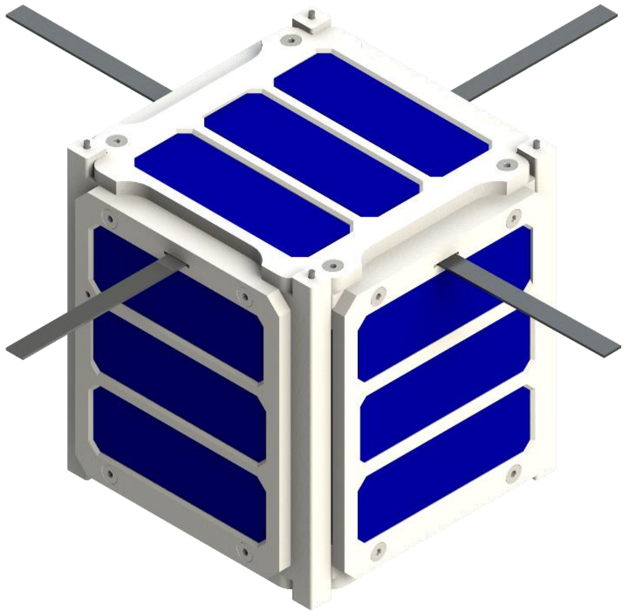

Figure 2: Isometric View

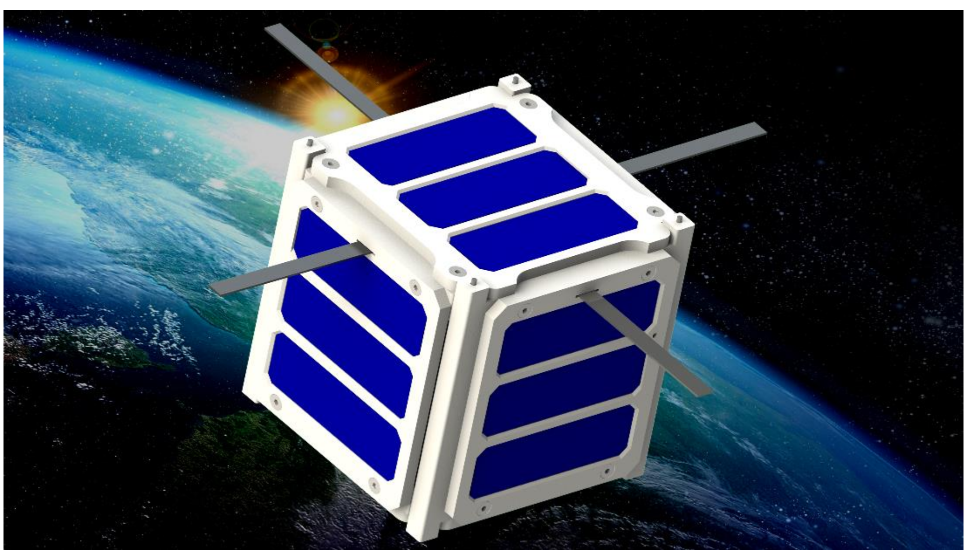

Figure 3: Poster Image

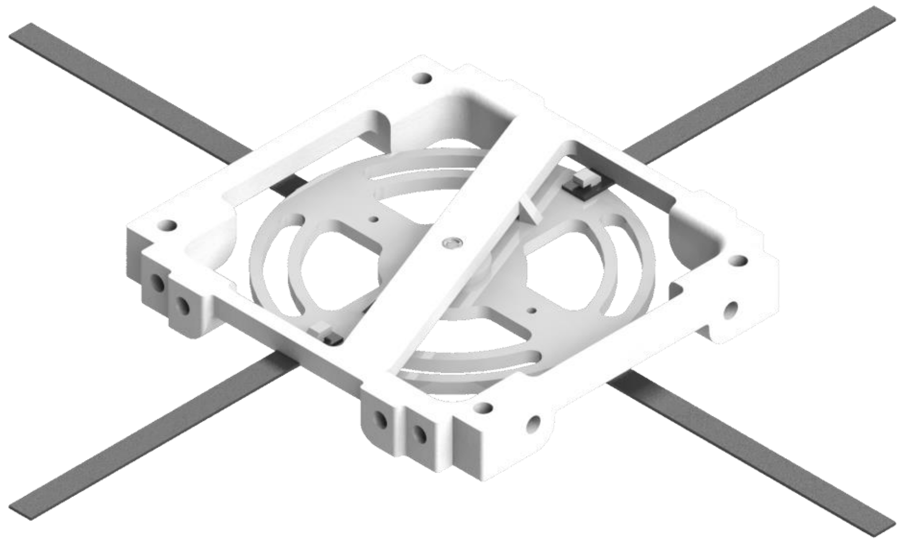

Figure 4: Antenna Deployment System