MME 4499 – Mechanical Engineering Design Project

CubeSat "Opportunity"

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Final Project Report 5

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Executive Summary

The Western-Nunavut Arctic College CubeSat Project is a collaborative effort between the University of Western Ontario (UWO), The Nunavut Arctic College, and the Canadian Space Agency (CSA) to provide experiential learning and training opportunities for students in space development and operations. Western has received one of the fifteen grants given by the CSA as part of the Canadian CubeSat Project, with the goal of deploying a 2U satellite in 2021-22. A comprehensive 3-year plan is in effect to maximize the chance of mission success. A year has been designated for preliminary design, detailed design, and the final Assembly/integration/testing. This report will cover the full extent of the structural and thermal management for the preliminary design of the CubeSat. This project has been 8 months in the making, through collaborations with other subsystem groups and industry professionals.

This report can be divided into 5 sections:

- Specification Design
- Conceptual Design
- Detailed Design
- Prototype Design
- Final Design

In Specification Design, the background of the CubeSat project is reviewed in detail to set the knowledge base for the project. This was a critical aspect of the project because of the nature of space missions. To have a successful launch all background information, objectives, and constraints must match established standards set by the other subsystems. There is also a need to ensure that the fine details match standards set by the CSA/NASA's CubeSat SOTA report. Finally, the report also covers the schedule used to plan out the project.

In Conceptual Design, concept generation techniques were used to define the necessary parameters, determine all options available, and narrow down the choices to potential designs. A strategic approach had to be taken to determine the best components and configuration of the CubeSat structure and thermal control. Decision making tools were also used to analyze the advantages and disadvantages of concepts quantitatively. The report ends with a proposal for a final design.

In Detailed Design the final design from the previous report is expanded on in detail. SolidWorks CAD models of all the components and a conceptual assembly plan are made along with drawings for all essential components. This report also reviews the final design in detail and how the features have been implemented in the model. Collaborations and information exchange between other subsystems were necessary at this point to ensure that all subsystem components were compatible with the structural design and adhering to the mass budget.

Prototype design focuses on the fabrication of a prototype of the final design for testing. Features planned out during detailed design that were out of the project's budget and resource capacity had to be modified to make a functional prototype. For this reason, some redesigning had to be done on the structure for it to be manufactured. Components from other subsystems were also not available and had to be replaced by equivalent dummy masses that were also machined to size. Thermal testing is also summarized in this section.

Final Design covers the results from the vibration testing that were done after Interim Report 4. This includes a summary of the fixture design, testing procedure, and results. At this point the prototype has been fully assembled and assembly instructions as well as potential improvements has been proposed. The Final Design Showcase and judge critique and criticisms are also covered in detail. Finally, a section is dedicated to lessons learned and things that would be done differently if the Capstone project was repeated.

This capstone project is only the first of a three-year endeavor. The goal was to develop a firm base for the detailed design capstone phase that is to happen in 2019-2020. Throughout this project many challenges were overcome in order to make the final product. Features determined in the design and validated through testing have the potential to be carried over to the next phase and may even be on the CubeSat design that goes to space. The project as a whole is proceeding according to plan and hopefully the final structural and thermal management design will benefit from the preliminary design specifications that were determined in this report.

Stage 1 - Specification Design

Introduction

On October 20th, 2017 the Canadian Space Agency (CSA) published "The Announcement of Opportunity" [1] for the Canadian CubeSat Project (CCP). Through this initiative the CSA provides post-secondary institutions across Canada with an opportunity to engage their students in a real space mission. Students participate in projects that consist of designing, building, launching and operating a CubeSat in space. In response, Western University submitted a CubeSat project proposal, in partnership with the Nunavut Arctic College, which was chosen as one of 15 proposals approved for funding. Through this approval, Western has taken up the task of executing a successful space mission.

Western University will be designing two 2U CubeSats, *Spirit* and *Opportunity*. Each CubeSat will have a different design and method of communication, producing different benefits and drawbacks. In partnership with Western University, Canadensys Aerospace Corporation introduced the challenge of integrating two AR/VR cameras to the CubeSat design [2]. The Western CubeSat Team of 2018-19, consisting of subsystem groups from various engineering disciplines, must work together to advance the preliminary design phase of both satellites. The most important goal shared by all subsystems is to have a successful launch.

This report examines the research, methodology and planning behind the preliminary structural & thermal design of *Opportunity*. A thorough understanding of CubeSats, mission objectives, customer requirements, and engineering specifications is required before proceeding to the next phase of the project.

Problem Statement

A CubeSat mission is considered successful if the CubeSat is able to operate for 90 days or longer [3]. As of August 11, 2018, 875 CubeSats have been successfully deployed. The number of CubeSats in space continues to increase, however the mission success rates stay relatively low. The missions conducted in the industry have an average success rate of 77 percent, while missions led by academia have an average of 45 percent [4]. The problem is that many of these mission failures were due to design flaws and inadequate testing and analysis [5]. To ensure a successful mission, there is a need for a well-designed and thoroughly tested CubeSat.

Background

Western University, in collaboration with Nunavut Arctic College, will be designing and building two 2U CubeSats, Spirit and Opportunity. The main objective of Spirit and Opportunity is to transmit satellite imagery back to Earth [6]. Both satellites will be equipped with dual cameras, which will provide an uninterrupted 360 degree view of space. Spirit will utilize S-Band communications to transmit data while Opportunity will utilize UHF omni-directional communications. S-Band has the advantage of a higher bandwidth and lower power consumption, but is imposed with a greater pointing requirement. UHF has fewer pointing requirements, but transmits at a lower bandwidth. This disparity between technical aspects of Spirit and Opportunity has presented the need for a trade-off study.

The Structural and Thermal Subsystem team for Opportunity must design a satellite that can survive the transport, deployment, and orbital conditions of space. During transport, forces will resonate through the launch vehicle and vibrate the dispensers. The satellite must be able to maintain structural integrity while enduring various forces and vibrations. During deployment, a signal will be sent to the NanoRacks CubeSat Deployer (NRCSD), which will then open the housing and eject the CubeSat [7]. The CubeSats must meet all the requirements outlined by the NRCSD to successfully deploy. When deployed and in orbit, the CubeSat must endure harsh thermal conditions of extreme heat and cold. Internal Systems temperature must be monitored and regulated to prevent system failure (refer to section 7 for requirement details). To persevere in this endeavor, it is important to have a thorough review of the CubeSat Project.

History of the CubeSat

CubeSat began in 1999 as a collaborative effort between California Polytechnic State University and Stanford University. The goal was to promote skills and interest in space initiatives by developing the framework of small-scale satellite deployment and missions. Through partnerships with NASA, CSA, and other space agencies, universities were given access to space at an affordable cost. NASA generously offered to cover the transportation and deployment costs for the satellites in exchange for valuable data and mission reports. The smaller scale and development costs make CubeSat Projects ideal for conducting multiple high risk and single-purpose missions. CubeSat Projects are also ideal learning experiences for students who plan on progressing their career in the space-systems engineering field [8].

What is a CubeSat?

CubeSats are small spacecraft's designed to specifications established by Cal Poly and Stanford. Like the name suggests, CubeSats are satellites comprised of cube units referred to as 1U's (one unit). Each 1U CubeSat is 10 cm x 10cm x 10cm with a mass of approximately 1 to 1.33kg (see Figure 1). This design specification reduces the cost by standardizing components to a size that is cheaper to transport and deploy. Established standards also help ensure that all satellites will be compatible with NASA's third-party payload dispensers. CubeSats can be composed of multiple 1Us presenting a variety of possibilities in terms of structural design (see Figure 2). The naming convention of CubeSats are also based on the number of 1Us in the structure [9].

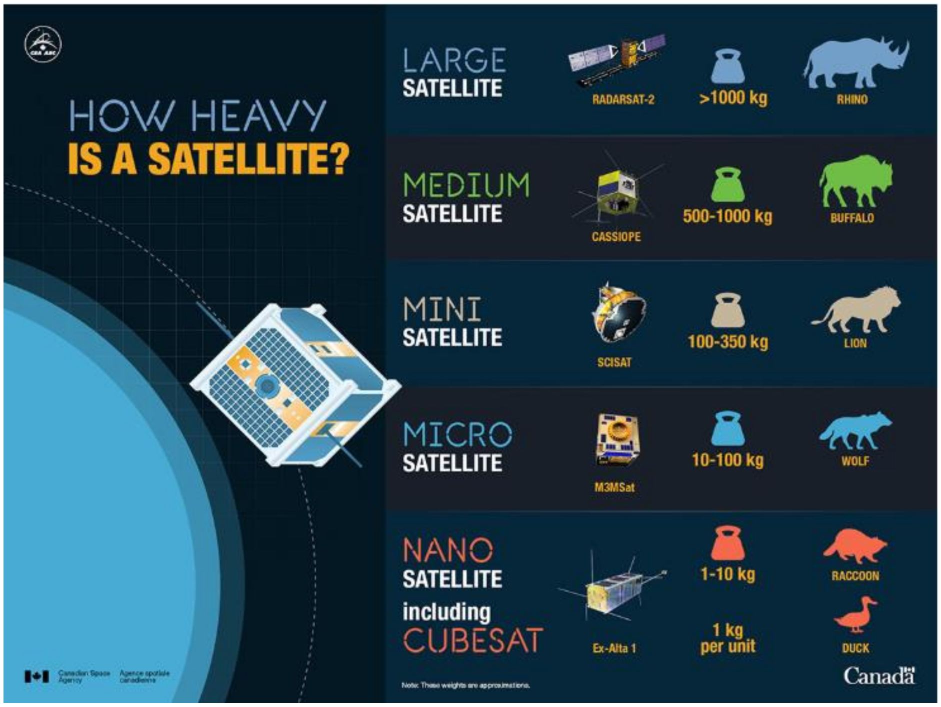

Figure 1- Size of a 1U CubeSat

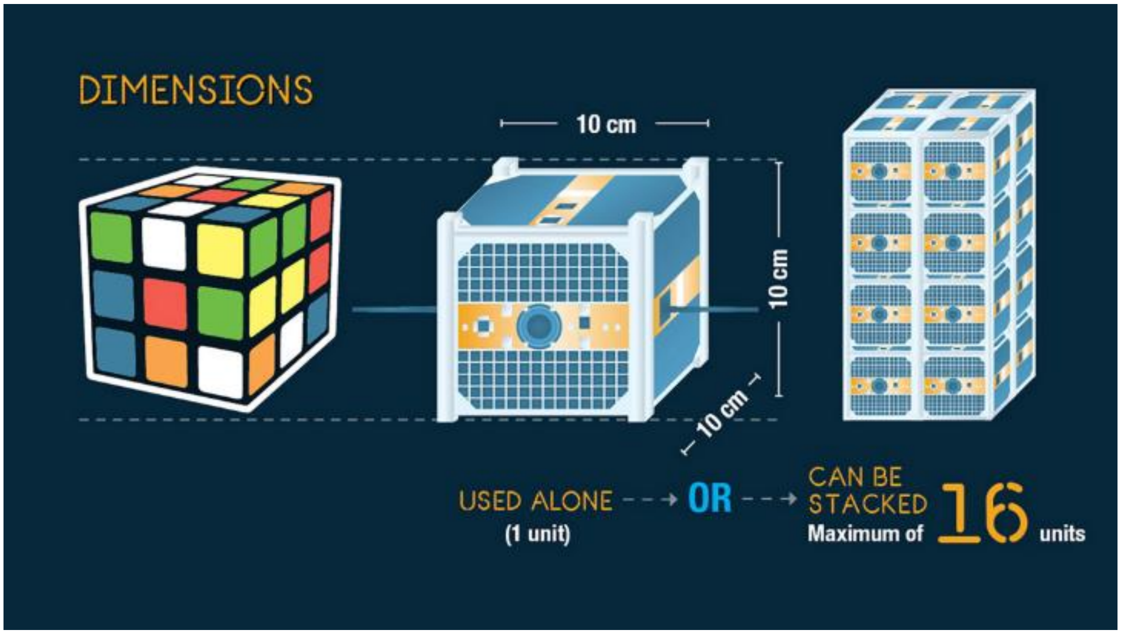

Figure 2 - CubeSat Stacking

Dispensing Device

When the CubeSats are ready for transport into space, they are loaded into dispensers and fastened to the launch vehicle. Dispensers hold the CubeSats during travel and eject them into space on command. CubeSat dispensers come in various designs to accommodate for different CubeSat sizes. Each dispenser also has specified constraints which the CubeSat must adhere to. The designated dispenser for deploying the CCP CubeSat is the NRCSD. NanoRacks has launched 14 CubeSats as of July 13th, 2018, with 9 of them being sent into Low-Earth Orbit (LEO) [7].

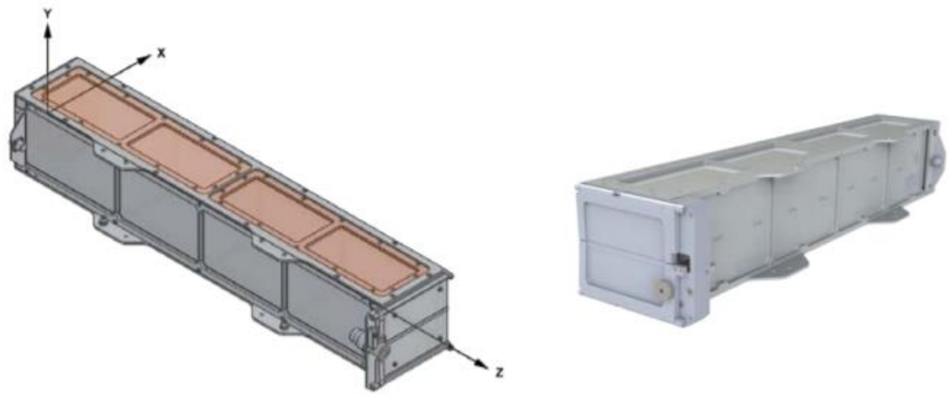

Figure 0-3 - CAD Model and actual picture of NRSCD [1]

Review of Previous CubeSat Projects

Ex-Alta 1

The CSA collaborated and funded a CubeSat project with students at the University of Alberta, making it their first ever CubeSat, illustrated in Figure 0-4. The Ex-Alta 1 CubeSat was successfully deployed on May 26th, 2017 with the mission to collect information on space weather. Refer to Appendix A-3 for mission details. This marked one of the first Canadian University student teams to launch a CubeSat into space [10]. The University of Alberta was able to provide students with hands on experience and the ability to send their own designs into space primarily through the CSA's contributions, similar to the recent opportunity given to Western University students [11].

Figure 0-4 - Ex-Alta 1 CubeSat by the University of Alberta [9]

SwissCube

In September, 2009, SwissCube became the first successful satellite ever launched by Switzerland, illustrated in Figure 0-5 [12]. Designed by École Polytechnique Fédérale de Lausanne in collaboration with the European Space Agency, the Swisscube's primary objective was to photograph a phenomenon known as "nightglow", which exists 100 km above Earth's surface [13]. Refer to Appendix A-3 for mission details. With an initial expected lifespan of 1 year, the Swisscube has now been added to a program called "CleanSpace One", launched by the Swiss Space Center. This project is tasked with collecting space debris, most notably the SwissCube, which is still in orbit and active in 2018 (now commanded by amateur radio enthusiasts) [12].

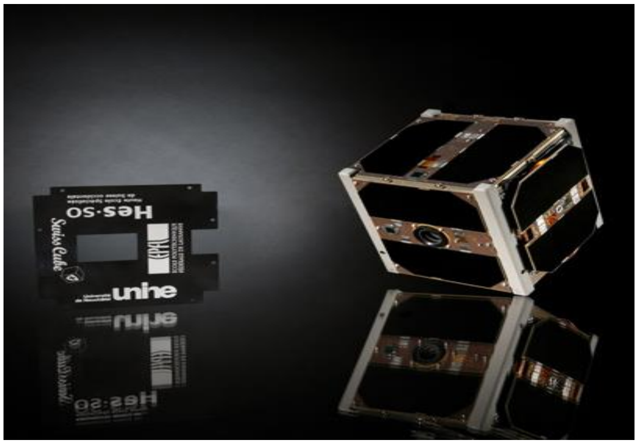

Figure 0-5 - SwissCube by École Polytechnique Fédérale de Lausanne [12]

The Swisscube structural design was focused on low cost and simplicity. This resulted in a structure design called a Monobloc, which is a frame machined from a single block of Certal aluminum alloy. Although there was a focus on low-cost solutions, the Monobloc is a more expensive design option. The satellite is then enclosed with composite panels sandwiched between aluminum plates screwed to the Monobloc frame to protect the various subsystems and payload, and provide a passive thermal control. This CubeSat is an excellent example of a simple yet effective design, however it poses one main issue of being costly. [14]

Mission Failures

A study of the first 100 CubeSat's deployed showed that the majority of CubeSat failures have been through university-led missions [15]. Mission failures can result from power supply, communications, software, radiation control, or mechanical interface design flaws. As shown in Figure 0-6 below**,** failures from a mechanical cause account for 8% of all CubeSat failures from 2000 to 2012. It can also be inferred that many of the electrical breakdowns or system failures result from radiation related causes. Commercial off-the-shelf electronics and inadequate thermal design contribute to missions not meeting their potential lifespan.

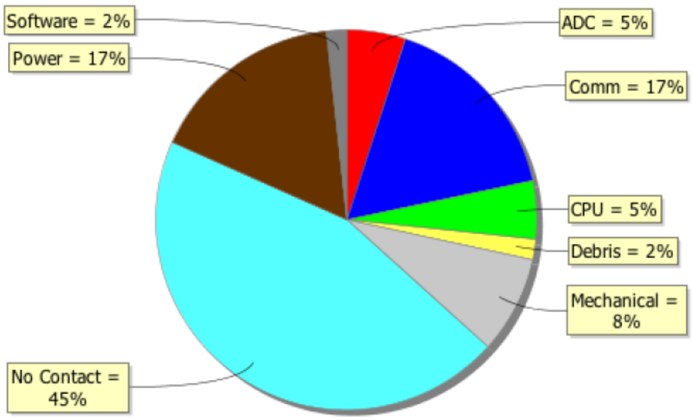

Figure 0-6 - Distribution of Root Causes of Failure in CubeSat Launches [15]

Most of these errors can be attributed to a lack of system-level functional tests performed on the CubeSat once fully constructed. The issue of time constraints makes it difficult for students to allocate enough time for adequate testing. Michael Swartwout states that “more time needs to be devoted to system-level functional testing rather than mechanical, thermal, and radiation issues.” [15]

Project Objectives and Scope

Project Objectives

The primary objective of the Structural and Thermal (Opportunity) team is to design and develop the exterior structure of the CubeSat and to build the structure strong enough so that it can withstand the intense and random vibrations that it will endure during launch. The secondary objective is to utilize thermal regulating techniques to ensure the satellite survives the harsh environmental conditions of space once it has been deployed from the International Space Station.

Project Scope

Launching a 2U CubeSat equipped with two AR/VR cameras into orbit entails many jobs and responsibilities, however the structural and thermal team will only focus on constructing the structure as well as selecting the necessary feasible methods for thermal regulation. This is to ensure the satellite can survive the thermal limits of space while also maintaining an appropriate internal temperature for the components inside to be able to operate as requested. Stated by the CSA, the temperature range of space is found to be -20˚C to +50˚C so this will be the base temperature range used for analysis [3] by the team. The structure must also be able to withstand the random vibrations during launch and the tumbling which will occur following deployment from the NRCSD. NanoRacks has stated that this range of vibrational frequencies is found to be between 20 Hz and 2000 Hz [7].

Finite Element Analysis will be initially used by the structural and thermal team on a CAD model of the chosen design to ensure the environmental conditions are being met before proceeding to building a full scale prototype. With the full scale prototype the team will carry out vibration tests on a shaker table to test various vibrational frequencies as well as perform a thermal test. There are many common techniques to do thermal testing for a satellite such as a bake-out test, thermal cycle test, or thermal vacuum cycling test [16]. The bake-out test is the more feasible method of thermal testing for the team considering the technology available for use at Western's facilities. The Experimental Mineralogy Laboratory in the Earth Sciences building offers high-temperature furnaces [17].

The internal components and features such as communications, power and power distribution, attitude control, and software are outside of the scope for the structural and thermal team and will be completed by other sub-teams. The ground operations and onboard data handling are also not in scope for the this project, however the mass and thermal budgets must be enforced to those sub-teams by the structural and thermal team to ensure the CubeSat does not exceed the mass budget of 3.6 kg as set by NanoRacks [7].

The project will be determined to be a success if the structure is able to withstand the random vibrations experienced during launch to ensure the internal components within will not be damaged as well as be able to survive the harsh and varying temperature ranges of space once the CubeSat has been deployed.

Customer Requirements

The CubeSat is to be designed, built, and prepared for the CSA as they will be making the arrangements for the launch and covering any related logistics costs. The CubeSat is also being designed for NanoRacks as it is to be launched from the NRCSD. The CSA is the primary customer to the CubeSat project and NanoRacks is the secondary customer, since all communication with them will be through the CSA.

The most important requirement mentioned by the CSA and NanoRacks, is that the CubeSat is to be deployed in a safe manner which will not affect the ISS and their mission. Ensuring a smooth and successful launch from the NRCSD is of the utmost importance to the CSA and NanoRacks. They have advised that "some CubeSat projects failed the final progress/safety review when the satellite structure could not fit smoothly into the NRCSD. The importance of the mechanical subsystems cannot be overlooked." [3]. NanoRacks emphasizes that the mechanical interface requirements are to be strictly adhered to for an optimally safe design. They expect the CubeSat to be constructed and assembled so that all critical dimensions are within the suitable tolerances determined by the NRCSD interface requirements.

The CSA has outlined specific launch environment characteristics that the CubeSat must endure once deployed from the ISS. All components must withstand these elements and be designed to operate after the anticipated worst-case scenarios. The satellite is to be designed to be operated in space and to survive the duration of the mission. The CubeSat structure and all of the integrated components must be environmentally friendly and safe within LEO. The CSA also prohibits any frangible materials to be used and the CubeSat itself is not to have any deployables.

The flight safety and integration requirements that govern the NRCSD have been provided by means of the NanoRack's Interface Definition Document (IDD). This document "provides the minimum requirement set to verify compatibility of a small satellite with the NanoRacks CubeSat Deployer system" [7]. This document provides all of the detailed, relevant information required to launch the CubeSat from the NRCSD. The structural and mechanical system categories provide the relevant information in regards to the manufacturing of the CubeSat assembly, installation into the NRCSD, vibrational conditions, thermal environments, and material selection (bill of materials). Further analysis of the requirements outlined in the IDD are stated below in the Design Specifications and Targets section.

The design of the CubeSat will be verified against these requirements to assure complete satisfaction by the CSA and NanoRacks.

Design Specifications and Targets

The design specifications for CubeSat satellites are based primarily upon the constraints set forward by the CSA and NanoRacks, as these are the parties responsible for putting the device into Low Earth-Orbit (LEO). Further specifications will be based upon the request from Canadensys for on-board cameras.

Targets to be met will be based upon the constraints given, as they are a requirement that must be met. There is no freedom pertaining to these constraints. The Structural and Thermal subsystem freedom is primarily in the structure design and choice of thermal control.

NanoRacks and CSA Requirements

The following subsections will provide summaries of the specific constraints developed by the CSA and NanoRacks. These constraints are firm, however they can be adjusted if necessary by submitting a Request for Deviation to the CSA and NanoRacks for consideration [7]. All requirements are outlined in the NRSCD Interface Definition Document (IDD) and the CCP Design Specification [3].

It is important to note that the CSA indicates in the CCP that the IDD is the primary source for requirements, and in the event of a contradiction between the CCP and IDD documents, the IDD is given priority. All requirements outlined in the following subsections are taken from the IDD, unless indicated otherwise. Refer to Appendix A-1 for the CCP Design Specification, as it is not readily available online.

Safety Requirements

This subsection presents requirements regarding the protection of crew, as well as the atmosphere and LEO.

- The CubeSat shall not have any sharp corners or edges on the chassis or any accessible area.
- Stress Corrosion resistant materials from Table 1 of MSFC-SPEC_522 are preferred
- Materials must comply with:
- JSC 27472 Rev. B
- JSC 63838 Rev. B
- JSC 66869
- Applicable NASA guidelines for hazardous materials and selecting non-metallic materials
- Shall not use any non-metallic materials with a Total Mass Loss greater than 1%
- Shall not use any non-metallic materials with a Collected Volatile Condensable Material greater than 0.1%
- The CubeSat shall have secondary locking features on all fasteners for components that would not be held captive by the structure should they come loose.

Mechanical Requirements

This subsection outlines many of the physical attributes that CubeSat designs must meet. For the Structural and Thermal Subsystems, it presents requirements for external dimensions and rails, mass and center of mass, and mechanical interfacing with both the NRCSD and the other CubeSats inside the NRCSD. The following list provides some details of these requirements (relating only to Structural and Thermal Subsystems):

- The CubeSat will be launched from a NRCSD, and must have an XYZ coordinate system that matches that of the NRCSD.
- The positive Z-face of the CubeSat will enter the NRCSD first [3]

- The CubeSat will have continuous rails in each of its four corners running along the Z-axis. These will be the only interface with the NRCSD, as illustrated in Figure 0-7 at the end of this subsection. The rails will be designed as follows:
- The rails will have a width of 6mm
- Rounded edges with a radius of 0.5mm ± 0.1mm
- 2U length of 227mm.
- The rails will extend in the Z direction a minimum of 2mm beyond the ± Z faces of the CubeSat
- The rail ends will be coplanar with a tolerance of ±0.1mm.
- The rails will have a hardness equal to or greater than Hard Anodized Aluminum (Rockwell C 65-70). See Figure 1 for an example of the rails.
- The rails will have a roughness equal to or less than 0.6 micron
- The XY face of the CubeSat will have dimensions as illustrated in Figure 0-8 at the end of this subsection.
- The CubeSat will have a mass less than the 2U mass requirement of 3.6 kilograms
- The CubeSat will have a center of mass that is within the following range relative to its geometric center: ±2mm in the X- and Y-direction, ±4mm in the Z-direction.
- The CubeSat shall withstand a deployment velocity of 0.5 to 2 m/s upon ejection from the NRCSD, and a tipoff rate of up to 5 deg./sec/axis.
- The CubeSat shall withstand a 1200N force across all rail ends in the Z-axis
- The CubeSat shall have deployment switches embedded in the -Z faces of the rails

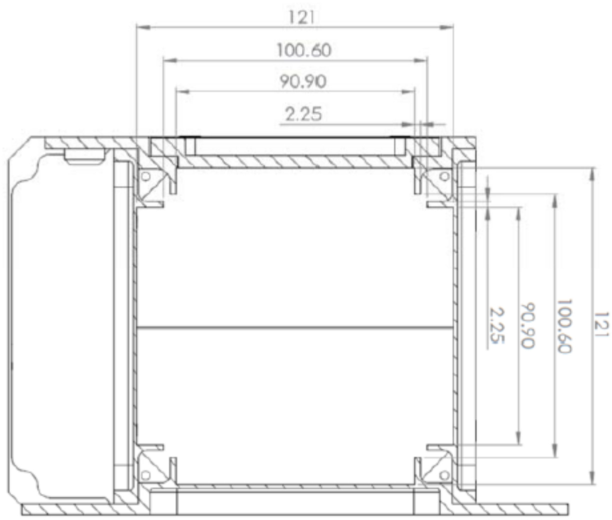

Figure 0-7 - Rail Receivers on NRCSD [3]

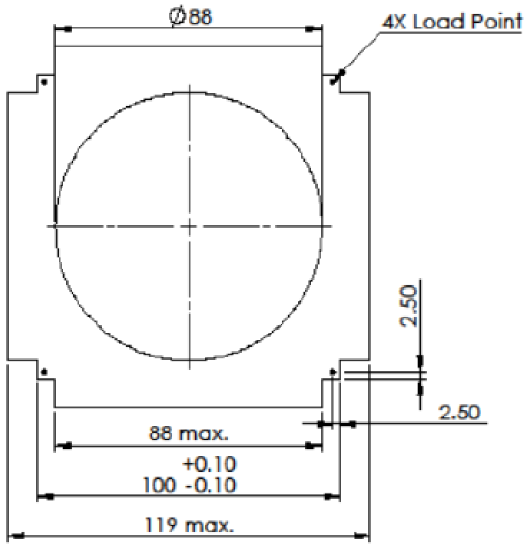

Figure 0-8 - CubeSat XY Face Dimension in mm [3]

Launch Environment

This subsection outlines requirements pertaining to the forces and atmospheric burdens that the CubeSat must withstand. These requirements will impact all components of the CubeSat, however as stated previously, the focus of this report is on the Structural and Thermal subsystems

- The CubeSat shall withstand quasi-static acceleration of ±4 time's gravity along the Y and Z axis, and ±7 time's gravity along the X axis.
- The CubeSat shall meet vibration testing requirements in both the soft-stow and hard-mount configurations. Refer to section 4.3.2 of the IDD for complete details.
- The CubeSat shall have a Maximum Effective Vent Ratio of no more than 5080cm. See Equation 1 at the end of this subsection.
- The CubeSat shall be capable of withstanding a relative humidity of 25% to 75%.
- The CubeSat shall be capable of withstanding a temperature range from -20 to 50 degree Celsius [2]. This value is taken from the CCP, as it is more conservative.
- The CubeSat shall withstand an airlock pressure of 104.8 kpa and a depressurization rate of 1 kpa/sec.

$$MEVR = \left(\frac{Internal\ Volume\ (cm)^3}{Effective\ Vent\ Area\ (cm)^2}\right) \leq 5080\ cm$$

Equation 1 – Maximum Effective Vent Ratio [1]

Operational Requirements

- The CubeSat shall have a minimum lifetime of 3 months

Ground Processing Requirements

- The CubeSat shall be developed in a clean environment of minimum Class 100,000 rating

Space Debris Mitigation Requirements

- The CubeSat shall not have detachable parts during operation
- CubeSat failure shall not create detachable parts

Canadensys Aerospace Corporation Requirements

Canadensys Aerospace Corporation (Canadensys) has presented a requirement that the CubeSat carry two 190 degree AR/VR capable cameras onboard. The cameras will be provided by Canadensys and will face in opposite directions and create 2 hemispheres of visual data, which can be stitched together to create a complete 360 degree video experience without capturing the CubeSat in the center. This aspect of the design is one of the unique features of this CubeSat, as it will be the first ever of its kind. Past CubeSat missions have featured onboard cameras, but they only provided photographs along a single axis, meaning the photo can only be taken based on the attitude of the CubeSat and its orbit, greatly limiting their use.

The cameras in this design, along with all other necessary controls, must communicate via a UHF or S-Band antenna. In order to utilize the UHF Antenna and to fit in the NRCSD, the cameras must be mounted on opposing X-Y-faces. This poses new requirements for the design, as they will limit the available surface area needed for solar panels.

At the moment, no details of the camera specifications are available except for the mass, volume and preliminary general dimensions. The design aspects and requirements are based upon discussions with Dr. Cross in meetings and via social media. Due to a lack of official documentation, this aspect of the design is subject to change, and will be formally updated in future reports. The following is a summary of the preliminary requirements:

Incorporate two cameras to create a complete 360 degree video or photograph from two 190 degree fields of view, with the following physical characteristics (per camera):

- Volume: 50x50x50mm
- Mass: 150g
- Power: >0.5W idle, 3W processing
- Maximize the quality of the images and the viewing area (countersunk or exposed)
- Utilize a UHF omni-directional antenna for communication with the ground station.
- Images must be of high enough quality to be used for learning purposes at the Nunavut Arctic College.
- Cameras to be provided by Canadensys

Conclusion

After an in-depth literature review of the requirements and constraints, as well as successful and unsuccessful past launches, a general direction for further project phases and milestones has been developed. From reviewing past launches, the trends indicate that almost all designs chose either a post and panel modular structure design, or a Monobloc style structure design with panels, with most groups using some form of aluminum alloy. This review also indicated that it is standard practice to employ passive thermal controls, due to space and power constraints.

The next steps in the design process will include concept generation, evaluation and selection. This will require a review of available materials and their feasibility, evaluation of fasteners including epoxy and mechanical fasteners, and also an evaluation of the machining techniques available in the student machine shop, UMS and off-campus service providers. Concept generation will also require research into available thermal regulation techniques, including possible proprietary techniques being developed at Western.

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Stage 2 - Conceptual Design

Introduction

The state of the art literature review performed previously for interim report 1 resulted in a large list of potential structural and thermal control features to be considered for the CubeSat Opportunity. The features must all interface with each other, requiring a thorough evaluation and selection process, which will be presented in this report.

As outlined in interim report 1, *Opportunity* is a 2U CubeSat. As per the NanoRacks IDD, a 2U CubeSat has maximum outer dimensions of 10 cm x 10 cm x 22.7 cm, and maximum mass of 3.6 kg [18]. All CubeSats must also interface with the NRCSD strictly with rails, no other contact can be made including communications. The unique payload of this CubeSat is a pair of cameras that will create an immersive 360 degree VR/AR viewing experience.

The design of a CubeSat is an iterative process due to the strict specifications and testing requirements. Along with these requirements, the CubeSat must be designed well enough that it can survive the extreme environment of both rocket launch and space. These environments present many challenges to designers. The CubeSat must endure high vibration and acceleration loads applied by the rocket during takeoff. These forces can cause parts to come loose, causing issues such as communication failure or power failure. Designing a structure to withstand these loads involves analyzing the forces themselves and the direction of their application, and using geometric designs to distribute loads evenly. Designers must avoid stress concentration or flaws that can cause stress fractures, especially where fasteners are used. Once in space, new challenges emerge, primarily in the form of thermal control. With temperatures plummeting as low as -150 degrees Celsius when the satellite enters the eclipse, and then rising as high as 100 degrees Celsius in direct sunlight, maintaining an operational temperature can be difficult, but there are many tools to choose from.

There are hundreds of possible combinations of thermal controls, and these present many more challenges. Designers must have a strong understanding of the thermal control interfaces and functionality to ensure the CubeSat does not leave the survival temperature range of any parts onboard. Both active and passive features must be considered, as well as the inherent thermal energy in the CubeSat from the onboard equipment.

The following report will provide a detailed technical analysis of the various thermal and structural design options available, as well as an examination of the complete concept generation, evaluation and selection process for the CubeSat *Opportunity*. A final conceptual design must be chosen, and all structural and thermal aspects evaluated for feasibility before moving into the detailed design phase of the project. This will be accomplished using a go/no-go screening, decision matrix and Failure Mode Effects Analysis.

Background

Quality Functional Deployment (QFD)

(Refer to Appendix B-1)

The Quality Functional Deployment (QFD) technique was used to identify the relationship between Engineering Specifications and Customer Requirements. A ranking system from 1-9 was used to measure the relevance of engineering specifications when compared to each other, and weightings of importance were established. The specifications of competing CubeSats (SwissCube and Exalta) were also ranked and used to help determine some of the final design target values. While this is an excellent tool for identifying design targets, the nature of the CubeSat project has rendered it somewhat redundant because said target values were already set by NASA and the CSA. Target values marked as "Variable" in the QFD will be determined in the detailed design phase once sufficient information has been received from the other subsystem groups.

Target Values:

- Mass: ≤ 3.60 kg
- Volume: ≤ 2.27e-3 m3
- Rotational Speed: 0.83 RPM / Axis
- Cost: < $30,000

Functional Decomposition and Morphological Analysis

(Refer to Appendix B-2)

The Function Decomposition Technique was used to break down complex objectives into simpler, essential functions. In this case, two flow charts were made to address the structural and thermal aspects of the design. Once the essential functions have been determined, the Morphological Analysis technique was used to further decompose said functions into specific solutions.

In terms of structural design, the essential function was structural integrity. This was further broken down into specific assembly properties and structural configurations. In terms of thermal design, the essential function was thermal regulation. This was also broken down into potential thermal devices and methods. The result was a variety of potential design implementations and features.

The results of the Functional Decomposition and Morphological Analysis provided a wide array of devices and methods to be analyzed for use in the design of *Opportunity*. The analysis of these devices is covered in Section 2.3 – Section 2.5. The individual structures and thermal devices are examined, as well as some of the scientific theory involved in the thermal devices.

Structure

Monoblock

The monoblock structure design is very simple in nature, and very effective. It is manufactured by machining the structure design from a single block of material. This type of structure was used in the design of the SwissCube, utilizing electrical discharge machining (EDM) [18]. This type of machining allows the designer to finish with squared corners, instead of round corners that result from more common manufacturing methods, such as a lathe or mill [19]. Once complete, holes can be tapped for fastening as needed, and panels attached to enclose the internal features or mount solar panels.

Due to the monoblock's manufacturing method, it can also take advantage of space between and outside the rails, something that is difficult to do with the post and panel assembly. As seen in Figure 9 below, this space allows the monoblock to increase its XY dimensions from 10cm x 10cm to 11.9cm x 11.9cm. This adds a large amount of internal volume that is typically missed in modular CubeSat designs.

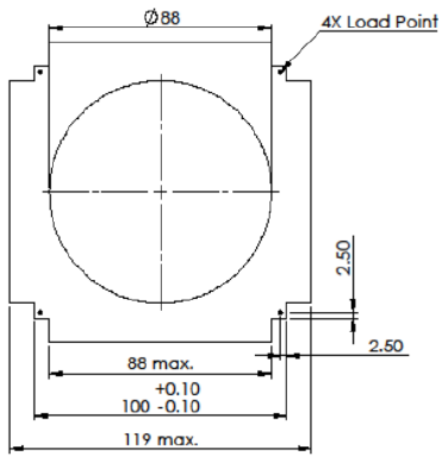

Figure 9 - Maximum Outer Dimensions of End-face of CubeSat from IDD [7]

Post and Panel

Post and panel (P&P) assembly is the most commonly used structural design for CubeSats due to its simplicity for construction and adaptability for various mounting configurations. The idea of P&P is to have the external loads carried by the posts (rails) to try and maximize the available internal volume inside the CubeSat. This is beneficial, considering a common problem with CubeSats is the limited volume for necessary payload and required components. There are many different post and panel designs that each offer different locations of pre-drilled holes for mounting solar panels and internal components. The designs can be optimized to reduce excess material, which also influences the base mass for the CubeSat.

Some P&P structures are available off the shelf from suppliers such as CubeSatShop and Innovative Solutions in Space (ISIS). Many P&P assemblies come pre-built, and some are designed to fit universally into a range of dispensers such as P-POD, ISIPOD, and NRSCD, while others are designed to fit into a single deployer [20].

Heat Transfer

The Law of conservation of energy states that energy cannot be created or destroyed. Energy can however be transferred by a system interfacing with its surroundings in the form of heat and work. There are three means of heat transfer: conduction, convection, and radiation [21].

Conduction

The most common mode of heat transfer is conduction. Conduction is the transfer of heat via a transfer of energy between particles or groups of particles through a solid or stationary fluid at the atomic level. Fourier's law of thermal conduction is used to find the heat flux [21]:

$$q" = -k\nabla T \ = \ -k(\frac{dT}{dx}\boldsymbol{i} + \frac{dT}{dy}\boldsymbol{j} + \frac{dT}{dz}\boldsymbol{k})$$

Equation 2 - Heat Flux [21]

The negative sign is placed to show that the heat transfer always travels in the direction of decreasing temperature gradient. In orbit, the CubeSat will specifically face transient conduction since the temperature difference that drives the process is always changing. The orbit of the Earth around the Sun follows an elliptical path and therefore the radiation absorbed by the CubeSat will vary between a maximum and minimum value depending on its distance from the Sun. This absorbed radiation will heat up the CubeSat and in turn initiate the temperature gradient required for conduction to take place.

Convection

Convection is the transfer of energy (in addition to conduction) between a fluid in motion and generally a pipe, duct, or along a surface. The transfer of heat is highly dependent on the nature of the flow. There are two types of convection: natural convection and forced convection. Natural convection involves the motion in a fluid due to gravity and a density gradient whereas forced convection takes place when the motion in the fluid is caused by a fan or pump. The simplified convection equation is presented in Equation 3 [20]:

$$\dot{q} = hA(T - T_w)$$

Equation 3 - Convection [21]

The CubeSat will not have to face any type of external convection due to the fact that space is a vacuum and has no medium for convection to take place. With the CubeSat also having a vent (as required by NanoRacks) to depressurize the interior in order to create a vacuum within the structure, the only internal convection would be introduced by heat pipes, which are discussed in Section 2.5.2.

Radiation

The third mode of heat transfer – radiation, is the transfer of thermal energy by electromagnetic waves. Radiation, unlike conduction and convection, does not require a material medium and in fact is most efficient when a vacuum is the medium. The net transfer of energy by radiation between two surfaces can be found using the simplified Equation 4:

$$\dot{q}_{12} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1F_{12}} + \frac{1-\epsilon_2}{A_2\epsilon_2}}$$

Equation 4 - Net Energy Transfer Between Surfaces [5]

There are three sources of radiation that the CubeSat will experience, making radiation the most dominant mode of heat transfer when compared to convection and conduction. Those sources of radiation are direct sunlight, sunlight reflected by the Earth (Albedo), and IR energy emitted from the Earth.

The thermal radiation energy that falls on a surface is subject to one of three actions; absorption, reflection, and transmission [22]. They can each be represented as a fraction of the total radiation fallen on the surface and their resulting sum must equal to one. Therefore it is expressed as shown in Equation 5:

$$\alpha + \rho + \tau = 1$$

Equation 5 - Total Radiation on Surface [22]

α=absorptance, the fraction of total incident thermal radiation absorbed
ρ=reflectance, the fraction of total incident thermal radiation reflected
τ=transmittance, the fraction of total incident thermal radiation transmitted through the body

The CubeSat itself may also radiate thermal energy as a method of cooling. In order to take advantage of this, it is important to analyze the emissivity of different materials, and compare it to the purpose of the surface the material will represent. A material with a high emissivity (an ideal radiator has an emissivity of 1 and is called a black body), is very efficient at emitting thermal energy. Emissivity can be calculated using the Stefan - Boltzmann equation, as follows in Equation 6 [23]:

$$J = \sigma T^4$$

Equation 6 - Stefan-Boltzmann Equation [23]

J=Energy radiated per unit area of a black body per unit time [$Jm^{-2}s^{-1}$]
σ=Stefan-Boltzmann Constant [5.67×10^{-8} $Js^{-1}m^{-2}K^{-4}$]
T=Absolute temperature [K]

The total energy absorbed by the surface can be determined using the cosine law, as follows in Equation 7:

$$Q_a = S_o \times \alpha \times A \times \cos(\theta)$$

Equation 7 - Cosine Law [24]

Q_a = power absorbed [W]
S_o = Solar Constant [1367 Wm^{-2}]
α = Absorptivity
θ = Angle of incidence

Thermal Devices

Thermistors

A thermistor, or Thermally Sensitive Resistor (their original name) are semiconductors in which the resistance of the material changes with temperature. They have many uses, however their primary application is as a temperature sensor. There are two types of thermistor, Negative Temperature Coefficient (NTC) and Positive Temperature Coefficient (PTC). NTC thermistors are used as temperature sensors and as such will be employed on the CubeSat Opportunity. Thermistors can be made of various materials, each with different benefits and drawbacks. An example of a copper wire thermistor is presented below, in Fig. 10. They also have coatings such as glass or epoxy, which are used as a shield from humidity, corrosion and physical damage [25]. The resistance of the thermistor is what determines the effective temperature range that it can sense, typically +/- 50 degree Celsius [26]. For this reason, it can be beneficial to have various thermistor types for the temperate ranges experienced in space.

Figure 10 - Copper Wire Thermistor [25]

Other temperature measuring devices include resistance temperature detectors (RTD's) and integrated circuits, however these are more expensive and less sensitive and stable. Due to the effectiveness of thermistors, their consistent use on other CubeSat's, and their low cost, no other temperature measuring devices will be evaluated in detail.

Heat Pipes

The function of a heat pipe is a passive liquid-vapor cycle influenced by a capillary pressure force. The construction of a heat pipe consists of a casing, a wick structure, and contains a saturated liquid and its vapor. When heat is applied to one end of a heat pipe that end becomes the evaporator and the other end in turn becomes the condenser. The saturated liquid vaporizes at the evaporator and leads to a decrease in pressure for the remaining liquid and an increase in vapor pressure at the evaporator. The increase in pressure causes the vapor to travel towards the condenser where it then drops in temperature and becomes a saturated liquid again. The saturated liquid is then moved from the condenser back towards the evaporator through the wick structure and the cycle is completed [27].

The casing is usually a highly conductive metal such as copper or aluminum. The working fluids most commonly used for heat pipes are water, ammonia, and methanol as these three have the highest heat flux densities. Certain working fluids are more beneficial than others for certain applications. To elaborate, water has a freezing point of 0 Celsius and therefore wouldn't work for temperatures lower than that. However ammonia can be used for temperatures as low as -70 Celsius [27]. Heat pipes also come in different types such as axial grooved, meshed, and sintered cross-sections, presented in Fig. 11, below. The axial grooved design has been shown to be more reliable and efficient than the other two based on the concept of increased surface area for conduction to take place. Heat pipes are also very functional due to their ability to be shaped and formed to any configuration to fit the available space which is a key benefit for CubeSats.

Figure 11 - Axially Grooved, Meshed and Sintered Heat Pipe Cross Sections [27]

Thermal Storage Unit

A thermal storage unit is a phase change material enclosed in a casing. The phase change material cycles between solid and liquid phase. When the temperature of the material is increased it begins to melt and absorb heat energy. When the temperature starts to drop the material begins to solidify again and releases energy to the surroundings. This cycle repeats as the temperature increases and decreases. The thermal storage unit can act as a sink or source, and as such it must be connected to any sinks or sources that require a storage unit by a thermal strap (discussed later in this section).

Electric Heater

A thermal device that converts electrical energy to heat. A standard electric heater used for CubeSats consists of a foil element (typically copper or another highly conductive element) covered with a thin film of Kapton, as seen below in Fig. 12. Current is run through the element and converted to heat energy that can be transferred to components through thermal straps. Electric heaters are often used in conjunction with temperature sensors to keep battery temperatures in the operating range [28]. They are great for precise temperature control.

Figure 12 - Flexible Electric Heater [28]

Thermal Straps

Thermal straps are a simple, tidy and effective way to connect heat sources to heat sinks, allowing thermal energy to be transferred via conduction in a controlled manner [20]. Today's thermal straps are often manufactured to be flexible braids or foil, allowing ease of implementation [29]. The most common materials used for thermal straps are copper and aluminum, however some manufacturers offer more uncommon materials such as carbon, graphite fibre and graphene. Examples of thermal straps made of copper, aluminum and graphene foils are presented in Fig. 13, below. Thermal straps have a conductivity

Figure 13 - Graphene, Copper and Aluminum Thermal Straps [14]

range from 225 W/m.K for aluminum, up to 3500 W/m.K for graphene [30]. Due to their passive nature, they can be any size, which makes them a good thermal control for CubeSats, where space is limited.

Radiators

Radiators act as a heat sink, allowing accumulated thermal energy to be transferred into them via conduction, and then emitted into the environment. Radiators are typically made of materials with a high emissivity and conductance, and as low absorptivity as possible, allowing thermal energy to transfer and distribute evenly from the rest of the satellite. They can be mounted directly to a structure, be deployed as needed, or be deployed once, permanently. A challenge that can be faced in the space environment is the presence of various wavelengths coming from multiple sources of radiation. This makes material and surface finish selection difficult, as some materials can have a very high emissivity at one wavelength, and a much different emissivity at another [31]. An object that is white in the visible spectrum appears black in the IR spectrum [24]. This is evident in the radiators used on the ISS, as some appear light and shiny, and others appear dark and matte, as seen in Fig. 14 below.

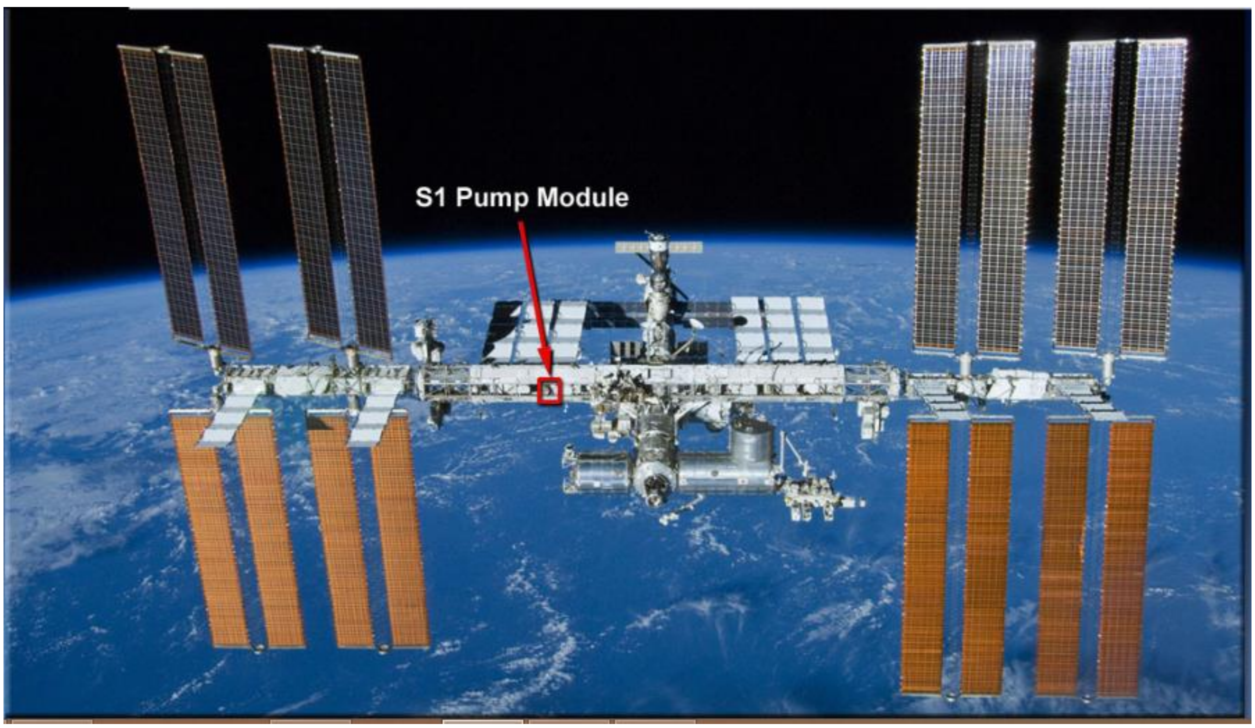

Figure 14 - ISS Radiator Array [32]

In some radiators, such as those used on the ISS, a network of tubes are sandwiched between two radiator plates, allowing it to operate as a heat exchanger [33]. The tubes are charged with a working fluid such as ammonia. The tubes then circulate the fluid throughout the satellite, absorbing thermal energy, and then transferring it to the radiator plates. This type of radiator is likely too large and heavy for use in a CubeSat.

Concept Generation

Concept A - Heat Pipes + Thermal Storage Unit

(Refer to Appendix B-3, Concept A)

Concept A uses the combination of a heat pipe and a thermal storage unit to transport heat away from the circuit boards and other electronics and stores it to be used later. On a circuit board there is a single heatsink where all the heat generated from the processor is expelled. For the CubeSat, this location will be a heat source and therefore create a hotspot. The use of the heat pipe is to move the heat expelled from the heatsink on the circuit board to the thermal storage unit. As illustrated in the model in Appendix B-3, two identical custom plates the size of the heatsink and made of copper would be directly placed on the heatsink. Copper is chosen as the material because it has a high conductivity and therefore will be efficient to transport the heat from the heatsink to the heat pipe directly through conduction. A custom round groove the same diameter as the heat pipe would be carved into the plates. This allows for a snug fit when the plates are combined by screws in order to secure the heat pipe to the circuit board. The grooves would also increase the surface area at the interface between the heat pipe and plate which results in an increase of conductive heat transfer.

The configuration of the heat pipe is designed so that a single heat pipe will act as two separate heat pipes. It is achieved because of where the heatsink is connected. The heatsink will heat up the heat pipe at its midpoint rather than at one of its ends. This then makes two separate condensers, one on either end of the heat pipe. This is desired for simplicity and it also minimizes the parts required for the same purpose. The interface between the condensers and the thermal storage unit is similar however only one plate is used to fasten the ends of the heat pipe to the thermal storage unit. In an effort to again increase the surface area at the interface, the condenser ends are flattened slightly to allow for more contact area to the thermal storage unit.

The design works based on the idea that when the CubeSat is operating, the circuit board will generate some heat which will be transported to the thermal storage unit via the heat pipe and stored. When the CubeSat enters into the eclipse period the circuit board will be powered down to standby mode and therefore will no longer be generating additional heat. This causes the thermal storage unit to eventually become the heat source and the interface at the circuit board to become the condenser. As a result the circuit board is maintained at a temperature within its survivability range at all times during the CubeSat's orbit as the process cycles back and forth. This also ensures that the heat pipe does not fully freeze at any time and therefore wouldn't require time to thaw before restarting its process.

Concept B - Thermal Electric Heaters + Thermal Straps

(Refer to Appendix B-3, Concept B)

Concept B utilizes electrical heaters and thermal straps to regulate the CubeSat's temperature. Electrical heaters will draw power from the main power supply and convert it into heat energy. The heat is then transported to the component panels through thermal straps situated along the CubeSat. Panels near the cameras on both ends of the CubeSat are dedicated to the electrical heaters. These panels will hold three sets of electric heaters, which will be mounted around the camera fasteners, and fastened with screws. Thermal washers will be incorporated to reduce heat conduction to the screws. In the event that more space for components is required, electric heaters can also be mounted to the inside walls. Refer to Appendix B-3 for a visual model. The electric heaters will be fastened with screws.

In a worst case hot (WCH) situation, heat from the panels will be transferred to thermal sinks mounted outside the satellite body. The thermal sinks will consist of aluminum blocks due to their high heat capacity (857-990 J/kg.K) and thermal conductivity (76-235 W/m.K), as seen in the property table presented in Appendix B-4. The thermal properties of aluminum allows it to take excess heat from the components inside the CubeSat. This is advantageous for handling excess heat but comes at the cost of some surface area on the outer panel. Electric heaters will still be operable in this scenario due to their high operating temperature (up to 250°C), as presented in the table in Appendix B-6 for thermal electric heaters.

In a worst case cold (WCC) situation, electric heaters will have an important role in regulating heat in the system. Batteries have a thermal operating range of -40° to +85°C and will rely on electric heaters to remain active. At certain points during the mission when the CubeSat is not in use, it will enter a low-power survival state to conserve energy. In order to go back to an active state, the CubeSat will rely on heat generated through the electric heaters to warm up the system. An active control system between thermistors and electric heaters will be used to regulate components temperatures.

Concept C - Deployable Radiators + Thermal Straps

(Refer to Appendix B-3, Concept C)

Concept C will focus on integrating deployable radiators and thermal straps in a Monobloc structure. The radiators are used to transfer internal heat into the surrounding environment. In order to do this, heat must be directed to the radiators. This is achieved with Thermal straps, which are relatively simple to employ; one end is connected to a heat source and the other to a heat sink (the radiator). Due to the passive nature of thermal straps, they can work both ways, allowing the sink and source to be reversed. This is beneficial in space environments, as temperatures are extremely hot in the sun, and extremely cold in eclipse, usually exceeding operational ranges of equipment at either extreme.

The radiators must be within the maximum allowable dimensions as per the IDD, until 30 minutes after deploying from the NRCSD. In order to meet this requirement, the radiators must be fastened flat against the structure on a hinge. In order to conserve energy, a loaded spring hinge would be used, and the radiator deployment would be controlled internally. Potential controls include a burn wire, which would tie down the radiator until deployment and then burn away, allowing it to extend. Another control could be a motor or actuator with a bar, which would slide/rotate through a slot on the bottom of the radiator. This method would require a part of the radiator to pass through the side panel of the structure, reducing solar panel space. The actuator design is visible in the model in Appendix B-3.

The thermal straps would connect to the radiator at the hinge. The hinge itself would be made of a highly conductive material, with two highly conductive fasteners passing through the structure. On the inside of the structure, there would be a small plate, which is where one end of the thermal strap would attach. This would provide an easy passage for thermal energy through the structure, from the strap to the radiator. By using insulators on the hinge, plate and fasteners, thermal energy can be prevented from transferring into the structure instead of from the strap to the radiator. The other end of the strap would pass through the internal space and connect to a source. In the model in Appendix B-3, it passes through a middle platform and connects to a potential location for batteries or computer chips. The setup presented in Appendix B-3 is preliminary and will change if this concept moves forward, as more details of other subsystems become available.

Concept D – Paints + Coatings

Concept D focuses on a purely passive thermal control system to keep the temperature of the satellite within its survival temperatures, as presented in Fig. 15. This design incorporates a low emissivity coating on the interior of the satellite with paint on the exterior of the satellite. All paints and coatings must be low – outgassing and meet the requirements outlined by the Canadian Space Agency (CSA). They also need to endure the harsh space environment which can reach temperatures greater than 100°C and lower than -150°C. The temperature of the CubeSat will be fluctuating dramatically as it rotates around the earth once every 90 minutes. For these reasons, the chosen materials will be thoroughly tested on previous space missions and adhere to all safety and environmental regulations provided.

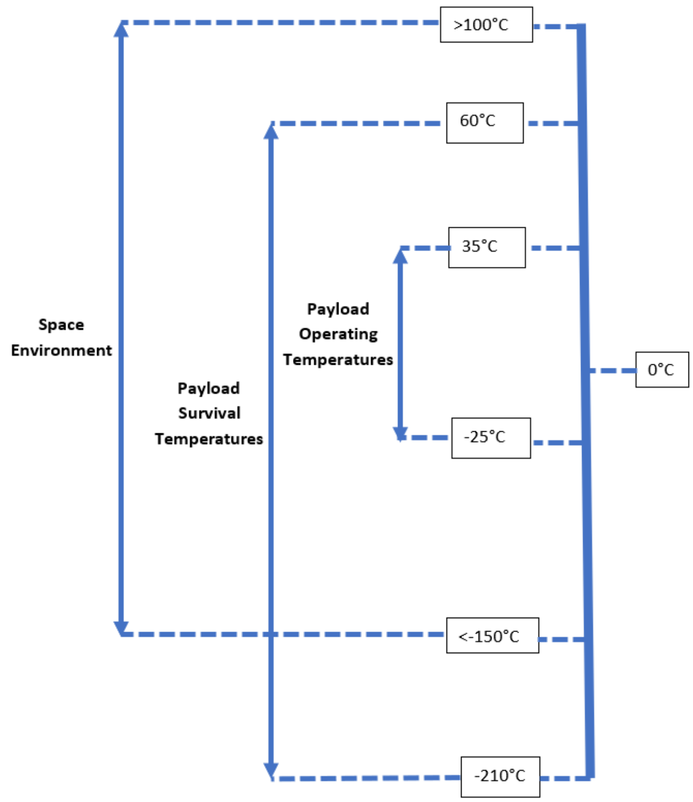

Figure 15 - Various Temperature Ranges

The payload of the CubeSat has an operating temperature range of -25 to 35 degrees Celsius. This is when the cameras will be used and the electrical components need to be operating efficiently. The payload survival temperature range is from -210 to 60 degrees Celsius. Outside the range the electrical components of the payload will reach their thermal limits and fail. Additionally, the space environment range is from -150 to over 100 degrees Celsius. Therefore it is important to cool the satellite when exposed to the sun and heat the satellite in eclipse periods in order to stay within the operating range during orbit.

Applying paint to the exterior of a satellite is one of the simplest ways to limit the solar energy being absorbed and emitted into space. White paint has a high emittance value and a low absorptance value and is therefore good at rejecting heat and limiting the heat absorbed. For an optimal design, the entire outer surface of the CubeSat would be painted white to keep the payload and electronics as cool as possible in the non-eclipse phase of orbit. This would be useful when applied to the exterior of the CubeSat, specifically in the non-eclipse period when the payload is vulnerable to overheating. However, when facing the sun, the CubeSat needs to use the sun's energy and charge the batteries for the payload by means of solar panels. These solar panels will need to take up as much surface area as possible to generate sufficient power for the payload. With the solar panels mounted, the only exposed surfaces will be in between each solar cell and on the end faces where the camera is located. This alone will not be sufficient to limit how much heat the satellite absorbs from the sun. Therefore, thermal control from the interior of the satellite must be implemented. The interior of the CubeSat will have a thermal coating with low emissivity to reduce the radiation through the walls.

Passive thermal control systems are very popular for small satellites and have been continuously developed and implemented since the 1960's [34]. Advantages of a passive thermal control system include the simplicity, relatively low cost, and reliability of the design.

Concept Evaluation and Selection

Concept Evaluation

Go-NoGo Screening

(Refer to Appendix B-7)

Go-NoGo Screening is a pass/fail screening technique used to determine feasibility at the most basic level based on customer requirements. Each concept was analyzed and given a Go or NoGo based on if they were able to conform to customer requirements or not.

Since Post and Panel and Monoblock are both established and popular methods of CubeSat structure, they were given a Go across the board. In terms of the thermal aspects of the Go/NoGo table, any design that has a method of generating and dissipating heat was given a Go. Concept C was given a NoGo for thermal regulation because it has no method of generating heat in a worst case cold (WCC) situation. Concept C was also given a NoGo for structural reliability because deployables present more failure modes in the structure resulting in a higher chance of failure. Deployables have to be approved by the NanoRacks CubeSat Deployer (NRCSD) before they can be given a Go for conformance, hence why Concept C was given a NoGo for conformance. Overall, the materials used for all concepts are environmentally friendly and will not be a problem during re-entry. Payload integration and manufacturability was given a Go across the board because the structural designs were all made with accommodating components in mind, and because the modular nature of CubeSats makes them easy to assemble.

Through Go-NoGo Screening, Concept C was ruled out as a feasible concept.

Decision Matrix

(Refer to Appendix B-8)

A decision matrix is a means of scoring and comparing concept feasibility. A list of customer requirements oriented in rows and columns are scored based on significance, and weightings are established for each value. Each concept is then scored based on how well they meet the customer requirements, with +1 meaning that the concept exceeds the requirement, 0 meaning it just meets the minimum requirements, and -1 meaning the concept does not meet the requirement. The weightings are then multiplied by scores given to the concept, and a final grade is calculated. Through this process, qualitative information is converted to quantitative scores and used to determine which product is objectively superior.

In terms of thermal regulation, only Concept B was given a +1 because it was the only concept capable of both generating heat (through electric heaters) and dissipating heat (through heat sinks). Concept A and D are unable to generate their own heat and must rely on retained heat to survive during WCC periods. In terms of structural reliability, vibration resistance, and NRCSD compliance, all concepts conform and are structurally adequate hence the +1 across the board.

Concept A gets a score of 0 for environmental friendliness due to the nature of the heat pipes. If they are based on ammonia or other chemical it may leave harmful waste in the atmosphere.

In terms of manufacturability Concept D gets a score of 0 because of the extra work involved in the design (installing several solar panels and applying coatings). Payload integration is 0 across the board due to all concepts being adjustable enough to accommodate the components. A score of +1 is given to every concept for ease of handling because hazards will be minimized in the final design.

The final outcome suggests that Concept B has the highest score but concepts A and D also show some promise.

Final Design Concept Selection and Justification

The final concept incorporates various solutions from the concept generation. The pros and cons generated from the concept evaluation provide the necessary information to analyze the concepts and select an optimal design. Solutions were initially eliminated in the evaluation stage due to violations against design constraints and specifications. Through risk evaluation and feasibility analysis, more solutions were deemed unrealistic and did not require further investigation. No individual concept appeared to be completely superior to any of the others, and each had many positive characteristics unique to the design. As a result, the selected final concept focuses on the best aspects of the thermal control systems and structural solutions that were thoroughly explored and researched.

The final concept chosen will be built out of a post and panel structure and incorporates a combination of electrical heaters, a thermal storage unit and thermal straps, and a white painted exterior. The post and panel structure is easier to manufacture and will reduce the difficulty when integrating the other subsystems. The electric heaters are versatile and can be used in different sections of the CubeSat that will require more heat in the worst case cold condition. They are also easily mountable and can be rearranged easily for optimal design. The use of thermistors will communicate the temperature required from the electrical heaters to the satellite computer and let them know when to turn them on. The thermal storage unit can collect heat or release it, depending on the satellites temperature fluctuations due to its location in orbit. The thermal straps will carry the heat and be located such that the heat dissipated goes where required. The exterior of the CubeSat will be painted white to help keep the internal temperature to a minimum when exposed directly to the sun. This combination of both active and passive thermal control systems will ensure the CubeSat always remains within its survival temperatures.

A detailed CAD model of the final design will be created for the next report in order to incorporate the currently unavailable components of the other subsystems.

Failure Mode and Effects Analysis

(Refer to Appendix B-9)

The potential failure modes and effects analysis (FMEA) was performed to identify all possible failures in the design [35]. The consequences of the failures has been studied in the effects analysis portion of FMEA. The structural and thermal capstone team for Opportunity assembled together to work through the design tool, presented in Appendix B-9. The process function was separated into thermal and structural considerations. The severity of the structure failing is slightly greater than the electrical components / payload overheating or freezing since the satellites function relies on the structure staying together. Both values of severity are very high since each failure mode would likely cause a mission failure. The occurrence value is the probability of the failure occurring throughout the lifetime of the mission. These values were kept low since the thermal control systems and the structure are designed based off of research from other CubeSats and their failures and successes. The causes of failure were identified next, and the current process in place to control the failure was re-evaluated. The recommended actions are put in place to reduce the severity and occurrence values.

As a result of this analysis, the CubeSat will need to be tested thoroughly on the ground before it is sent into orbit. The thermistors will be able to provide information about the temperature of the satellite when in space, but the structure will not have a process to control the structural integrity while in orbit. The thermal control systems must be tested in a vacuum setting to simulate the effects of the temperature fluctuations in space. The temperature will need to be monitored in certain locations and the time it takes for sections to heat and cool also needs to be determined. The structure will need to be tested on a vibration table to find out if it will hold up to the vibrations that it will experience prior to deployment. The insight gained from using FMEA has prepared the capstone group for the next stage of the design process.

Conclusion

By using concept generation engineering techniques and following a comprehensive process, several device options were discovered. From these options, four creative concepts were developed and evaluated. With the use of concept evaluation tools, rigorous discussion, and by combining the best elements of the concepts created, a final design that can accommodate all needs has been created. The final design will be able to withstand the harsh conditions of space while also conforming to the needs of NRCSD and the payload.

The next step in the CubeSat project will be working with the other subsystem group's specifications to determine and apply the fine details and changes to the final design. Vibrational and thermal testing will also be necessary to determine any flaws in the final concept. This concept will serve as a firm base for iterating until all constraints from all subsystems are satisfied, and a highly optimized prototype is proven through testing, and can be made.

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Stage 3 - Detailed Design

Introduction

The success of the CubeSat mission will heavily depend on the detailed design of both the thermal control system and structure. The detailed design will focus on a single concept selected from the previous stage of the design process. The selected concept was generated amongst other concepts and evaluated as the optimal solution to the CubeSat design problem.

To ensure a thorough analysis, every individual component of the final assembly must be taken into consideration. A bill of materials (BOM) will be generated to keep track of all the components and their properties. The mass budget and thermal budget will be updated and maintained in parallel to the BOM. The budget requirements will drive iterations to specific components and ensure the margins are followed. Various design parameters will be optimized and defined before the prototype construction can be considered.

Thermal calculations will be performed to ensure the temperature of the CubeSat stays within an acceptable range during the non-eclipse and eclipse phases of orbit. The radiation experienced from the exterior of the CubeSat will be transferred inside through a combination of conduction and radiation. The internal temperature on the inside of the CubeSat will justify the use of the chosen thermal control systems and their arrangement.

The CubeSat will be designed to withstand the ascent into orbit, the launch from the NanoRacks CubeSat Deployer (NRCD), and the anticipated harsh space environment. To design the CubeSat to withstand the vibrations from the ascent into orbit, a simulation of the vibrations will be performed on SOLIDWORKS using finite element simulation analysis (FEA). The acceleration loads from the launch will have to be taken into consideration and simulated using SOLIDWORKS. The thermal environment will also be simulated through SOLIDWORKS to ensure the temperatures at specific nodes are within an acceptable range. The CubeSat will need to be designed for each phase of the satellite's life to ensure a successful mission.

The Concept

The selected solution to the CubeSat consists of a post and panel assembly structure along with a thermal storage unit, thermal straps, electrical resistance heaters, and a white painted exterior to control the internal temperature. The shape of the CubeSat utilizes the maximum possible volume available in the NRCSD while adhering to the dimensional tolerances and constraints. The thermal storage unit will occupy one of the many layers of the CubeSat and will act as a heat sink in the non-eclipse phase of orbit. The heat will be directed towards the heat sink through means of thermal straps which are connected to the electrical components that are generating heat. In the eclipse phase of orbit, the thermal storage unit will act as a heat source alternatively, and dissipate heat throughout the CubeSat. The electrical heaters will ensure that electrical components, including the payload, don't freeze or drop below their survival temperature when turned off. The white exterior of the CubeSat will passively control the temperature of the CubeSat throughout the entire orbit by emitting heat in the eclipse phase and limiting the heat absorbed in the non-eclipse phase. To provide the ground team with a live temperature reading of the CubeSat, thermistors will be positioned strategically around certain internal components. The concept selected incorporates an optimal approach to thermal control as well as a relatively simplistic, yet robust structure.

As the subsystem teams learned more about their requirements and limitations, the decision to remove some of the thermal control techniques were made. The removal of electrical resistance heaters, and replacing white paint with black paint will be discussed later in this report.

Payload Integration

The payload consists of two deep space cameras which will provide a 360-degree field of view for immersive AR/VR imaging and recording. The cameras, presented in Fig. 16 below, will be mounted to each end face so the stitch line generated from combining both cameras will not be obstructing the view of earth. The location of the cameras is fixed and will determine the configuration of the other components of the design. The cameras will be mounted with 4 threaded rods (one in each corner) which will be fastened to a customized structural panel. The power consumed from one camera during full processing is 3W. Therefore, the cameras will act as sources of heat at either end of the CubeSat when running. The structural panel will allow the heat to dissipate by conduction to the rest of the CubeSat structure.

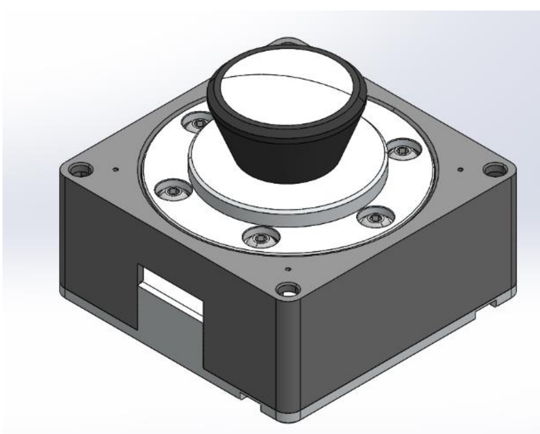

Figure 16 - Canadensys AR/VR Camera

Subsystems

Some of the subsystems involved in the CubeSat project require various components to be added to the CubeSat to meet their functional requirements. These subsystems include attitude determination and control subsystem (ADCS), electrical power subsystem (EPS), and the communications subsystem (COMMS). All of these subsystems will be controlled by the on-board data handling computer (OBDH). As components were defined throughout each of the subsystems individual design process, the structure and thermal team gathered the relevant information and created the BOM. The unique requirements specific to each subsystem component were identified and communicated to the structure and thermal team for further analysis.

It is important to note that do to the preliminary nature of the component selections so far, all subsystem components will be represented in the CAD models (Section 6) by solid bodies. The solids will represent the maximum dimensions of the component, as well as some basic geometric features, and will have the relevant mass applied.

Attitude Determination and Control System

The ADCS subsystem requires six sun sensors, three gyroscopes, one magnetometer, and three magnetorquers. The primary objective of the ADCS team is to provide accuracy and stability for the CubeSat as it orbits around the earth.

The six sun sensors will have to be mounted onto each face of the CubeSat to ensure that there is a reference location for every possible orientation [1]. There is no preference for location of the sun sensor on each face. Therefore, they can be mounted and positioned so that they do not obstruct the solar panels or camera lenses. The power consumed by each sun sensor is 130 mW at its peak. However, since the sun sensors are on the placed on the exterior of the CubeSat the majority of heat generated will be assumed to be radiated out into space. The current sun sensor being investigated by ADCS is presented below in Fig. 17.

Figure 17 - ADCS Sun Sensor [1]

The three gyroscopes will all fit onto one printed circuit board (PCB) **[2].** Each gyroscope will be in-line with one of the primary axes with respect to the CubeSat. The volume of the gyroscopes is relatively small compared to other components and there is no preferred location within the CubeSat. The gyroscopes have a very low power consumption of 4mA and produce little to no heat within the CubeSat. An example of a typical gyroscope PCB configuration is presented in Fig. 18 below.

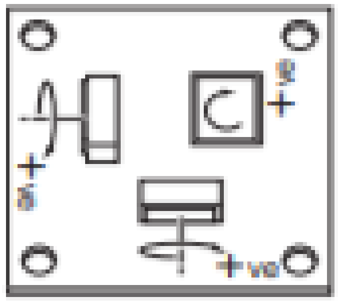

Figure 18 - Gyroscope Configuration [2]

The three magnetorquers, will be aligned with each primary axis and act as a direct method of attitude control [2]. The same magnetorquers model is used for all 3 axes, and is presented below in Fig. 19. To produce more torque, the magnetorquers will be located near, but not on, the center of mass (COM). However, if the magnetorquers are too far from the COM, overshooting will occur, which is unfavorable. Two of the magnetorquers will fit onto one PCB which will occupy one of the layers. The third magnetorquers will be in-line with the Z-axis and requires strategic positioning to prevent unused volume within the CubeSat. Therefore, the camera mounting plate will have a slot cut out of it to make space for the Z magnetorquer beside one of the cameras.

Figure 19 - Magnetorquer Rod [3]

The magnetometer, presented in Fig. 20, is the smallest subsystem component required by ACDS. The magnetometer will be located as far away from any magnetic field as possible. The magnetic properties of the sensor sensitive and subject to change when placed near magnetic parts such as the magnetorquers or the on-board computer. The magnetometer and magnetorquer work synchronously together such that when the magnetometer turns on, the magnetorquer turns off and when the magnetometer is turned off, the magnetorquer turns back on.

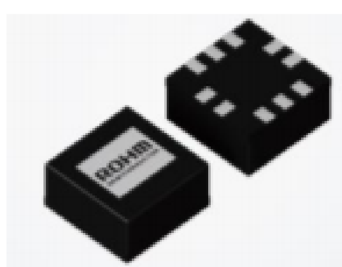

Figure 20 – Magnetometer [4]

Communications

The communications subsystem requires a transceiver and an antenna to send signals to and from the satellite when in orbit. The transceiver and antenna selected by the COMMS team are designed to be incorporated into standard CubeSat sizes. Both components will occupy one of the many layers within the CubeSat.

The UHF antenna will be positioned in the middle of the CubeSat, half way along the z-axis. This will ensure that when the antenna is deployed the extending arms will line up with the stitch line between both cameras. Therefore, the view of earth will be unobstructed which is an advantage of the *Opportunity* design. Fig. 21 below presents the current antenna model being investigated.

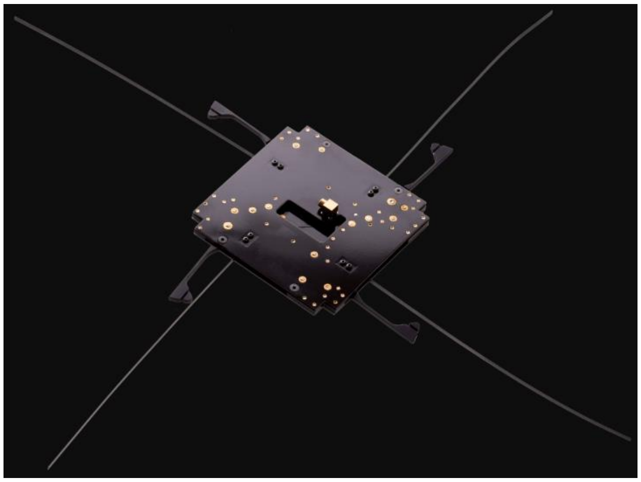

Figure 21 - UHF Antenna [5]

The transceiver, will receive information from the on-board computer and will have wires connecting the two components. The transceiver will be placed on top of the antenna which will simplify the wire connection between these two components. The transceiver currently being investigated is presented below in Fig. 22.

Figure 22 - COMMS Transceiver [6]

Electrical Power System

The EPS team requires two batteries charged by sixteen solar panels mounted on the exterior faces of the CubeSat. The solar panels will be connected to the batteries to recharge them when the CubeSat is facing the sun.

The two batteries selected from the EPS team are contained within a battery pack that is designed to be mounted in a standard CubeSat, as presented in Fig. 23 [7]. There are four holes with a 3.2mm diameter (one in each corner) for mounting the battery pack to the CubeSat structure. The batteries will be positioned as close to the center of the CubeSat as possible to ensure that the heat dissipates evenly to all the components. Since the battery pack has a mass of 278g, it is beneficial to the COM requirements that it is located near the center.

Figure 23 - EPS Battery Pack [7]

The solar panels, presented in Fig. 24, selected by the EPS team are designed for a standard 1U CubeSat with two panels on each face [8]. *Opportunity*, as a 2U CubeSat, will require 16 solar panels in total. The solar panel walls have countersunk holes in each corner, allowing them to be fastened to the rails and remain flat on their surface. Of the eight panel walls needed, six will be fastened with M3 flat head screws and M3 nuts. Due to lack of internal access, the final two will have an M3 screw that fastens to a square nut. The square nut will be glued to the inside of the rail with low strength adhesive (to temporarily hold it in place). By having the edges of the square nut flush with interior surfaces, it will not spin and will allow the screw to be tightened from one side.

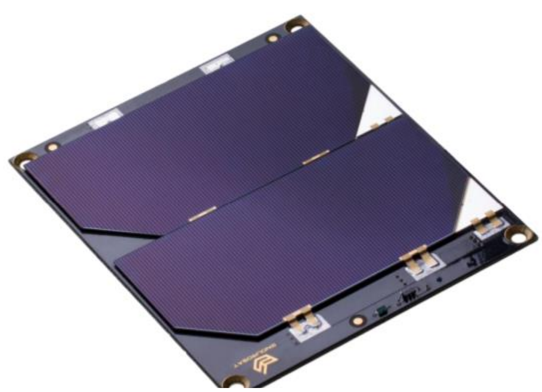

Figure 24 - EPS Solar Panel [8]

On-Board Data Handling

The on-board computer selected by the OBDH team is designed to be integrated into the standard CubeSat size [1]. There is no preference from the OBDH team for the location of the on-board computer. Since the computer is made from a printed circuit board, which has a relatively low mass, it will not need to be located near the COM. The PCB will be mounted with four M3 screws, one in each corner. Spare volume is needed around the computer to ensure that there is enough room for all of the wire connections. As the OBDH team defines these connections, space will be allocated for each wire. A common on-board computer is presented below in Fig. 25, however a computer selection has not yet been finalized.

Figure 25 - Common On-Board Computer [9]

Structural Members and Fasteners

The CubeSat structure must be designed in such a way that all components are supported and fastened so that nothing can come loose or escape the CubeSat interior, as per the NanoRacks IDD [10]. Although the CubeSat will be in a zero-gravity environment, it will experience violent vibrations and acceleration forces, as outlined in Interim Report 1. After many iterations, the best structural design was chosen, along with the appropriate fasteners for each mounting application. For details on the simulations and FEA performed on the design, refer to Section 5 of this report.

Structural Members

The *Opportunity* structure consists of 11 unique components, with 31 components in total. These components are designed specifically to act as either a supporting structure or as a mounting structure. All structural members will be made of aluminum alloy 6061-T6 with a thickness of 3mm, unless stated otherwise.

Supporting structures serve the purpose of absorbing all external forces applied during deployment, including inertial, gravitational and reaction forces from the NRCSD.

Mounting structures serve the purpose of providing a surface for the components needed by other subsystems (OBDH, EPS, ADCS, COMMS) to be fastened to. They also act as a secondary structural support. Due to the varying shapes, sizes and mounting requirements, a variety of brackets and panels have been designed to accommodate all subsystems.

The following list will provide a description of each components design and its purpose. Refer to part drawings in Appendix C-1, and the BOM in Appendix C-2 for complete details:

- Rail (OPP-STRU-001) – Supporting structure – These rails serve as the primary interface between the CubeSat and the NRCSD, and must endure the most external forces. The rails were designed to have high tensile and shear strength, with maximum surface area and minimized mass.
- Structural Panels (OPP-STRU-002, 003A, 003B, 004, 005, 007, 009, 010)– The structural panels serve as a mounting location for the various subsystem components, and act as a secondary structural support. They are all designed from the same base structure, but have various fastening hole locations and excess material removed. The cover panel configuration will be a solid panel, intended to shield the cameras from direct sunlight and help moderate internal temperatures.
- Antenna Slot Bracket (OPP-STRU-011,) – Supporting structure – The slot cover was designed in order to minimize open space between the solar panels at the location where the UHF Antenna extends. As well as adding structural rigidity, they will prevent sunlight from entering the internal volume of the CubeSat and also add more external surface area for radiative heat dissipation.
- Gyroscope Bracket (OPP-STRU-006)– This component was designed in order to save mass when mounting the gyroscope for the ADCS subsystem. The gyroscope is large enough that it needs its own mounting location, but small enough that the structural panels would be very wasteful in terms of mass budget. The bracket mounts to the bottom of the transceiver structure panel, allowing both components to share fasteners and mounting locations. The bracket will be bent to add a small space between the gyroscope and transceiver to prevent excess conduction.
- Z-Magnetorquer Bracket (OPP-STRU-008) – this component was designed from necessity. Due to the requirement for one magnetorquer rod to be parallel to the z-axis, a bracket was needed to fasten one end of the rod to the nearest surface, as the other end needed to be mounted at a location where there was space for the rod to pass through multiple other components structural panels. The mag

bracket is a u-shaped bracket with bends for mounting. It will fasten the end of the z-axis magnetorquer rod to the camera structural panel.

Fasteners

Many common fastening techniques are viable options in the design of a CubeSat, including screws and nuts, epoxy, welding and brazing, threaded rods and rivets. Each of these fasteners has benefits and drawbacks that are considered prior to their implementation in the design. It is also important to reiterate that all external fasteners must have a secondary locking feature as per the CSA and NanoRacks IDD.

Welding/Brazing

Welding or brazing is one of the most permanent fastening method available. Welding is not a good option, among others, due to the material choice for the rails. The anodized surface of the 6061-T6 aluminum will have different material properties than the untreated aluminum below it, which creates major weld-quality issues regardless of the type of weld. The permanence of both welding and brazing is another major issue. This topic was discussed with a structural engineer from Magellan Aerospace, and they strongly advised against the use of welding because it prevents disassembly of the CubeSat, something which will be important during testing. These factors allowed for the decision to not use welding or brazing for any fastening in this design.

Epoxy and Liquid Locking Compounds

Epoxy is another more permanent fastening method, and for this reason was not considered as a primary fastener. However, due to the requirement that all external fasteners have a secondary locking feature, an epoxy in the form of a liquid locking compound (LLC) will be applied to all threaded fasteners when mounting the solar panels. The most common epoxy in this case is Loctite Threadlocker. NASA performed an extensive study on the strength and reliability of Loctite 271 and 242 for use on the ISS, resulting in its approval [11]. NanoRacks and the CSA have also pre-approved Threadlocker Red 271 and Blue 242 for use on CubeSats. Any other epoxy must be approved by NanoRacks prior to use. These epoxies are very strong, however not completely permanent. The seal they create can be broken if enough force is applied, usually requiring leverage from a wrench.

A common alternative to using a LLC is to use nylock-nuts. These are standard nuts (M1, M2, etc.) with a built in nylon sleeve locking mechanism. Although convenient, the nylon is not as strong as a LLC, and they also leave more room for human error. If the installer backs the nut off the screw at all, it can damage the nylon and greatly reduce its effectiveness. Threadlock does not have this issue, as the epoxy is applied as a liquid and only locks the nut once dried. Standard non-locking nuts will be discussed in the following subsection.

Screws, Threaded Rods and Nuts

Screws are one of the most common fastening methods among CubeSat's and can be used to fasten almost all components in this design. Due to their low cost, ease of implementation and relatively small impact on mass, screws and nuts were chosen as the primary fastening feature in this design. These fasteners are all readily available from suppliers such as McMaster-Carr.

All structural components will be fastened using 18-8 stainless steel M3x05 pan-head or flat-head screws, and M3 class 10 nuts. The flat-head screws will be used for fastening components to the rails, in order to keep the rail surface flush for solar panel mounting. Pan-head screws will be used in all other instances. One exception to this is for the mounting of the final two solar panel walls, which will require square nuts as outlined in the Structural Members subsection, above.

All non-structural components will be mounted to their appropriate mounting panel using the manufacturers recommended hardware. This includes the COMMS, EPS, OBDH, ADCS and thermal subsystem components. Holes will be drilled in the mounting panels to match the diameter of the mounting holes on each individual component, once those details become available. M3 unthreaded holes have been used as an arbitrary representation until that time.

The onboard cameras must be mounted to a panel using 18-8 stainless steel M3 threaded rods as per the CAD model from Canadensys. The rod passes through the threaded holes on the bottom of each corner of the camera, and exit out the top. An M3 nut will be placed on either end to fasten the rod in place, as the mounting panels are not threaded. These rods were chosen for the same reasons as the screws and nuts, however due to the size of the camera and lack of a comparably sized rod, larger rods must be ordered and cut down to fit. The rods to be used will be 50mm in length, and will be cut down and grinded so the threads can make clean contact.

Rivets

Rivets are another permanent fastening method, and like epoxy and welding, were not considered in this design. A rivet becomes permanent upon its implementation, as the rivet gun pulls the mandrel, it deforms the shank to create the tail, which is essentially a second head. The only way to remove a rivet is to drill it out or snap it. They were initially investigated as a fastening method for the final two solar panels, since they can be implemented blind, however their permanence prevented them from being used in the design.

Thermal Model

In order to achieve a thermal analysis it is first important to establish the environment in which the CubeSat will be exposed to by determining the upper and lower temperature extremes. There are three types of radiation that are incident on the CubeSat while in orbit. The first and strongest source of radiation is direct solar radiation from the Sun (G_{solar}). This results in an average flux of about 1377 W/m2 however, depending on the distance between the Earth and the Sun due to the Earth's elliptical orbit this can vary by about plus or minus 50 W/m2 which gives a range of approximately 1327 W/m2 to 1427 W/m2 [12]. The second is Albedo radiation (G_{Albedo}) which is solar radiation reflected from the Earth's surface back into space. This value can vary due to cloud cover, whether the surface is water or soil, or snow compared to dessert however it's accepted that an average of 35% is reflected. The last source of radiation is the solar radiation that is absorbed by the Earth and then emitted back into space as infrared radiation. The resultant IR flux (GIR) is 237 W/m2 with a variation of plus or minus 20 W/m2.

For a body to be in thermal equilibrium and therefore achieving steady state heat transfer, it needs to radiate the same amount of energy that it is absorbing. This energy balance can be used for a preliminary and basic analysis of the CubeSat's skin temperature. To simplify the model further it is assumed that the CubeSat is an isothermal sphere with the same surface area as the actual 2U CubeSat. This assumption does introduce some error however this will be accounted for later. The resulting heat balance equation is:

$$G_{solar}\frac{A_s}{4}\alpha + G_{IR}\epsilon A_s(sin^2\rho)\frac{(1-cos\rho)}{2} + G_{Albedo}\alpha A_s(AF)(sin^2\rho)\frac{(1-cos\rho)}{2} + Q_{Gen} = \epsilon\sigma A_s T^4$$

Equation 8 - Heat Balance Equation

Where:

A_s = Surface area of CubeSat (4πr-2)
AF = Albedo factor (0.35)
α = Absorptivity of CubeSat
Q_{Gen} = Internal heat generated
ε = Emissivity of CubeSat
σ = Stefan-Boltzmann constant (5.67e-8 W/m-2K-4)
ρ = Earth angular radius (rad)
T = CubeSat skin temperature (K)

It should be noted that the surface area in the first term is the absorbing area of the sphere and assumed to be a circular disk with the same radius of the sphere and hence ¼ of the spherical surface area. The sin2ρ and (1-cosρ) terms also account for the view factor of a large sphere to a small hemisphere where:

$$\rho = sin^{-1}\left(\frac{R_{Earth}}{R_{Earth}+Altitude}\right)$$

Equation 9 - View Factor

With an altitude of 408,000 m (the same as the ISS) and the Earth's radius to be 6,371,000 m, ρ is found to be 1.22 radians. The values for each different source of radiation and internal heat generation are as follows in Table 1 and Table 2:

Extreme Hot	G_{Solar} (W/m²)	G_{IR} (W/m²)	G_{Albedo} (W/m²)	Q_{Gen} (W)
Upper Limits	1427	257	499.5	3
Lower Limits	1327	217	464.5	3

Table 1 - Radiation and Heat Generation Values for WCH

Extreme Cold	G_{Solar} (W/m²)	G_{IR} (W/m²)	G_{Albedo} (W/m²)	Q_{Gen} (W)
Upper Limits	0	257	0	1
Lower Limits	0	217	0	1

Table 2 - Radiation and Heat Generation Values for WCC

The extreme cold case occurs when the CubeSat is in the eclipse portion of its orbit which accounts for 31% of its full orbit period. During this time it only experiences emitted IR radiation from the Earth. With the fluctuations present in these radiation sources it was appropriate to consider a case for the upper limits and one for the lower limits. The internal heat being generated by the components within the CubeSat were roughly estimated based on the power budget provided. During the eclipse period most of the components would be turned off or on standby while when not in eclipse the average heat generated was about 3W.

It is also necessary to find the overall emissivity and absorptivity of the CubeSat by taking into consideration the different optical values for the exposed surfaces and weight it according to the percent that it covers the outside skin on the CubeSat. The Aluminum rails were anodized, turning them black, and the area on the solar panels not covered by solar cells were painted with black paint to alter their optical properties. Table 3 on the following page summarizes this data.

	Emissivity ε	Absorptivity α	Surface Area Percentage (%)
Black-Dyed Anodised Aluminum [13]	0.75	0.54	15.9
Solar Cell [14] [15]	0.85	0.903	47.9
RM-550-IB (Black Paint) [16]	0.97	0.91	36.2
Weighted Total	**0.852**	**0.869**	**100**

Table 3 - Surface Optical Values

The total surface area of the 2U CubeSat (10cm x 10cm x 20cm) is found by the equation:

$$A_s = 4(0.1 * 0.2) + 2(0.1 * 0.1) = 0.1\ m^2$$

Equation 10 - Total CubeSat Surface Area

Using the appropriate values for worst-case cold and worst-case hot and rearranging Equation 1 to isolate for the skin temperature it was found that our upper and lower limit for worst-case hot was 69°C and 62°C respectively. Accounting for margin of error of 5°C as mentioned before due to the assumption of an isothermal sphere the upper and lower limits are then 74°C and 67°C. Likewise, our worst-case cold upper and lower limits were found to be -51°C and -59°C respectively but with the margin of error applied became -56°C and -64°C. The resulting differential is 138°C which is similar to a typical differential of 135°C for satellites.

It was originally assumed that the solar panels would be painted with a white paint to reduce the absorptance of the CubeSat to counter the worst-case hot conditions however after completing the initial calculations it was found that the white paint (ε=0.12) was in fact making the CubeSat too cold in when in eclipse, dropping the skin temperature to -112°C. It was then determined necessary to find a black paint with a higher emissivity (ε=0.97) in order to increase the overall emissivity of the CubeSat. This iteration was found to be effective in raising the CubeSat emissivity from 0.56 to 0.85 and therefore raising the worst-case temperature to its more acceptable present range.

Finite Element Analysis

In order to determine the effectiveness of the CubeSat design, many simulations must be run to determine weak points and poor design aspects. The simulations that will be run are iterative frequency analyses as well as static analysis of gravitational forces and a thermal analysis. The model used in the simulations is a simplified version. The thermal strap is treated as one continuous shape and fasteners are removed. The drawings in Appendix B-3 and C-1 may not reflect the model used in the simulation exactly.

Center of Mass (COM)

An important piece of information regarding these simulations is the center of mass of the model. NanoRacks and the CSA have a requirement that the COM be within ± 2cm of the XY geometric center, and ±4cm of the ZX and ZY geometric centers [10]. By including arbitrary solids of constant density and mass distribution, and a mass based on typical off-the-shelf components, a COM of the complete CubeSat Model can be determined using SolidWorks. This COM takes into account every component except fasteners. Refer to Figure 26, Figure 27 and Figure 28 for a visual representation of the COM.

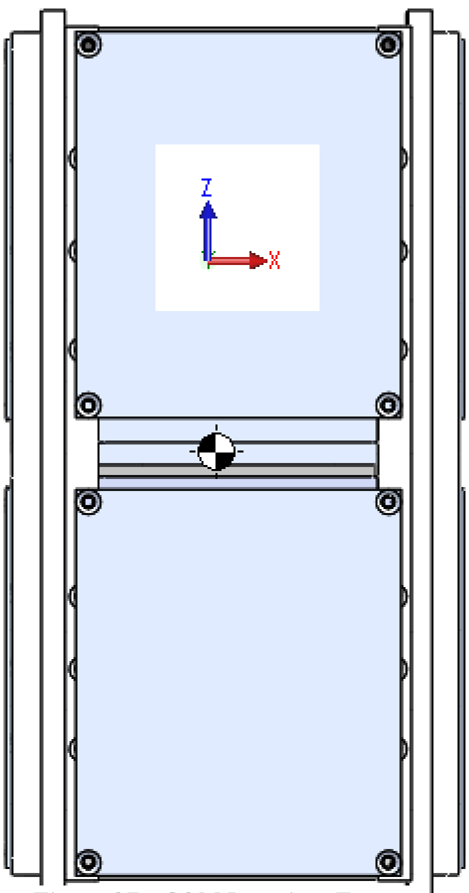

Figure 27 - COM Location, Front

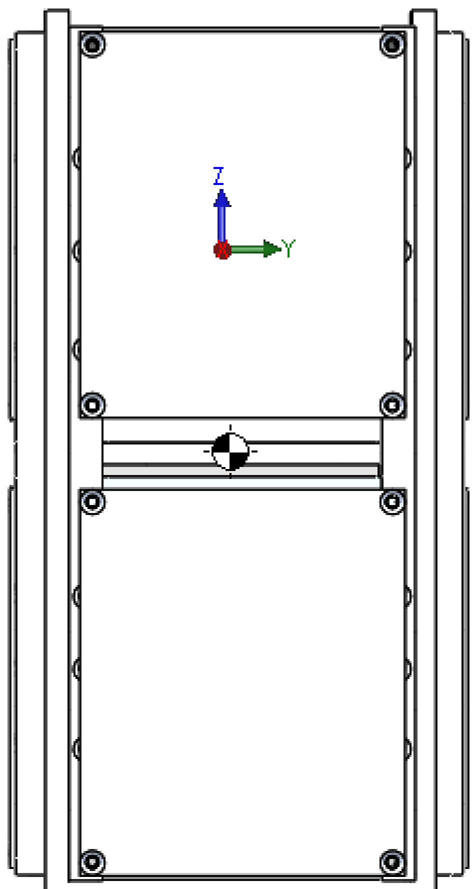

Figure 26 - COM Location, Right

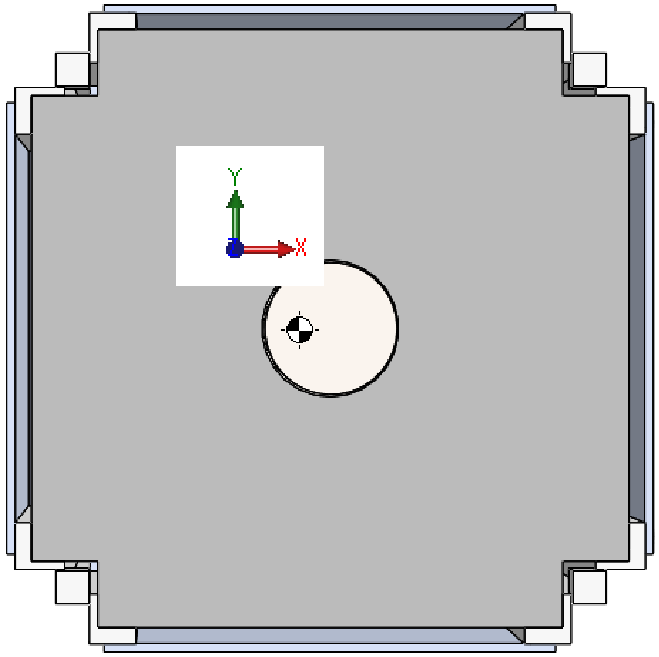

Figure 28 - COM Location, Bottom

With the bottom left corner of the CubeSat (facing the front) as the origin, the COM is located in the following position:

X: 56.34mm
Y: 59.49mm
Z: 114.23mm

Therefore, the COM is well within the required range based upon the IDD specifications.

Quasi-Static Analysis

The CSA and NanoRacks require that CubeSats be capable of withstanding specific gravitational loads without suffering structural failure. These gravitational loads, referred to as quasi-static loads, are acceleration forces on all 3 axes [10].

The purpose of this simulation is to determine how the CubeSat will respond to heavy acceleration loads during launch, and if these loads can elastically or plastically deform it.

For this simulation, a static analysis was run with the rails fixed, since the CubeSat will be essentially locked in place within the NRCSD. As per the NanoRacks IDD, the CubeSat must withstand 4g along the X and Y axes, and 7g along the Z axis [10]. SolidWorks allows the application of gravitational accelerations along all axes. They were applied, and the standard gravitational acceleration was overridden with 39.24 m/s^2 in X and Y, and 68.67 m/s^2 in Z. Soft springs and automatic solver selection options were used. All components were assigned aluminum alloy 6061-T6, except for the camera (plain carbon steel), the thermal strap (standard copper), and the heat accumulator (standard aluminum alloy).

The test results, as presented in Figure 29, 30, and 31 below, indicate stress and strain concentrations as well as deformations around the camera structural panel. A similar result will be seen in the harmonic analysis following, however in this case both cameras displaced in the negative Z direction ("down"). This is because gravitational forces are opposing the CubeSat's acceleration towards space. SolidWorks indicates a deformation scale of over 3000:1, so the visuals are simply a representation of the direction of motion. The actual displacement values are a fraction of a millimeter, however the stress is very high. As with many SolidWorks simulations, the resulting values should not be focused on, however the locations of stress and direction of displacement are accurate.

NanoRacks and the CSA indicate in the IDD that the CubeSat must withstand forces of up to 1200N across the rail ends. In the stress result plot of Fig. 29, it can be seen that the distributed load on the CubeSat reaches 5200kN, and as such, it can be concluded that this deformation will not be experienced in a launch environment. The result is simply the simulation exceeding the realistic load levels and continuing into unrealistic levels.

No design changes were implemented based on this simulation.

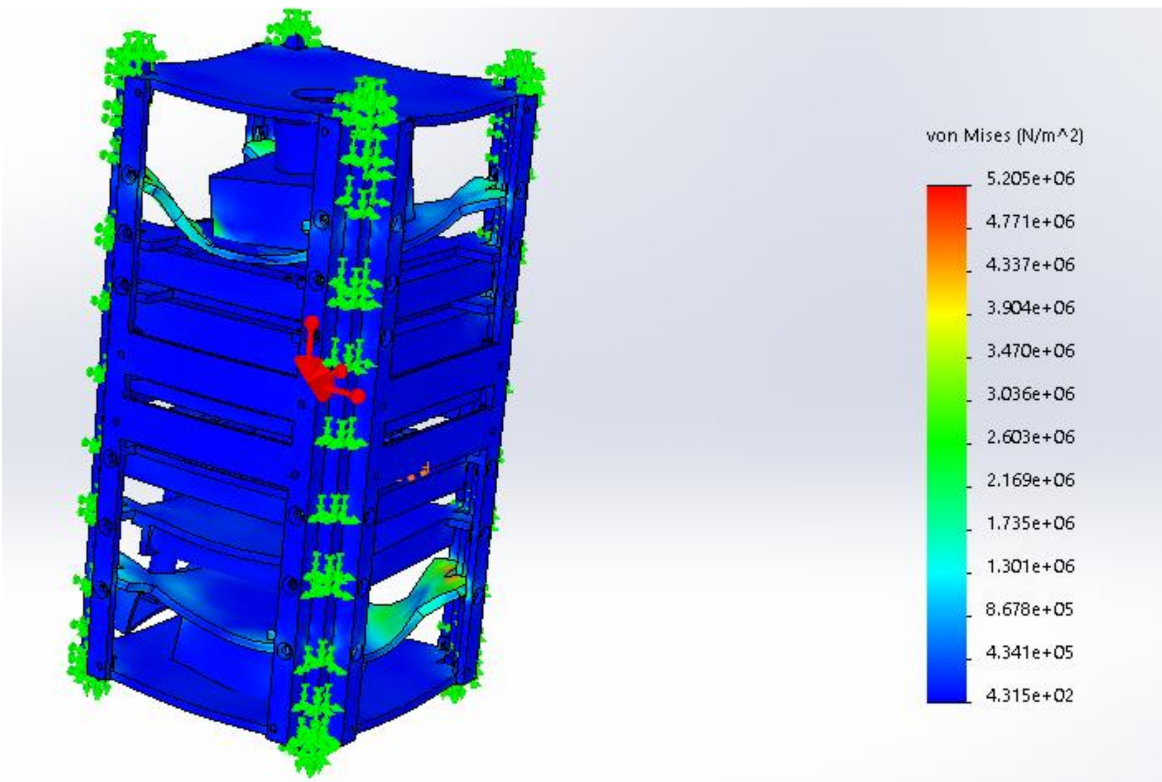

Figure 29 - Quasi-Static VM Stress Result

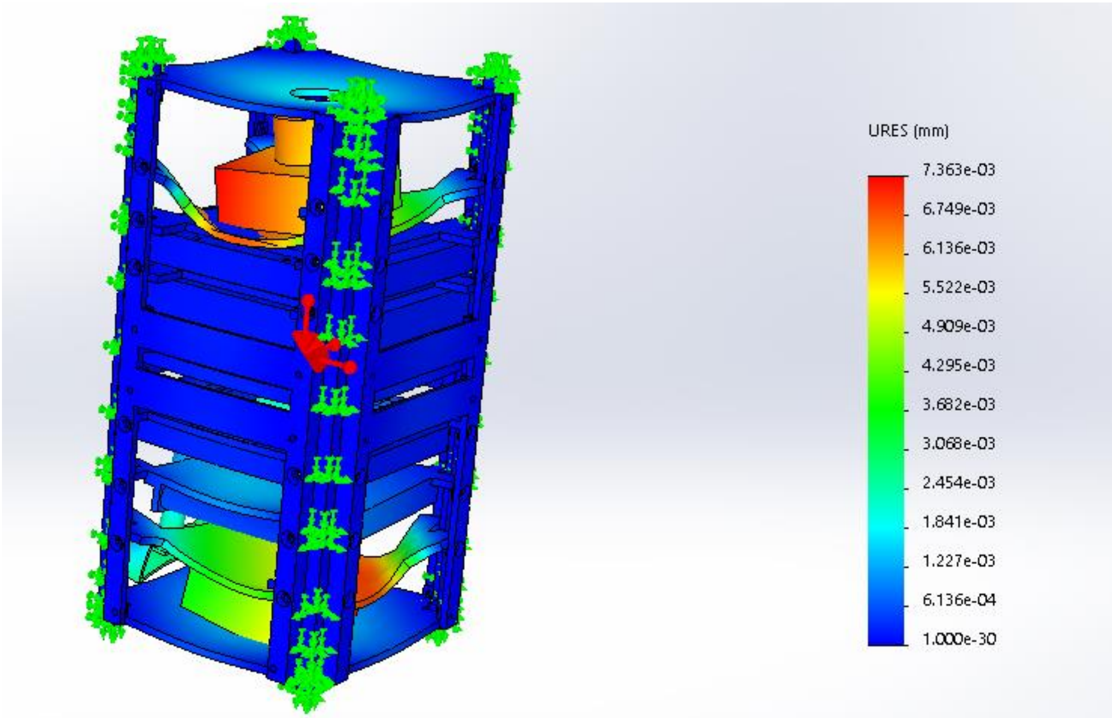

Figure 30 - Quasi-Static Displacement Result

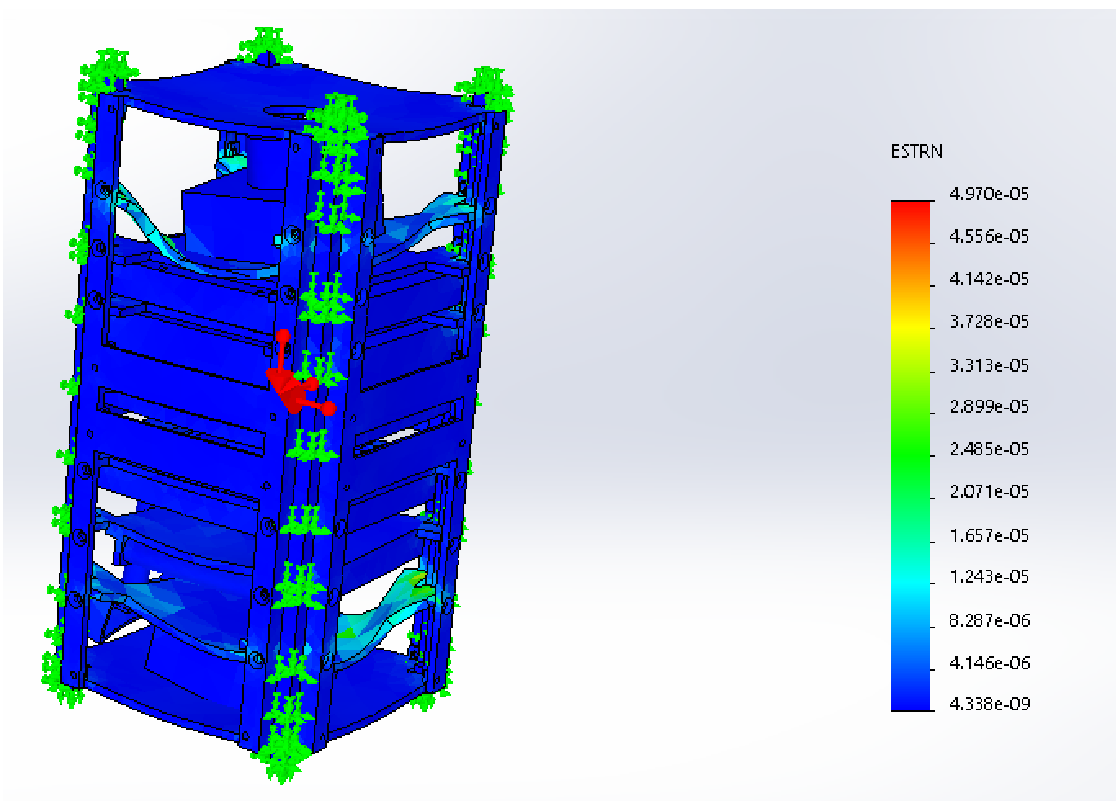

Figure 31 - Quasi-Static Strain Result

Harmonic Analysis

Harmonic analysis is a simulation in which the load on the structure is a function of frequency. It is a form of linear dynamic analysis, and due to the slow rate of change of frequency, is often referred to as steady state. In the case of a CubeSat, the best harmonic analysis is a frequency response with base excitation. This means that the model will experience a harmonic excitation of fixed support structures, in this case the rails of the CubeSat. This type of simulation can be compared to a shaker table vibration test. The linear dynamic model was created using the SolidWorks Simulation add-in [17].

The result of the simulation will provide Von Mises stress and displacement values at different frequencies, which can help determine if there are natural frequencies that exist within the vibrational frequency range that will be experienced during launch. If natural frequencies exist in the same range as the vibration to be experienced, the forces can be amplified and become destructive. This information allows designers to determine if the CubeSat will suffer deformation during the vibration, and presents the locations of deformation. Designers can then reinforce or redesign as necessary. The actual displacement values given by SolidWorks are typically unreliable, however the locations of deformation and ratios of deformation can be accurate.

Since the masses and mounting locations of all components, including subsystem components, can impact the results of this type of simulation, all components had to be represented in the model. Solid blocks were created for each subsystem components to represent the maximum dimensions of preliminary component choices. The components were all assigned the same aluminum alloy as the structural components, with the exception of the thermal straps (standard copper), the heat accumulator (standard aluminum alloy), and the cameras (plain carbon steel). The mass of the components was overridden and forced to equal the preliminary mass estimates provided by other subsystem teams.

The simulation will be run with the following conditions:

- 10 frequencies total
- Upper frequency limit of 5000 Hz
- Automatic solver selection, no soft springs
- Fixtures applied along rails and rail ends, 2mm displacement in X and Y directions only
- 5% global damping (as percent of critical damping)
- Solar panel walls are "hidden" for viewing purposes, but are still included in the simulation

The CSA and NR have maximum vibration ranges provided. The range of frequencies that the CubeSat will experience is 0-2000 Hz. The upper frequency limit was set to 5000 Hz in order to be conservative, however natural frequencies substantially higher than 2000 Hz are not important.

Run 1 (See Figure 32 and 33 below): The first run resulted in displacements of both cameras and their structural mounting panels. This indicates a possible structural issue at these locations. In an attempt to resolve the issues, the camera material was set to aluminum alloy 6061-T6 (mass remained the same), and all structural panels had their thickness doubled from 1.5mm to 3mm. Similar to the Quasi-Static loading results, the resulting stress can be seen to be far beyond any expected stresses that will be experienced by the CubeSat.

Run 2: The changes to the model made no difference in the outcome. Due to other components with the same mounting conditions and similar masses experiencing no displacement, it was concluded that the displacement here must be negligible. The displacement presented was concluded to be the only displacement that occurred within the frequency range. The structural panels will remain with the 3mm thickness since this is more conservative in terms of structural integrity.

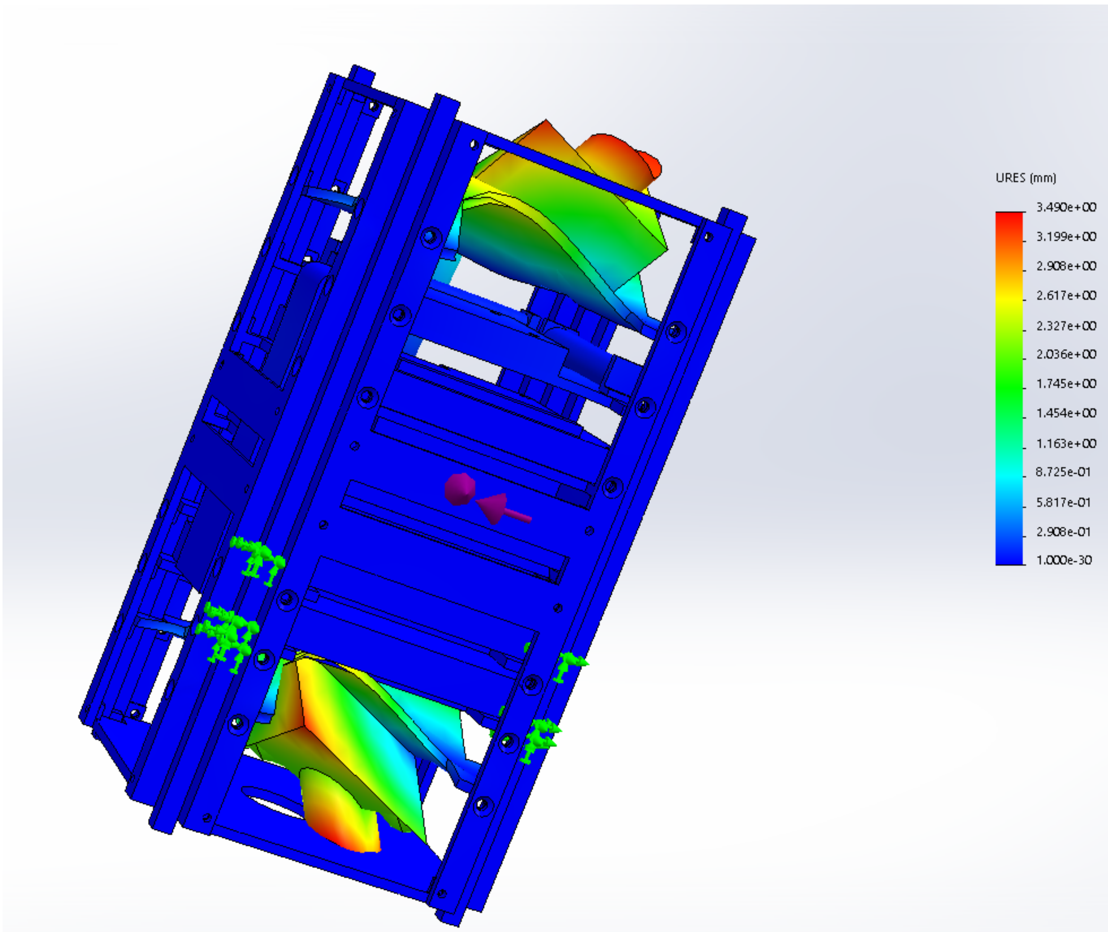

Figure 32 - Harmonic Simulation Displacement Result

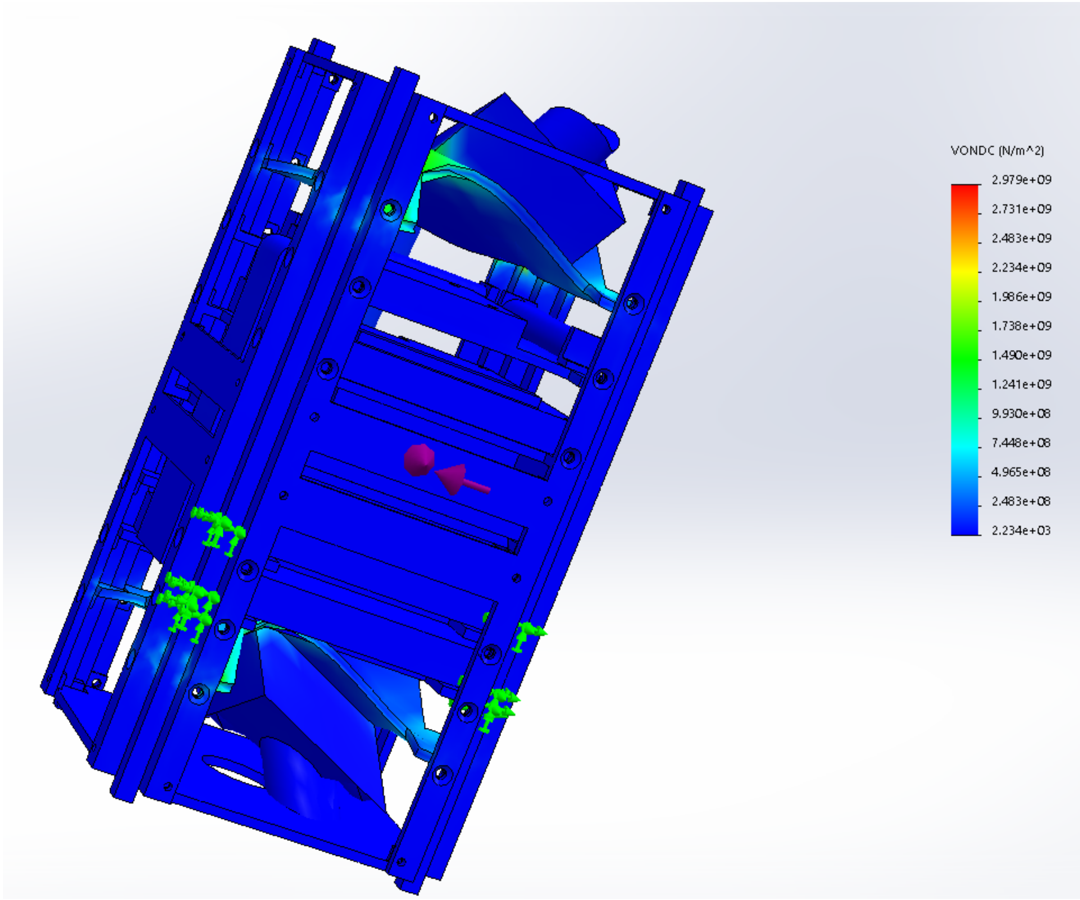

Figure 33 - Harmonic Simulation VM Stress Result

Thermal Analysis

SolidWorks thermal simulation was used to do a thermal analysis of the heat transfer throughout the CubeSat due to the resulting radiation incident on the solar panels. Many assumptions and simplifications were made due to the errors associated with using SolidWorks simulation for thermal analysis in a vacuum environment. At the time of this report the team was awaiting a response for approval to a license for Thermal Desktop. This program would be able to achieve a more accurate transient analysis as well as determine if the internal components were sufficiently being thermally regulated without an electric heater as mentioned before. It is used specifically for spacecraft applications however, the team did not have access and therefore SolidWorks was used.

The simulation was set up by first finding the resulting heat flux due to the three types of radiation incident on the CubeSat, the angle of incidence, and the absorptivity of the CubeSat. The following equation was used:

$$(Q_{Solar} + Q_{IR} + Q_{Albedo}) * \cos(45^{o}) * \alpha = Heat\ Flux$$

Equation 11 - Heat Flux

This resultant heat flux was applied to three surfaces for the worst-case hot condition and only one face for the worst-case cold condition. For worst-case hot conditions, the resultant heat flux was 1331 W/m^2 and for worst-case cold it was found to be 132 W/m^2. The figures below illustrate the temperature gradient present in the CubeSat's outer surface when these conditions are applied.

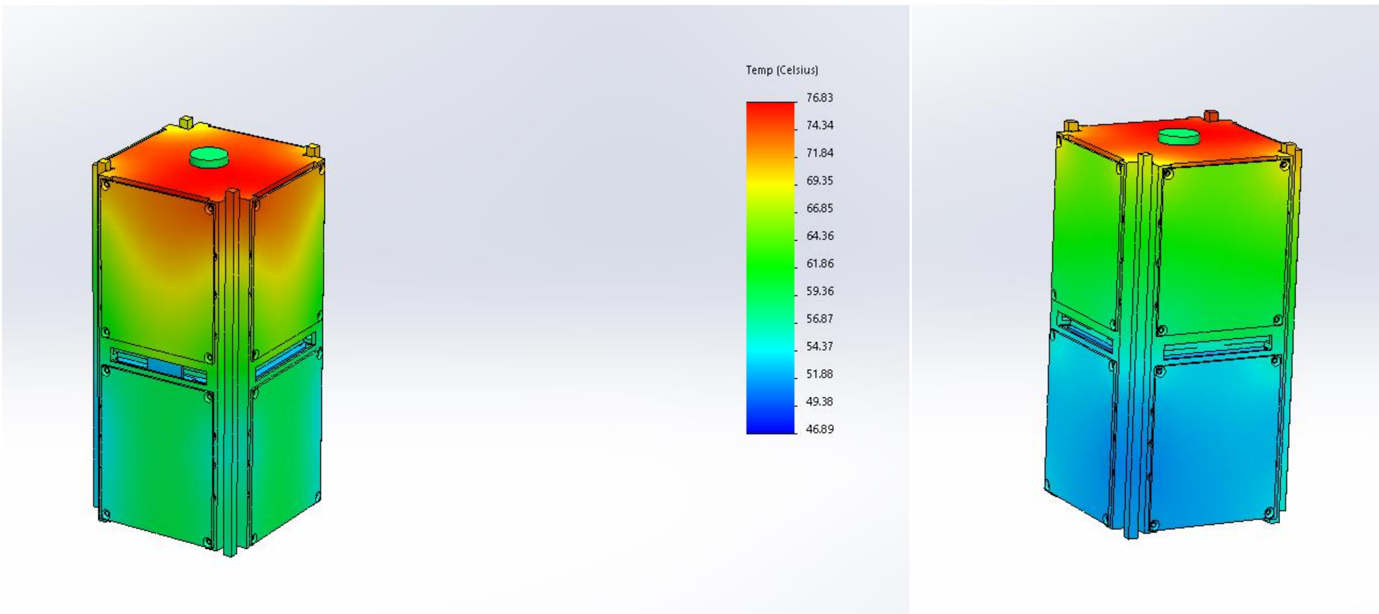

Figure 34 - Thermal Simulation Result WCH

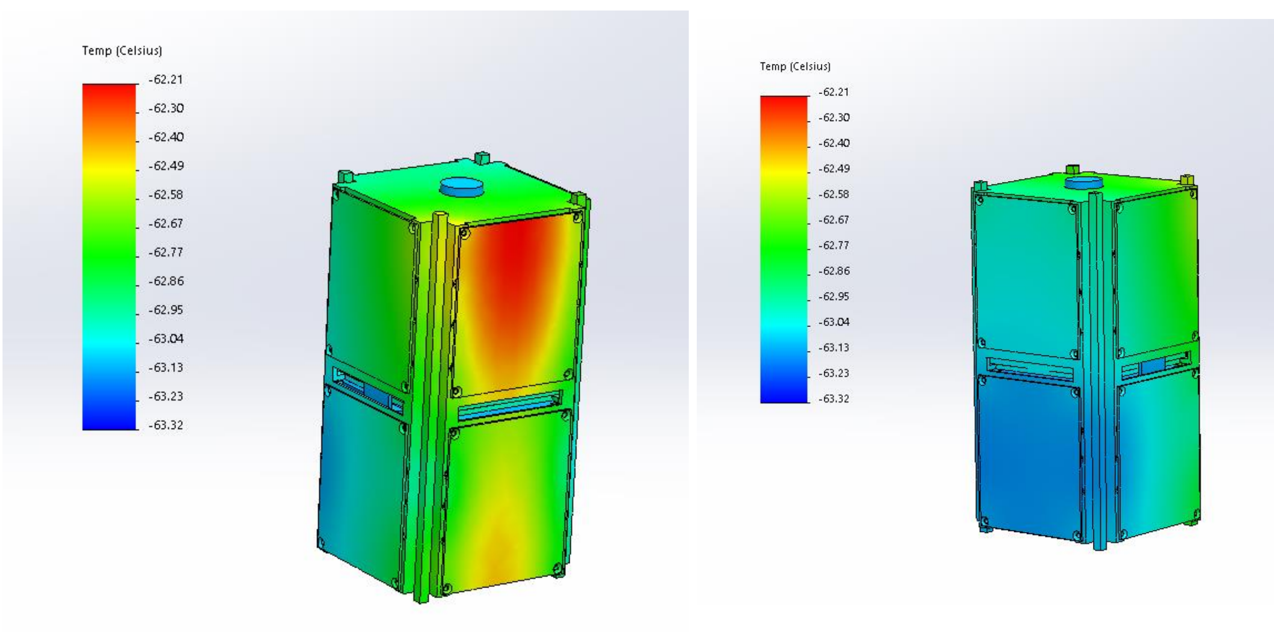

Figure 35 - Thermal SImulation Result WCC

Manufacturing

CAD Model

The following are 3 views of the final design CAD model of the CubeSat Opportunity (solar panels hidden for viewing purposes). It consists of 306 individual components including fasteners. As mentioned in the Finite Element Analysis section, the thermal straps are not a single strap, but instead consist of 2 separate straps to allow room for the antenna to roll out in between. The only feature missing from this model are the sun sensors, wiring and wiring harnesses. The total mass at this stage in the design is 2.04 kg. The mass budget was 2.88 kg, and therefore there is plenty of space in the budget for the remaining features.

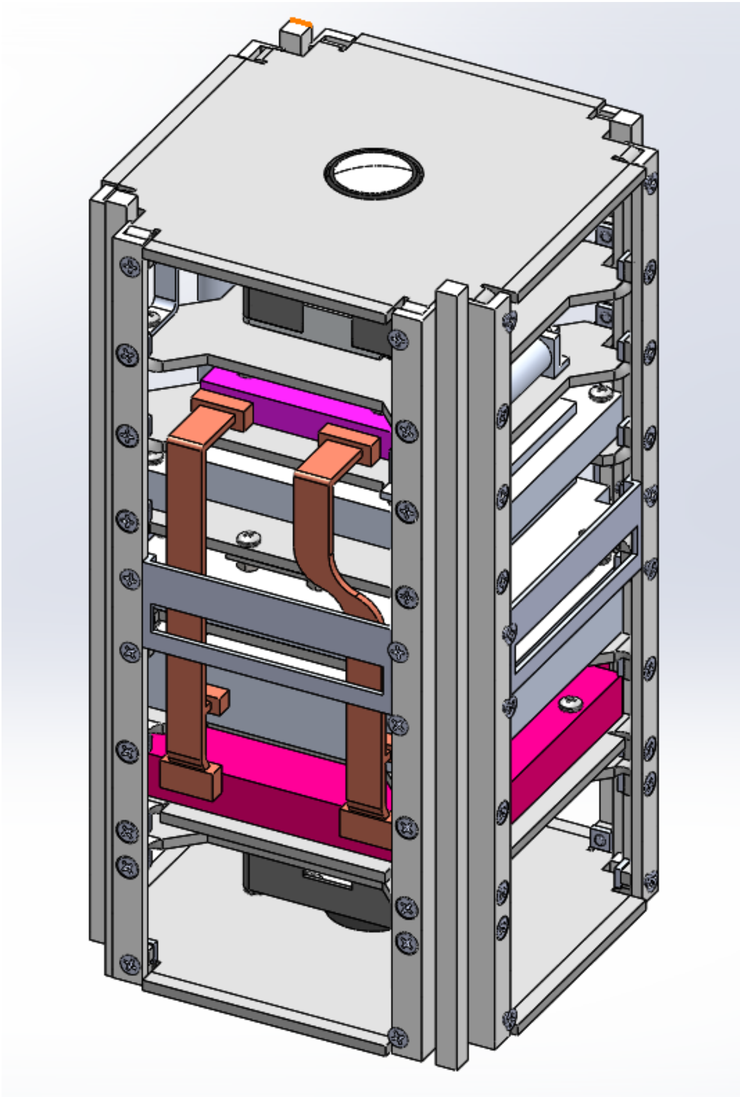

Figure 36 - CAD Model of Opportunity – ISO View

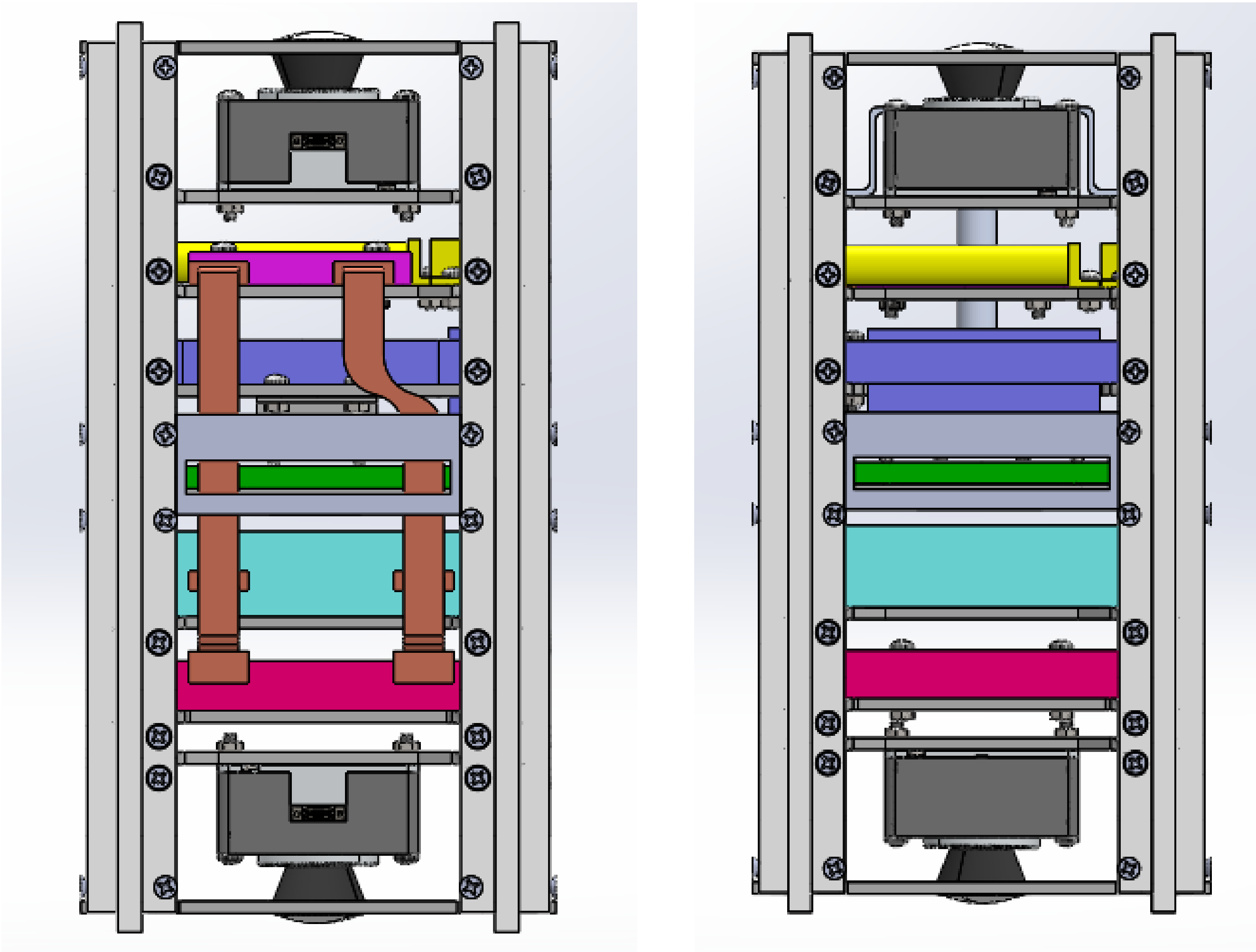

Figure 37 - CAD Model of Opportunity - Front and Right Side Views

Complete drawings with dimensions, tolerances and manufacturing information can be found in Appendix D-6

Bill of Materials (BOM)

Refer to Appendix C-2 for the complete BOM and Assembly Drawings

Assembly Instructions

Due to our design having the cameras placed on the ends of the CubeSat, the antenna which is typically placed on the end face had to be repositioned. It was decided that the antenna was to be placed in the center of the CubeSat to allow it to be able to deploy monopole antennas without being obstructed by the solar panels. Therefore to assemble the CubeSat it is necessary to start by first placing and mounting the antenna to the structure and then assemble each piece in order outwards towards the ends. Certain components are mounted to structural boards made of the same aluminum as the frame. This acts as a natural heat sink by conduction to the outer structure when attached by the custom U-brackets.

The antenna is enclosed by two of these structural boards on either side. The UHF transceiver is mounted next onto the structural board above the antenna along with the ADCS magnetorquer. Mounted to the outer frame above the transceiver is another board in which the ADCS PCB is mounted. There are two magnetorquers attached directly to the PCB and the third is mounted directly to the structural board and placed vertically to be effective in the z-axis. Lastly for the top end is another structural board to mount the camera to. A special end panel with a sized hole cut out to enable the camera lens to poke through is then placed over the camera and mounted to the outer frame. On the other end the battery is mounted to the structural panel below the antenna followed by the OBDH PCB being mounted to the next structural panel. Afterwards said structural panel is mounted using the custom U-bracket to the outer frame to enable the second camera to be mounted. Then an identical end panel to the one on the other end encloses the second camera and is mounted to the outer frame.

The last steps are to first attach the thermal straps from the OBDH board and battery to the heat sinks near the bottom of the CubeSat followed by screwing in the first 7 solar panels. The last solar panel requires the square nuts to be glued onto the inside of the panel first and then screwed on last. This is because no tool would be able to be get inside the CubeSat at this point to hold the nuts in place while the screws are being fastened in

Design Tools

Design for Manufacturing (DFM)

The CubeSat structure is composed of four rails braced together with mounting plates layered along the Z-axis, commonly referred to as a post and panel assembly. From a manufacturing perspective, the post and panel structure can be constructed from parts easily machined and formed. The three chosen manufacturing methods for the structural components of the CubeSat are CNC milling, water jet cutting, and sheet metal bending. Refer to Appendix C-3 for each parts corresponding manufacturing method.

The rails will be CNC milled to ensure each rail is dimensionally identical and to remove the possibility of human error. The complexity of the rails is relatively low and is within the capabilities of a CNC mill. The various mounting plates and brackets will be cut to shape using a water jet cutter. This allows each part to be customizable and have a unique shape optimal for mounting the subsystem components. All sheet metal edges will be deburred before installation to ensure that the structure is safe to assemble. The aluminum sheets were chosen due to their high formability and high yield strength properties. The 90° tabs will be easily bent with a sheet metal bender and will also be strong enough to hold the four rails together. Once every manufactured part is ready, and all ordered components have arrived, the assembly of the structure can take place.

Design for Assembly (DFA)

Design for assembly is a method of analyzing a design against criteria to determine if there are features that can be improved to speed up production or make it safer. The common approach is to list the criteria, which relate to ease of insertion, limited reorientation, part symmetry and part counts, and rank them using a weighting from “poor” to “excellent”. This approach is most effective for products designed for mass production. In the case of a CubeSat, the results become much less valuable because the design is very complex and very small scale. It will be assembled very few times and require many precise motions and tools. To analyze the design for assembly of the CubeSat Opportunity, a qualitative approach must be taken, primarily based on complexity of the design. The main purpose will be to determine any possible major issues in the design that could prevent the design from being successfully assembled.

The design of Opportunity will be evaluated based on the advantages and disadvantages of various assembly operations and features.

Advantages:

- All fasteners are metric Philips head or hex nuts, which limits tools to various sizes of Philips screwdrivers and a small adjustable wrench
- Four overall steps make assembly simple and systematic. Subsystem components are mounted to structural panels, structural panels are mounted to two of four rails. Remaining two rails are attached. Solar panels are mounted.
- Final two solar panels were designed with limited access in mind. They can be fastened blind into a square nut that is fixed in place.
- Limited number of unique structural components

Disadvantages:

- Large number of fasteners required (#### in total)
- Loctite liquid locking compound must be applied individually to each fastener
- Loctite makes fasteners very difficult to remove. If a mistake is made it will be difficult to remove parts

Overall, the design of Opportunity is relatively simple, and assembly is not complicated. The main issue with the design is that it will be very tedious to assemble due to the number of fasteners required. This number could only be reduced marginally, however doing so would have negative impacts on the thermal model as it would require components to be mounted closer together.

Design for Environment (DFE)

The CSA and NanoRacks set requirements for environmental impact in the IDD and CCP documents, refer to IDD section 4.4.6 Space Debris Compliance, and CCP section 3.8.1 Space Debris Mitigation Requirements [10] [18]. The main requirement is that the CubeSat shall not create any space debris during launch or normal operation, and should not be intentionally destroyed in orbit.

Although there is no requirement regarding re-entry into Earth's atmosphere, NASA orbital debris mitigation requirements set a limit for projectiles created from spacecraft. All debris re-entering Earth’s atmosphere that do not burn up must hit the ground with less than 15J of kinetic energy. A study was completed by NASA that determined various limits on materials to ensure they burn up or reduce in mass enough that they meet these requirements. An Aluminum CubeSat structure under 11kg will successfully burn up upon re-entry, and therefor CubeSat Opportunity meets the requirement [19].

Conclusion

The design of the CubeSat has been evaluated and defined throughout the preceding detailed design process. Modifications to the structure have been made based off the results in the FEA analysis and the overall design has been improved. The thermal techniques have been clarified and redundant thermal control has been removed from the design. The thermal analysis shows what the temperature at the outside of the CubeSat is in a certain orientation and provides insight to what the CubeSat will be experiencing in space. The manufacturing methods of the CubeSat were researched and the best approach was chosen. The CubeSat has also been designed with the environment taken into consideration. The assembly of the CubeSat has been outlined and will serve as a guide in the next stage of the design process.

The Opportunity CubeSat design has been put through extensive detailed analysis and the design has been iterated to ensure various parameters are optimized. The detailed design has been thoroughly completed and the prototype formulation can now begin.

Current Stage 3 References

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Stage 4 - Prototype Design

Introduction

At this stage of the CubeSat Project, strategic iterations have to be made in order for the Prototype design to be successfully fabricated. This involves changing some of the components with the goal of producing a prototype that is functionally equivalent the Final Design. This prototype must then undergo thermal and structural integrity testing to determine if it works and if any additional changes are required. Any results produced during testing will be taken into consideration and carried forward for the next phase of the Western CubeSat Project as a whole.

This report will cover prototype specifications and differences between the prototype and final design. Throughout the course of prototype design many iterations had to be made to satisfy budget targets, resource limitations, and deadlines. Prototype assembly instructions and changes to the initial assembly plan will also be covered, as well as a full breakdown of all CubeSat prototype expenses. Testing status will also be specified, with results that have been acquired and future plans for any pending tests.

Design

Design Documentation

Due to changes in the design for manufacturing purposes, prototype design documentation has been created. Changes that were made during iteration are discussed in the “Design Iteration” section following, and noteworthy CAD models/drawings are found in the Appendices. A complete assembly with drawings will be included as a zipped file with this report.

Design Iterations

The CubeSat structure must be designed in such a way that all components are supported and fastened so that nothing can come loose or escape the CubeSat interior, as specified by NanoRacks [1]. Although the CubeSat will be in a zero-gravity environment, it will experience violent vibrations and acceleration forces. After many iterations, the best structural design was chosen, along with the appropriate fasteners for each mounting application.

The Opportunity structure consists of 12 unique components, with 39 components in total. These components are designed specifically to act as either a supporting structure or as a mounting structure. All structural members will be made of aluminum alloy 6061-T6 with a thickness of 3mm, unless stated otherwise.

The four corner rails serve as the only interface between the CubeSat structure and the NRCSD. The design in Interim Report 3 specified the rails to be a single piece machined out of a stock bar to reduce the fasteners needed. However due to the budget of the project and from the input of UMS to simplify the manufacturing and assembly process it was decided that the rails would be split into three separate components (2 L-Brackets and 1 square stock piece of aluminum) to ensure that the shape of the rails remained unchanged, as shown in 38. These components were fastened together using screws at the interfaces facing inside the CubeSat to ensure the faces that contact the NRCSD are kept flush without any screw heads to possibly cause issues during deployment.

Figure 38 – Assembled CubeSat 3-Piece Rails

Each component was fastened to a mounting plate to secure it to the structure as well as assisting with heat distribution, the plates are shown below in Figure 39. The plates also provide additional structural rigidity to the rails along the length of the CubeSat. These mounting plates were all manufactured with the same base design however each plate required different screw hole locations due to the variability of each component's size and design for fastening them down. In addition, the plates each had 8 tabs (2 per corner) that were bent to 90 degrees, as seen in Figure 40, below. These tabs were designed to fasten the mounting plates to the rails. The end panels are solid plates with a hole cut out in the middle to allow the camera lens to fit through. These end panels ensure the rails stay square with one another while also shielding the camera from direct sunlight. The panels also help with temperature regulation by limiting exposed internal surfaces and provide an excellent surface for heat dissipation into deep space once painted.

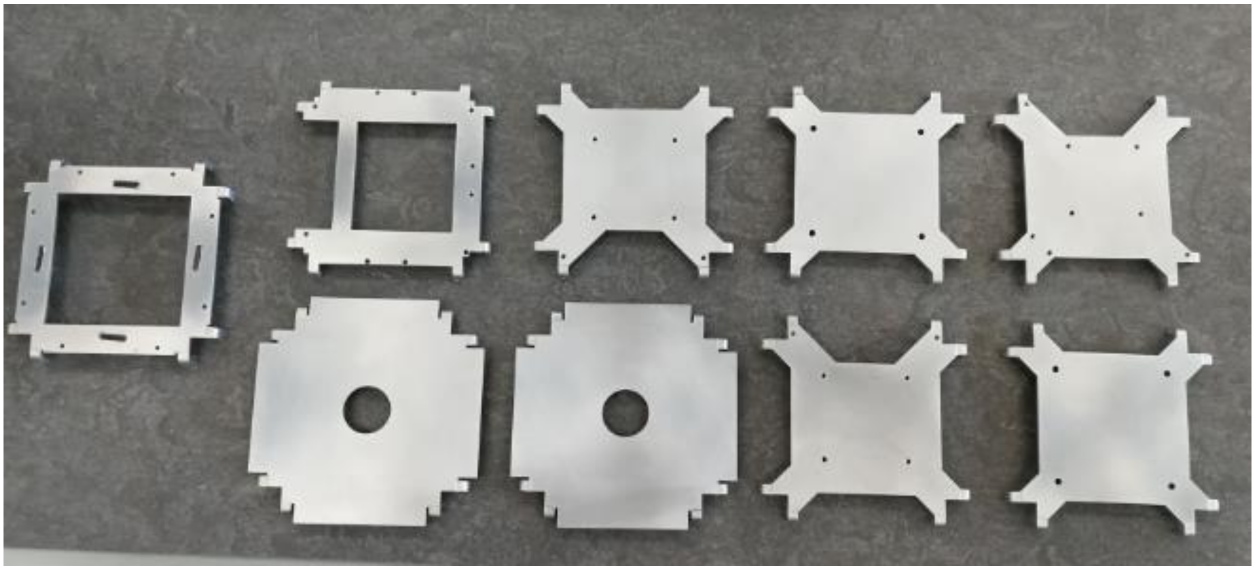

Figure 39 - Laser Cut Mounting Plates

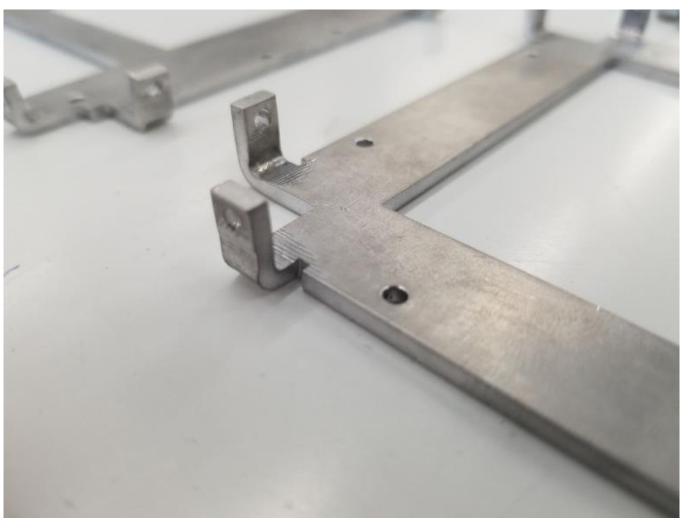

Figure 40 - Mounting Plate Tabs

The gyroscope however required a different mounting plate. Due to its very small size it was decided that a full mounting plate like one used for the other components would be a waste in terms of the mass budget. Therefore, the gyroscope would be mounted to a relatively narrow metal bracket that would be bent to shape and provide a gap of space with the transceiver to eliminate unwanted thermal conduction due to bridging. This specialized bracket was then fastened to the bottom side of the mounting plate used to fasten the transceiver. When assembling the prototype, it was noticed that not using flat head screws presented an unwanted contact point between the screw heads and the top of the antenna. The mounting bracket used to fasten the gyroscope was too thin to counter sink and therefore the location of the gyroscope was flipped to the other side and place between its bracket and the transceiver mounting plate, as presented in Figure 41 - Partially Assembled CubeSat, below.

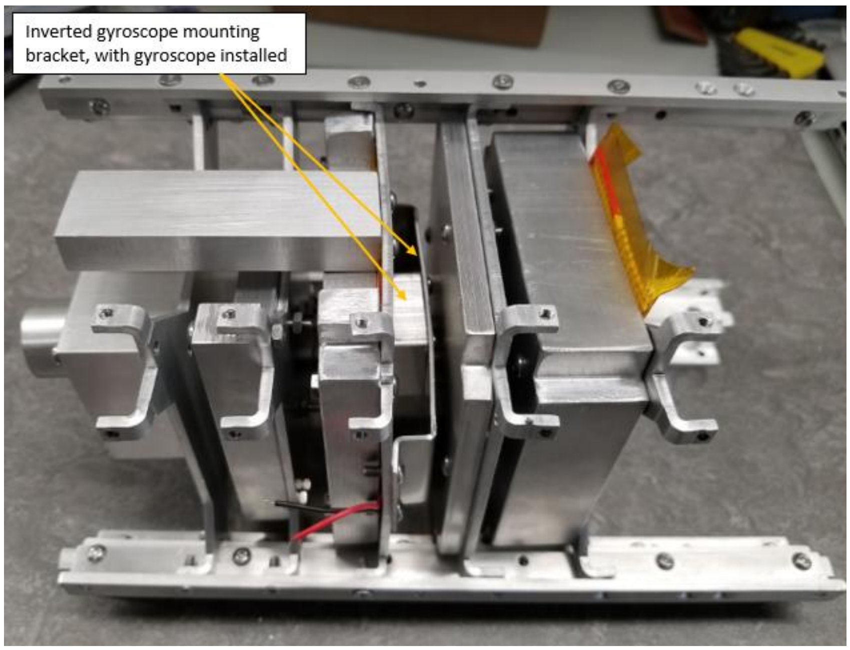

Figure 41 - Partially Assembled CubeSat

The slot cover was designed in order to minimize open space between the solar panels at the location where the UHF Antenna extends. As well as adding structural rigidity, they will prevent sunlight from entering the internal volume of the CubeSat and also add more external surface area for radiative heat dissipation. For the prototype, these are simply for visual purposes and will be included as Plexiglas inserts.

Heat straps are essential for the CubeSat as they provide controlled temperature distribution from hot spots or heat generating components to a heat sink via conduction. In the design outlined in Interim Report 3 the heat strap was designed as a 3-way heat strap meaning the battery, OBDH, and heat sink were all connected through one strap. It was found that connecting both the battery and OBDH to the heatsink resulted in the battery mainly distributing its heat to the OBDH thus making it hotter than normal and only some of the heat was distributed to the heat sink. This is because of the location of the battery with respect to the heatsink and OBDH as well as the length of the thermal strap between the battery and heatsink being longer than the strap from the battery to OBDH. The design was changed to use two separate straps to connect the two components to the heatsink. The heat straps can be seen in Figure 58 in the Testing section.

Parts Manufacturing

Cutting the Rails

The angle pieces used for the rails were cut from two 40” pieces of stock aluminum angle. The angle was clamped to the vice on the horizontal band saw such that the blade would not force the angle to rotate when cutting. Using a built-in length stop on the horizontal band saw, the distance was set to 217mm from the blade to the stop. This method reduced human error and is more accurate than measuring the stock piece and lining up the blade with a sketched-on line. The same process was done to the square rod except the stop was set at a distance of 227mm from the blade. The end faces on both the angles and the square rods were sanded using the belt sander to remove any burrs. In total, there were 8 angle pieces and 4 square rods that were cut using the horizontal band saw, as shown in Figure 42.

Figure 42 - Cut-to-Length Rail Pieces

Milling Rails to Size

The angle pieces were elevated using parallels and clamped to the vice on the mill, as presented in Figure 43. Similar to the method used on the horizontal bandsaw, a length stop was clamped to the t-slots on the mill table and was used as the part zero in the y- axis. The face on the further side of the vice acted as the part zero in the x-axis. This set-up was repeatable for all the rails and was more precise than using a bandsaw to make the cuts. A ¼” flat end mill was installed on the machine and the spindle speed was set to 1000 rpm. The stock angle pieces were 0.75” X 0.75” and needed to be milled down to 10mm X 13.6mm. This was done by removing a slight bit of material off the face to be machined and then removing the piece from the vice and measuring the height of the cut. This measurement subtracted from the desired length equaled the distance that the mill needed to be lowered to. The milling was performed in two passes to ensure a highly accurate surface finish. The edges were sanded and deburred using the belt sander and the rails were now ready to be drilled.

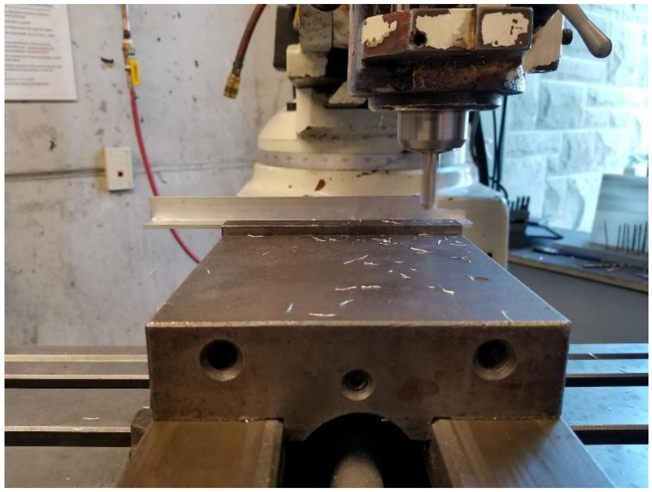

Figure 43 - First Pass of Milling Angles

Hole Drilling

The holes for the angle pieces and the square rod were also drilled using the milling machine. This was more accurate than drilling the holes with a drill press and trying to line up each hole with a marked location. The mill was set-up with a 1/8" drill bit to drill the clearance holes on the angle pieces. The part zero was set at the far-left corner of the clamped piece using an edge finder. After lining the edge finder up each face, the value of -0.1" (the radius of the edge finder) was inputted into the user interface on the milling machine. The drawings that were created for the rails replicated this set-up and the part zero was chosen to be in the same location (Reference Drawings XXX). The coordinates of the holes were taken from the drawings and the mill was manually turned to each location using the machines user interface. The holes were drilled using the pecking cycle method and lubricant was applied to the work piece and the drill bit before each drill. The holes in the square rods are blind and will be tapped later in the process. This required the tool to be changed to a 7/64" drill bit so that the diameter of the holes could be tapped using a M3 tap. The square rods were clamped similarly to the angle pieces and the same part zero in the x-axis and y-axis was used. After lining up the drill bit with the top face of the square rod, the z-axis stop dial was set to a distance of 4.5 mm, which is the depth of the blind holes. A shorter pecking cycle was used and lubricant was again applied to the part and the drill bit before each drill. Once the drilling was completed on all of the rails, the holes were deburred by turning a larger drill bit (3/16") in the holes until the edge that was created from the drilling operation was removed. See Figure 44 and Figure 45 for the finished products of the rail components.

Figure 44 - Finished Square Rods

Figure 45 - Finished Angle Pieces

Bending the Mounting Plates

The mounting plates were laser cut out of 0.080” thick 3003 aluminum sheet metal. The thickness and grade of material allows for the parts to be bent using a standard sheet metal bender. The original CAD files created on SolidWorks were exported as .dxf files and sent to Chandco Manufacturing Inc., so that the laser cutting machine could read the shape of the parts. After receiving the laser-cut parts, all of the edges were deburred using a file and the parts were ready to be bent.

The challenge of bending the mounting plates was greater than anticipated. The sheet metal bender consisted of a lower die with a V-shape cut out of the top and an upper die in the shape of a ‘V’, each about 1 metre long. The issue is that the mounting plates at each end of the CubeSat extend past the bend line of the tabs on all four sides. Figure 46 presents the edge that will interfere during bending. The existing set-up on the sheet metal bender is incapable of bending the tabs since the upper and lower mounting plates would interfere with the dies. The solution was to create a new lower die that was capable of bending the tabs on these parts and switching it out with the existing die. The upper die would be replaced by two separate V-shaped fingers that were accessories to the sheet metal bender, presented in Figure 47, below. The lower die would be custom machined out of a stock plate of cold rolled steel. The lower die was machined to a height of approximately 4” and using a V-shaped parallel, the ‘V’ was machined out of the top face, as shown in Figure 48. The new lower and upper dies were installed on the 40-ton sheet metal press. The length of each tab was determined by a stop in the y-axis that was clamped to the table, also visible in Figure 48. The length of each tab was 2.5 mm and it was important that they were all bent identically so that the rails mount perpendicular to each other. The finished mounting plates with bent tabs are presented in Figure 49, below.

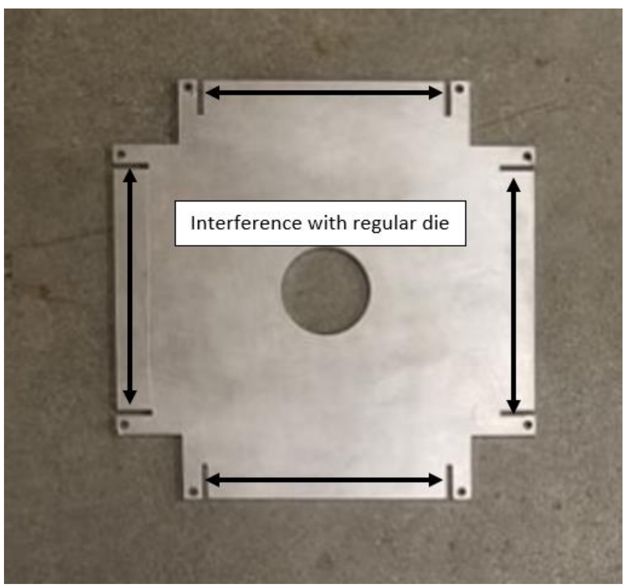

Figure 46 - Bend Interference

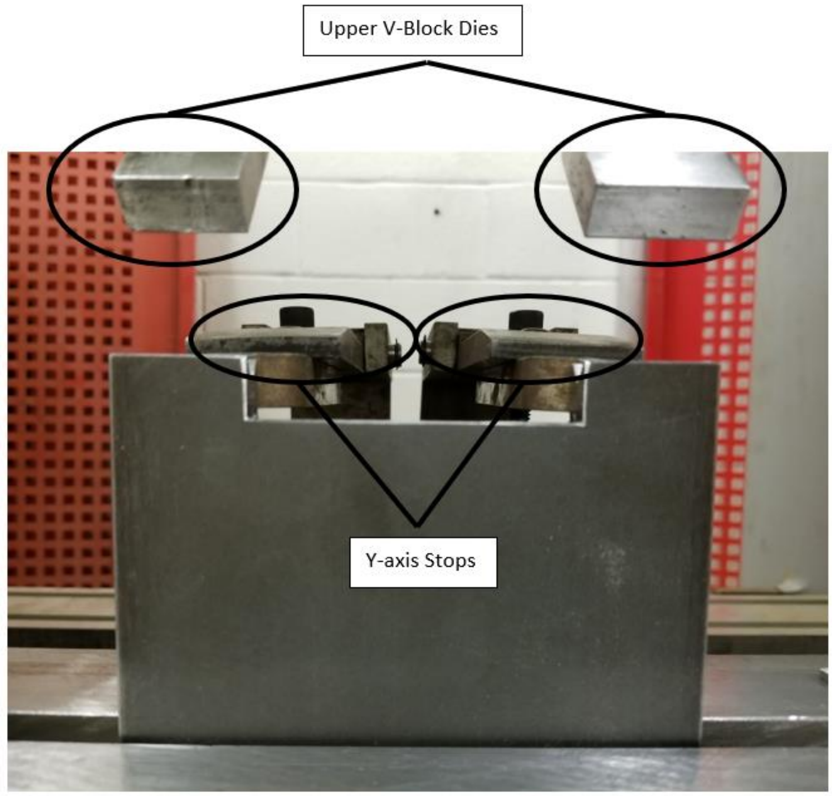

Figure 47 - 40-ton Press Stops and Upper Die

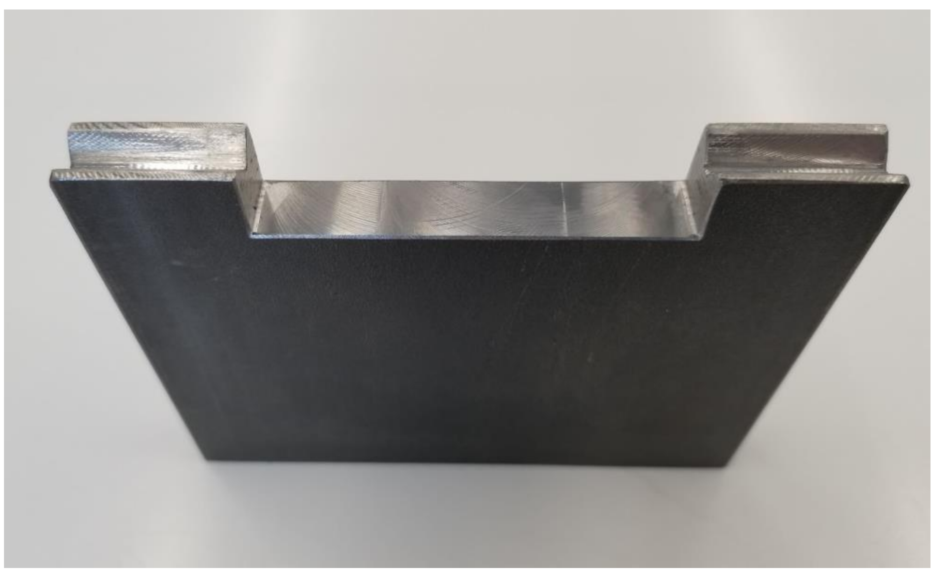

Figure 48 - Bottom of Custom Die

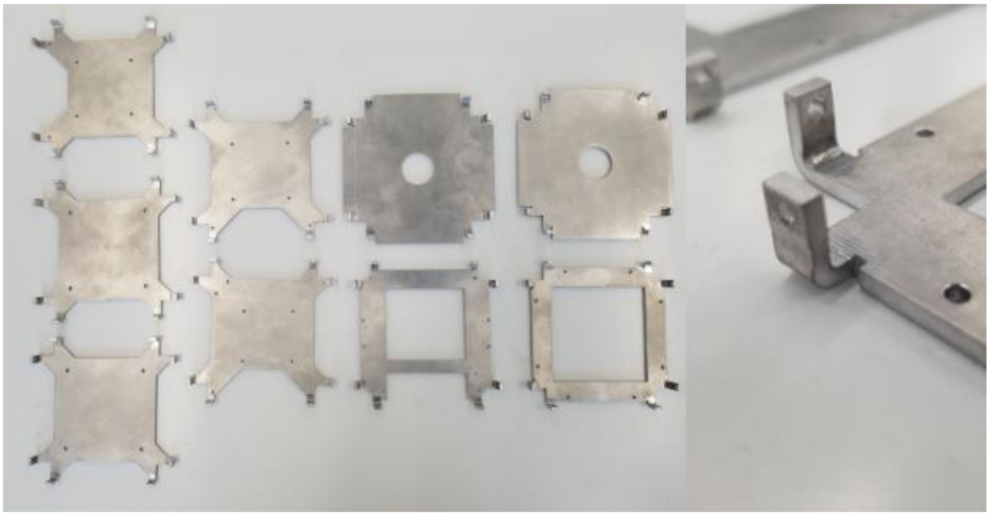

Figure 49 - Bent Mounting Plates

Tapping Holes

The holes on the tabs of the mounting plates were tapped using an M3 tap. This was done after bending the tabs to avoid damaging any threads when coining the tab. The tap was dipped in lubricant before threading each hole and was used cautiously to ensure that the tap wouldn't break and get stuck in the hole. The equipment for tapping is presented below in Figure 50. The blind holes in the 4 square rods also needed to be tapped using the M3 tap. This process was time consuming and would have been better performed on a drill press with a repeatable setup. This would also ensure that each thread is tapped concentric with the center of the hole and would reduce the tolerance stack up of the overall assembly.

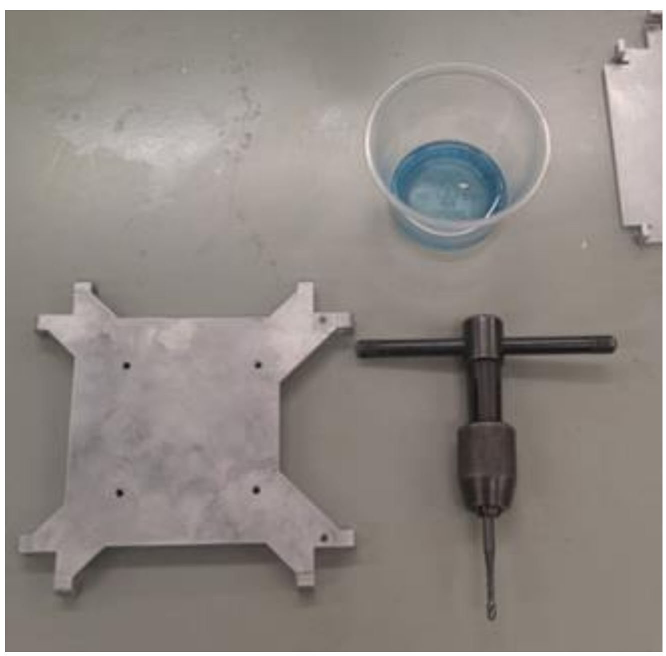

Figure 50 - M3 Tap and Lubricant

Machining Dummy Masses

The dummy masses represented the various subsystems on the CubeSat for testing. The blocks were made from 6061 aluminum and their volumes were equivalent to that of the subsystems. The blocks were machined down to size using the mill due to the simple geometry of each part. All parts were sanded using the belt sander and the edges were deburred using a file. The clearance holes on the dummy masses were drilled on the drill press because the alignment for the mounting screws was not critical. The holes were drilled with a 1/8” drill bit using the pecking cycle technique and again adding lubricant frequently. The holes were deburred with a larger drill bit (3/16”) until the edges from the drilling process were removed. See Figure 51 for the dummy masses attached to their mounting plates.

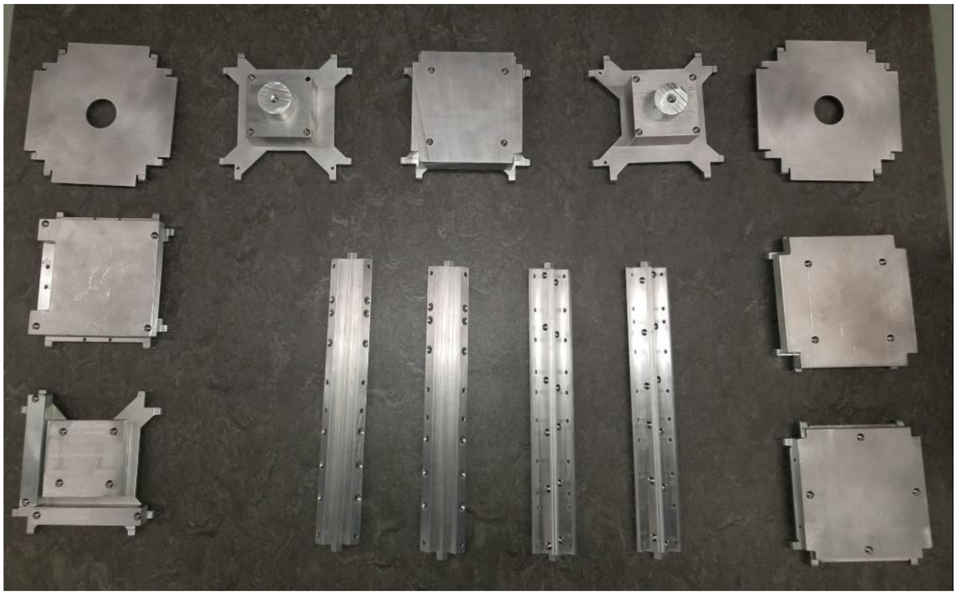

Figure 51 - Dummy Masses Mounted to Plates

Finishing

The rails, mounting plates, and dummy masses were all sanded roughly using a scotch pad, then refined using 400 and 600 grit sandpaper. Turtle wax was applied to all aluminum components to protect the surface finish since the prototype is to be used a classroom model as well as the Capstone showcase.

Prototype Assembly

The plan for assembling the CubeSat was initially generated in the detailed design phase of the project. The plan was to assemble the mounting plates to the rails, starting in the middle with the antenna and work outwards, finishing with the camera covers. This procedure proved to not work with the prototype due to the abundance of internal screws and poor alignment, but would work for the final design with the improvements that are inherent in a fully machined product with less components overall.

The use of button head screws to fasten the rail components was problematic when attaching some of the mounting plates to the rails. The button head screws had to be removed before inserting the mounting plates between the rails and then screwed in again afterwards. This added significant time to the assembly process and was an unseen error in the design. The reason button head screws were chosen was because they were stronger than countersinking the rail and using flat head screws. In hindsight, it would have been better to use a thicker aluminum angle and to countersink the holes for the screws that fasten the angles to the square rods. This would have made it possible to mount all four rails to the first mounting plate (antenna) and slide the other mounting plates in one at a time, as originally planned.

Since the rail design changed and each rail is now made from three separate pieces, the first step in the process was to fasten the rails together. The angle pieces were screwed into the square rods through the tapped holes with button head M3 screws, as presented in Figure 52. The holes on the tabs of the mounting plates are threaded for M3 screws and the holes in the angle pieces are countersunk clearance holes. Flat head screws will be used to fasten the plates to the rails in a later step. It is important that the outer faces of the rails are flush so that the solar panels can mount properly.

Figure 52 - Fully Assembled Rails

The electrical resistance heaters were sandwiched between the dummy masses and mounting plates before being fastened together. The dummy masses were fastened to their corresponding mounting plates before the rails were mounted. The mounting plate with one of the camera dummy masses attached to it was the first to be fastened to the three rails. The next mounting plate and dummy mass to be fastened was ADCS, followed by the transceiver, antenna, battery, OBDH, and the other camera. After all of the subsystem mounting plates were fastened to three of the rails, the fourth rail was installed. This approach was necessary due to the problem with the button heads as stated previously. The camera covers at each end of the CubeSat were the last parts to be fastened to the rails. The thermal straps were cut to length and an epoxy was used to affix them to the dummy masses. The dummy masses that were used to simulate sources of heat were the battery, OBDH, and the transceiver, as presented in Figure 53. The thermal straps are to be cut to a shorter length and re-installed onto the dummy masses to promote more efficient heat transfer. Thermal Straps are show in the Testing section in Figure 58.

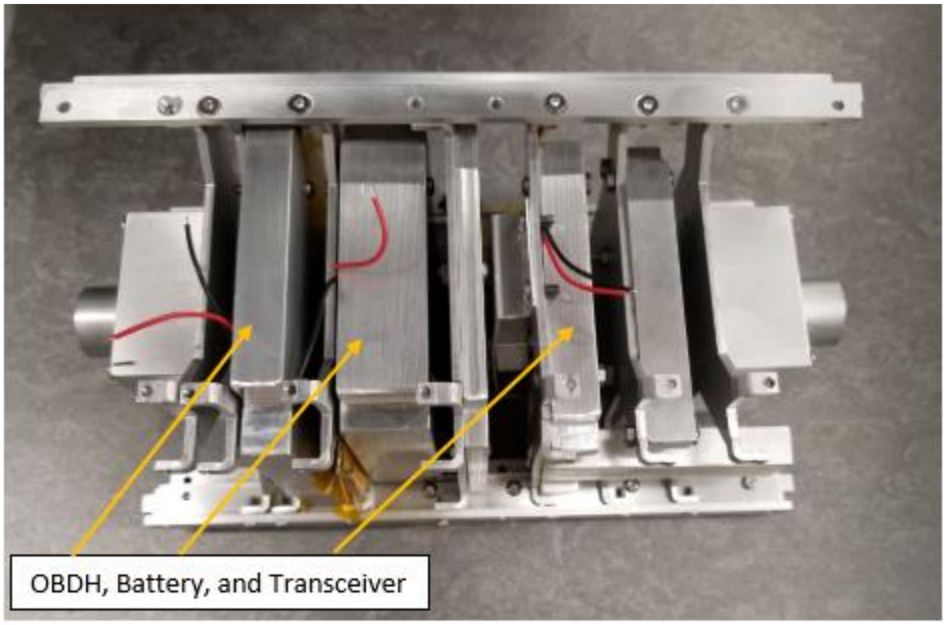

Figure 53 - Partially Assembled CubeSat

Once the fourth rail was installed, thermal straps were attached to the CubeSat. The straps were fastened to the faces of the battery and OBDH and to the heat sink using a 2-part high conductance epoxy. The straps were first bent into shape so that each end would be flat against the surfaces. The epoxy was prepared and applied quickly to the straps. The straps were then clamped to the CubeSat with large c-clamps, and left overnight to cure.

After thermal testing, prior to vibrational testing, the CubeSat will have to be disassembled to remove the heat pads, and to apply thread locker to all screws that lack a secondary locking mechanism. The same assembly procedure will be followed to accomplish this.

Testing

Due to the parallel design setup of Western University's CubeSat project, CubeSat teams Spirit and Opportunity agreed to each take responsibility for designing and testing both CubeSat's for either thermal or vibrational requirements. It was determined that Opportunity would design and perform vibrational testing, while spirit would design and perform thermal testing. Members of both teams are to be present for both tests. The testing and results for the CubeSat Opportunity only will be discussed.

Vibrational

Vibrational testing of the CubeSat Opportunity was not finished prior to submission of this report. The testing is still in progress. This section will outline the background, equipment, procedure and expected results.

The actual vibrational testing will be discussed later in the Progress since Last Report section.

Background

Prior to being launched to the ISS, the CSA requires that each CubeSat is tested for resistance to random vibration. Vibrational effects are experience throughout the flight to the ISS, and during deployment. The most extreme vibration will occur during rocket liftoff. The purpose of testing is to ensure that no components fail and become loose within the deployer, or cause the deployer to become jammed when activated. Either of these situations could cause a complete failure of all CubeSat's in that deployer. The CSA also considers lost parts in space (untrackable space debris) to be a catastrophic hazard to vehicles visiting the ISS [1].

The following table (Table 4) is the vibrational profile testing requirements, taken from the NanoRacks CubeSat Deployer Interface Definition Document (IDD) [1]. The IDD provides both hard-mount and soft-stow test profiles. The NRCSD is delivered to the ISS wrapped in bubble wrap, and as such it is considered to be soft-stowed. Figure 54 presents a visualization of the requirements [1].

Table 4- Soft-stow Test Profile [1]

Frequency (Hz)	ASD (g^2/Hz)
20	4.000E-02
25	4.000E-02
31.5	4.000E-02
40	4.000E-02
50	4.000E-02
63	4.490E-02
80	5.062E-02
100	5.660E-02
125	6.200E-02
160	6.200E-02
200	6.200E-02
250	5.558E-02
315	4.102E-02
400	2.998E-02
500	2.236E-02
630	1.651E-02
800	1.206E-02
1000	9.000E-03
1250	6.034E-03
1600	3.878E-03
2000	2.600E-03
Grms	5.76
Duration (sec)	60

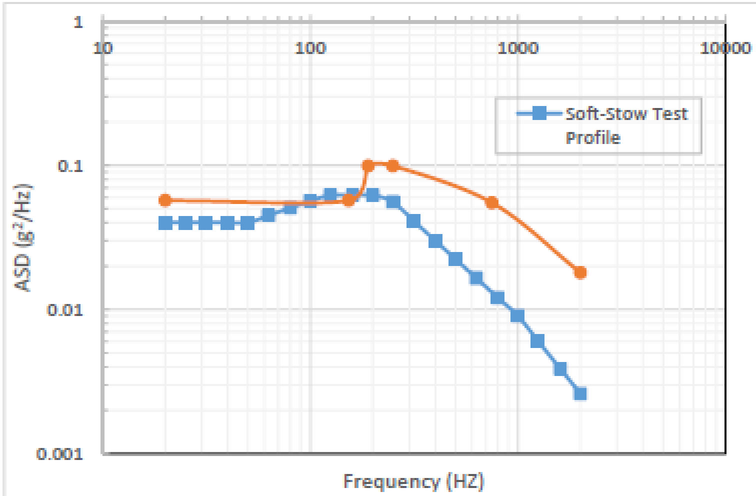

Figure 54 - Soft-stow and Hard-mount Test Profiles [1]

At the current stage of development of the CubeSat Opportunity, only preliminary testing must be performed to verify the structural integrity and overall design. Catastrophic failure of the structure during testing may indicate a flawed design and require a completely new design, while minor failures (hairline cracks, bends) can be dealt with through iteration of the design.

Random vibration testing is performed using a device called a shaker-table. A shaker table allows the test subject to be mounted into a fixture, and the fixture is then bolted to the test bed of the shaker table. Figure 55 below is a common automotive shaker table. The system consists of a “shaker”, which is the drum-shaped component in the rear, and the “slip table”, which is the flat component with mounting holes in the front. This style of shaker table is a 3-axis shaker. Meaning it can rotate to apply vibration on the x, y and z axes of the test subject.

Figure 55 - Common 3-Axis Shaker Table [2]

Due to the high cost of the individual subsystems, dummy masses will be used to represent them. Aluminum blocks (6061-T6) were cut down to roughly the size of the individual subsystems, and will be mounted with the same holes and fasteners as the real component would. The primary downside to this method is that the aluminum blocks are much heavier than the real subsystem components. An increased mass will result in an increased inertia, and also in a much higher force on the mounting screws. This means there is a higher likelihood for failure, however it is still an effective way to locate weak points in the design. The test configuration of the CubeSat Opportunity was not available to be included as an image, as it needed to be deconstructed to remove thermal testing equipment and have Loctite thread locker applied to all screws. Images will be included in the final report.

Equipment

- Shaker and Slip table
- Prototype
- Fixture with fasteners

Western University does not currently have a shaker table for use by capstone teams, and so one had to be located that was off-campus. Litens Automotive, in Concord Ontario, was contacted and agreed to provide access to their shaker table for testing purposes. Litens owns and operates a 3-axis table similar to the one presented in Figure 55. As mentioned previously, at the time of submission of this report, the testing had not been performed. This is due to delays in designing the test fixture.

Litens indicated that a fixture was to be designed to mount the CubeSat that can lock it on all 3 axes, and that can be mounted to the slip-table using M10 bolts. Litens provided the Opportunity team with a sample fixture image to display the mounting of the fixture to the slip table, as well as CAD models of the slip table. Refer to **Error! Reference source not found.** and **Error! Reference source not found.** for these images.

The fixture that is being designed, presented in Figure 56 is a rectangular frame connected by threaded rods. The corner rails of the fixture are made of opposing angled steel bar stock. The contact points will be between the corner of the fixture rails and the rails of the CubeSat. The fixture with the CubeSat mounted in it is presented in Figure 57. It will be fastened down to a bottom plate with nuts. The bottom plate will then be fastened to the slip table with M10 nuts. This design has been sent to Litens for review, and will be iterated based upon their suggestions and advice.

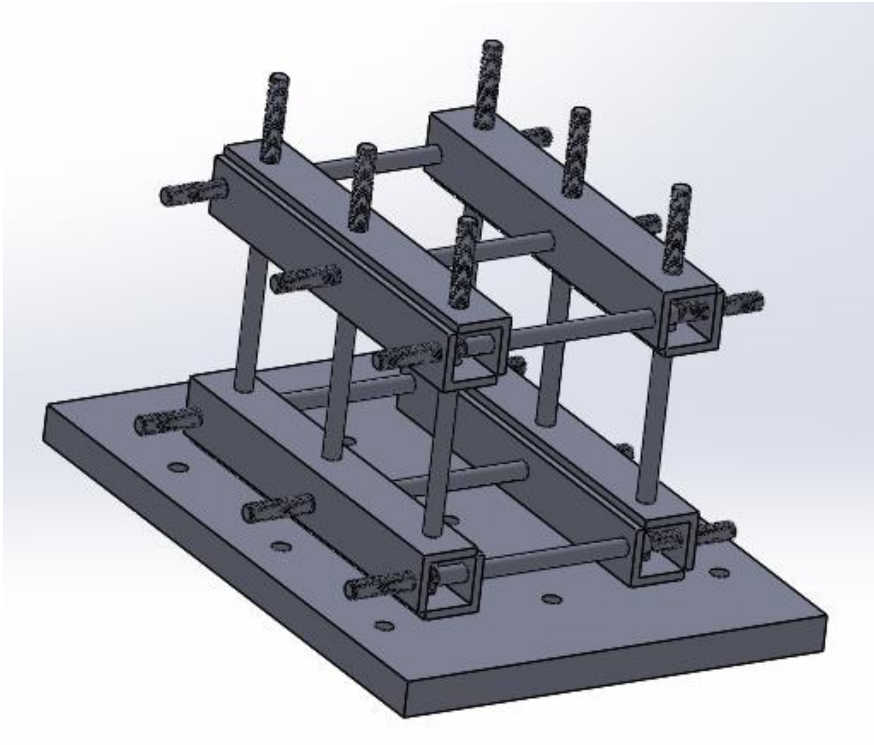

Figure 56 - Vibrational Testing Fixture

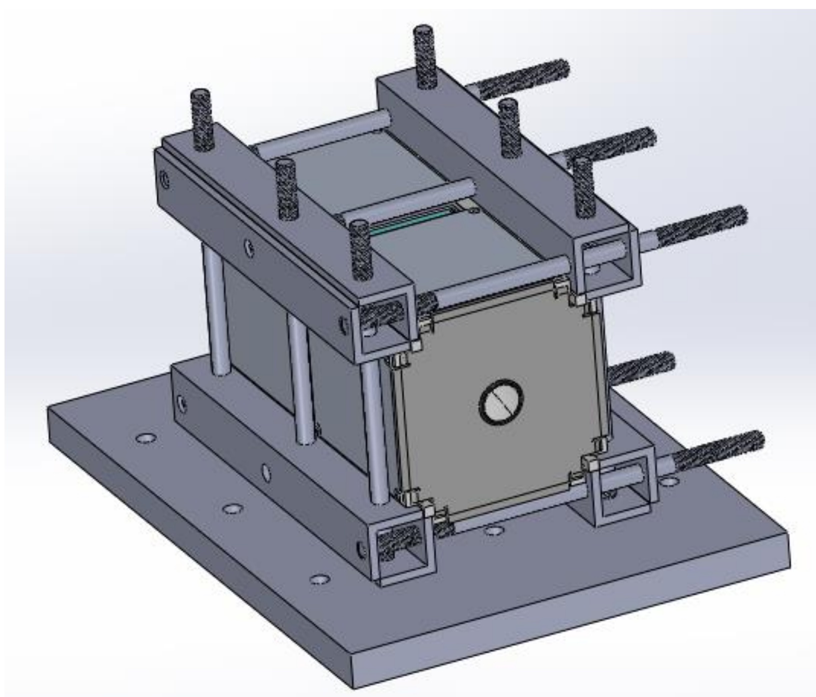

Figure 57 - Fixture with CubeSat Mounted

Procedure

Due to the preliminary nature of the CubeSat Opportunity, it is ideal if catastrophic failure is avoided. For this reason, the test will start at a low-sine frequency, which will provide the baseline reading for the prototype. Once this is complete, random vibration testing will be performed. The maximum frequency and amplitude will be slowly increased and carefully monitored until either the maximum frequency in the test profile envelope is reached, or severe displacements are being seen. Large displacements will lead to plastic deformation or fracture. If large displacements are seen, the test will be stopped and the result may be considered a catastrophic failure depending on the location of displacement or plastic deformation. If the prototype survives well until the highest frequency and amplitude of the test, the test will be stopped, and the prototype will be re-tested at the low-sine frequency. The purpose of the low-sine retest is to compare the output to the baseline created prior to the higher frequency testing. Differences in the outputs will indicate damage such as hairline fractures or minor deformations.

This test methodology was taught to the CubeSat Structural and Thermal Subsystem team by engineers at Neptec Design Group in Ottawa during a visit to see their testing facilities in February.

Results

The primary data output of a shaker table is visual. The test must be monitored and the prototype visually inspected after each stage for damage. Damage caused during testing will be obvious, and will appear in the form of cracks, breaks or deformation of the components. Secondary data is typically output in terms of force, strain and velocity, however the digital output capabilities of Liten's shaker table have not yet been shared.

The current prototype design of the CubeSat Opportunity uses sheet metal for internal mounting boards, rather than completely machined parts. In order to attach these to the rails, tabs had to be bent up in each corner. Redundancy was inherent in the design in that each corner had 2 tabs, resulting in 8 screws per mounting board, making the structure quite strong. However, the tabs themselves are a weak point due to slight necking during the bend. The metal itself can also become work-hardened when bent in a press, as per input from Chris Vandelaar of Western UMS. During vibrational testing, it is expected that any major or minor failure will occur at the location of these bends. Due to the redundancy in the number of screws and tabs, it will likely be a minor failure that will allow the testing to be completed.

Thermal Testing

Background

Thermal testing is not a requirement by the CSA prior to launch, however this testing is very important for a mission's success. Determining if the thermal management system functions as expected, and functions effectively, is key for the survival of the CubeSat. Ensuring that components have operating ranges beyond the environment expected is also necessary, due to the fact that failure of a single subsystem inevitably results in the failure of the entire system.

The structural and thermal subsystem team is required to develop the thermal management system to be used by the other subsystems. The thermal management for the CubeSat Opportunity consists of a heat sink, to which other subsystems will send or take heat throughout orbit. Thermal energy will be transferred to and from the sink via thermal traps. For the prototype, a simple weaved aluminium strap was used as a thermal strap, as seen in Figure 58 at the end of this section. They are much larger and thicker than what will likely be used in later models, but were cheaper and easily obtained. The straps will connect to subsystem components with highly conductive epoxy, and then connect to the heat sink. The prototype heat sink is a 6061-T6 aluminum block that is mounted similar to the other subsystems. For thermal testing, the two hottest subsystems were linked to the heat sink using these straps. The battery and on-board computer are expected to generate the most heat due to their constant operation.

In order to generate heat when using the dummy masses, heating elements had to be installed on the two components connecting to the heat sink. A third heater was installed on the transceiver which is between the heat sink and the battery/OBC to represent ambient heat and display where this heat might go. The heating element was a small mat with two small wires to connect it to a power source. The mats were sandwiched between the components and their mounting boards, to allow some heat to transfer through the structure itself. The setup can be seen in Figure 58 below.

One major issue with this thermal testing is the lack of a vacuum chamber. When the CubeSat is in outer space, it will be in a vacuum environment, which means there will be no convection heat transfer. This means the majority of thermal energy will be transferring through the structure and subsystems until it is expelled as radiation. This test will not be capable of simulating a vacuum environment. However if a vacuum test was possible, a bake-out test would first be performed to remove gases, water vapor, and other contaminants before the test. In addition we also would have performed a cycling test to see how the CubeSat performs when being exposed to the extreme hot and extreme cold temperatures of deep space repeatedly. The purpose of the test is to verify the functionality of the conductive thermal management system, so the issue then becomes providing enough heat to overcome the effects of convection.

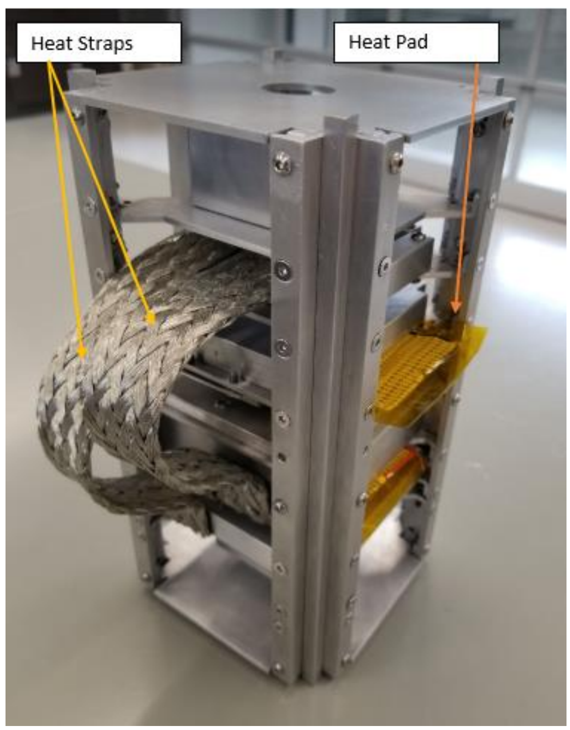

Figure 58 - CubeSat Opportunity with Heat Straps and Heat Pads

Equipment

- 3x heating pad
- Spare wires (~18 gauge)
- 12V Bench top power source
- Thermal imaging camera (FLIR, see Fig. ### below)
- Computer and DAQ system for FLIR
- Pliers or soldering iron/solder
- Timer

The thermal imaging camera, shown below in Figure 59, was graciously provided by Dr. Siddiqui for the purposes of this test. The power source was borrowed from one of the laboratories with permission from Dave Lunn. The remaining equipment was purchased or readily available.

Figure 59 - FLIR Camera

The forward looking infrared camera (FLIR) senses infrared radiation and converts it to an electrical signal that can be output to create a heat map image of whatever it is viewing [3].

Procedure

The general purpose of this test is to run current through the heating pads to heat up the components in the CubeSat, and view this through the FLIR camera to determine if the heat straps are functioning, and where the heat tends to travel. It is important that no heat sources (electronics, people, etc.) pass through the field of view of the camera during testing, or it can cause the camera to compensate and possibly affect the quality of the results. The procedure will begin with the heat pads already installed in the CubeSat.

Step:

1. Solder or twist and tape longer wires onto the heat pad connections, long enough to reach a power source outside the field of view of the FLIR camera.
2. Connect the FLIR camera to a power source and to the computer and power it on. Setup the DAQ and ensure the output data is being received.

3. On a long table, arrange the camera and CubeSat so that the CubeSat is entirely visible in the cameras output, about 4-5 feet apart. This may require lifting the camera slightly. See Figure 60 below.

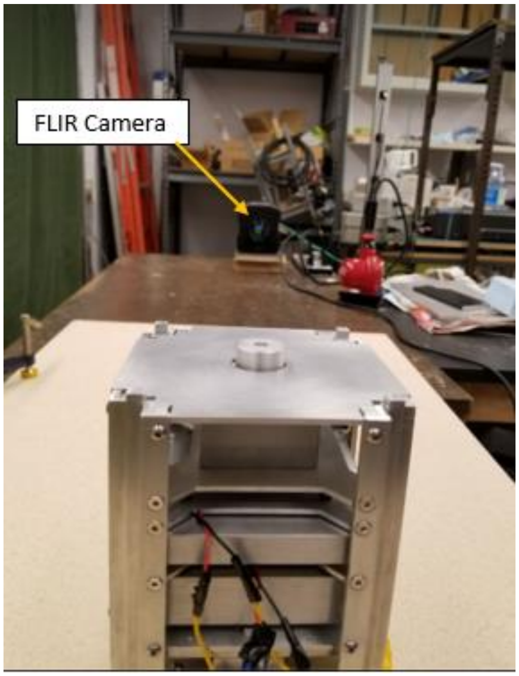

Figure 60 - FLIR and CubeSat Separation

4. Setup the bench top power source somewhere nearby but out of view of the camera.
5. Connect all the negative leads from the heat pads to the negative terminal on the power source by twisting them together and wrapping them around the terminal. Repeat for the positive wires and positive terminal, as shown below in Figure 61 and Figure 62.

Figure 62 – Wiring of CubeSat

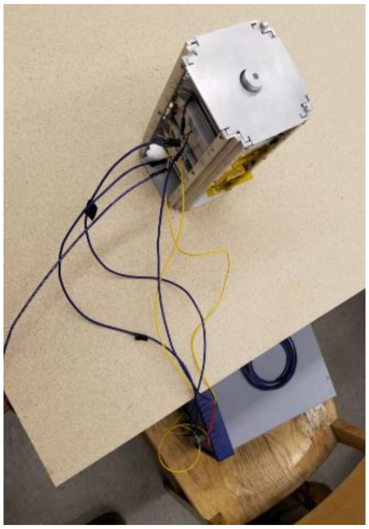

Figure 61 – Connecting to Power Source

6. Clear all heat sources other than the CubeSat from the FLIR field of view and orient the CubeSat so that the desired side is facing the camera. Turn on the power source to begin heating the CubeSat and start a timer
7. Record an image of the live thermal feed from the camera every 5 seconds for 25 seconds, and then at the 1, 2 and 3 minute mark. Power off the power source after 3 minutes.
8. Let the CubeSat cool for approximately 10 minutes, and then rotate the CubeSat and repeat the test.

Results

The results of the thermal test were for verification of the heat transfer to the straps, sink and structure. For testing, the heat sink is located at the bottom of the structure, and the battery and OBC are towards the top. The output from the FLIR camera are presented in Appendices D-4A and D-4B. The temperature ranges from room temperature (approx. 24 degrees Celsius) to a maximum of approximately 89.9 Celsius in orientation 1 and 75 Celsius in Orientation 2. The temperatures themselves are not of great importance at this stage. The result of importance is the fact that thermal energy was transferred from the subsystems into the thermal straps.

In orientation 1, the temperature of the lower strap is increasing around image 4 (15 second mark), and the other strap begins increasing around image 5-6 (20-25 second range). The second strap may be absorbing heat from the transceiver in the middle, as the top of the strap remains cool throughout. This would be due to convection heat transfer and should be considered error.

Similar results can be seen for Orientation 2, with both straps effectively removing heat from the subsystems in the last two images (2-3 minute range). The effects of convection are still evident for this trial as well.

Another important result is the rails, which also appear to be absorbing energy from the subsystems. This is a benefit of using aluminum for much of the structure, as it will provide additional thermal storage alongside the sink, as well as maintain a more even thermal distribution.

Overall, the test successfully proved that the heat straps can work as a method of heat transfer to and from the sink. Better results could be obtained by running the test longer (ideally 45 minutes, the time spent in direct sunlight during orbit), shortening the straps to be tighter against the structure, and if possible, running the test in a vacuum chamber.

Cost Analysis

The initial concept for the rails was to have them each machined out of one stock piece of aluminum since it was designed to be as strong as possible. The possibility of 3D printing the rails was suggested by the University Machine Shop (UMS) and they quoted them for $648.82. This did not fit within the budget and the material was not going to be the same aluminum grade as what was specified in the customer requirements.

The decision to change the rail design to a three-piece sub-assembly was made so that the design could be manufactured using conventional machines. The rail drawings and CAD files were sent out to various suppliers requesting for quotations. The UMS quoted the new rail design for $1,049.96. Attica Manufacturing quoted the machining of the rails for $1,100.00. Westool Precision Products quoted the machining of the rails for $2,292.00. All three of these quotes were outside of the capstone budget, so the group decided to machine the rails in the machine shop in SEB. This meant that all of the components had to be ordered and picked up/delivered with sufficient time left to manufacture the prototype.

The laser-cut parts were quoted from two different companies in London ON. Diversified Metal Fabrication Inc. quoted the laser-cut parts for $140.12 and Chandco Manufacturing Inc. quoted the laser-cut parts for $111.55. Chandco Manufacturing Inc. was awarded the job since they had the lower quote.

All quotes are presented in D-5: Quotes. Note that quote 6 for DigiKey was ordered by Dave Lunn. Quote 7 for McMaster Carr was ordered under Spirit's budget, and the epoxy was shared. An equal value of other parts (screws/nuts/spacers) was given to Spirit in return.

The total cost of all the components was $2812.48. The time it took to manufacture (mill, drill, deburr, finish) all of the parts was approximately 50 hours and another 50 hours for assembly, as a combined total for all group members (20 hours each). If a machinist working on this prototype was billed at $25/hour, the cost of the manual labour would be roughly $2500. The experience gained from manufacturing the prototype was invaluable and there were a lot of lessons learned throughout the process. For the final design, the rails and mounting plates will be machined by a professional and the CubeSat budget will have to be used. Refer to Table 5 below for a breakdown on the cost of the prototype.

Table 5 - Prototype Costs

Prototype Cost Breakdown		
Part Name:	QTY	Subtotal
Aluminum Angle 6063T5 0.750 X 0.750 X 0.125	2	$15.19
Aluminum Square Bar 6061T6511 0.250	1	$3.93
Laser-cut Aluminum Parts 0.080"	9	$111.55
Dummy Masses; Camera Blocks, Camera Cylinders, Transceiver, Antenna, OBDH, Battery, Magnetorquers, Gyroscope	14	$56.88
Heating Pads 5VDC 750MA 5X10cm	3	$17.82
Button Head Hex Drive Screw Passivated18-8 Stainless Steel, M3 x 0. 5mm Thread, 6 mm long	100	$5.06
Steel Hex Nut Medium-Strength class 8, M3 x 0.5 mm Thread	200	$1.76
Threadlocker Loctite 242, 0.34 oz. Bottle	1	$16.03
Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.5 mm Thread, 8 mm long	100	$9.37
Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.5 mm Thread, 18 mm long	50	$6.00
Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.5 mm Thread, 30 mm long	100	$6.55
18-8 Stainless Steel Hex Drive Flat Head Screw M3 x 0.5 mm Thread, 10 mm Long	100	$5.81
Heat Transfer Sealant (epoxy)	1	$46.23
Braided Thermal Strap	1	$10.30
		TOTAL: $312.48

Conclusion

As shown in this report, the CubeSat Project is well on its way to wrap up its final steps. Many changes were made and specified in detail to overcome obstacles presented when trying to fabricate the final design. The result was a prototype that is fully capable of replicating the final design's features while also being within the prototype budget. Subsystem components were replaced with dummy masses that are effectively the same for testing. New fabrication techniques and tooling not specified in Interim Report 3 were also used to create the functional prototype and described in full detail. The final steps are to complete the structural testing, compile and analyze all data, and present the final product at the Design Showcase. If all goes well with the prototype testing then CubeSat Team 46's goal of designing the preliminary design, as well as reporting all challenges along the way, will be complete and the information gained will be essential for the progression of this long-term project. With a strong and proven base for future design and modifications, Western University's CubeSat Project is well on its way to success!

Current Stage 4 References

[1] T. Prejean, "NanoRacks CubeSat Deployer Interface Definition Document," 2018.

[2] Bruel and Kjaer, "LDS LPT Slip Tables," [Online]. Available: https://www.bksv.com/en/products/shakers-and-exciters/LDS-shaker-systems/slip-tables-head-expanders-and-thermal-barriers/combo-systems-with-LPT-slip-tables. [Accessed 09 03 2019].

[3] FLIR Systems Inc., "What is Infrared?," [Online]. Available: https://www.flir.ca/discover/what-is-infrared/. [Accessed 09 03 2019].

Stage 5 - Final Design

The following section will discuss developments in the design of the CubeSat Opportunity that occurred since the submission of Report 4, as well as some closing thoughts and conclusions regarding the project as a whole.

Vibrational Testing

The CSA requires that all CubeSat's undergo random vibration testing within a test envelope provided in the CCP, presented in Figure 54 – Soft Stow and Hard Mount Test Profiles in the previous "Testing" section of this report.

Vibrational testing had not been performed prior to submission of Interim Report 4. Random Vibration Testing was completed on March 20 at Litens Automotive Manufacturing in Concord, Ontario. Previously, an outline of the background information and expected test, including equipment, procedure and results was discussed. This can be found under the Testing section in "Vibrational". The background information was accurate at the time and will not be discussed further, however the actual test procedure performed and results differ from what was expected, and will be outline below.

Equipment

As discussed previously, Litens Automotive Manufacturing provided the use of their shaker table for testing purposes. Figure 63, Figure 64 and Figure 65 below presents the vibration drum, slip table and amplifier that was used for testing:

Figure 63 – Litens Vibration Drum

Figure 64 – Litens Shaker Table Amplifier

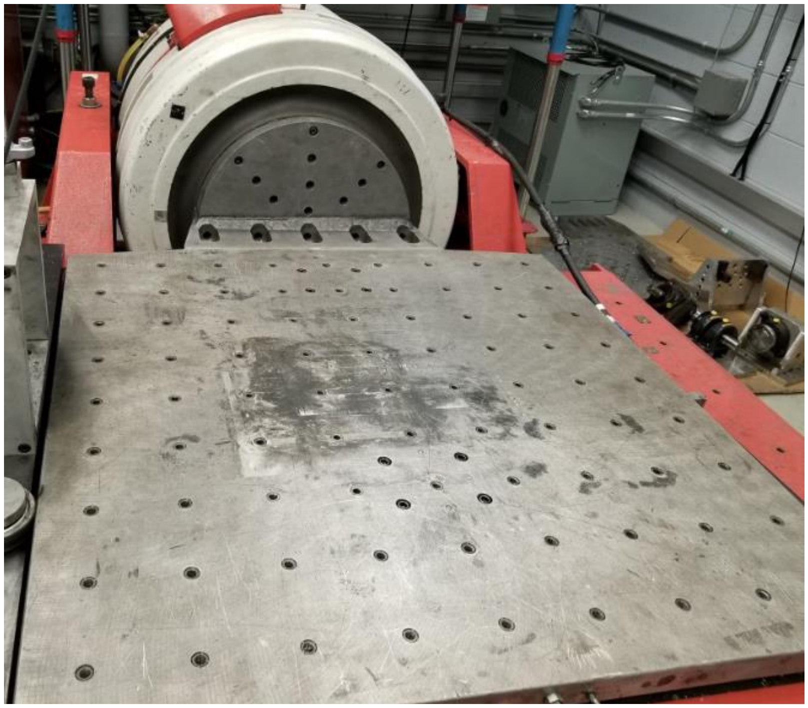

Figure 65 - Litens Slip Table

The shaker table functions using electrical pulses. Inside the vibration drum are coils, and when hit with a pulse train they create a displacement at the frequency of the pulse train. The slip table is fastened directly to the vibration drum and received the same displacement. The slip table can be removed, and the drum rotated for vertical testing, however this setup was not used.

In order to fasten the test CubeSat to the slip table, a unique fixture must be manufactured. An initial design, presented previously in Figure 61, was sent to Litens for review, and they suggested a more simple clamping style fixture. The final tested design is presented below in Figure 66, and an image of the CAD model is presented in Appendix D-8. CAD files are included in the attached .zip. Note that the manufactured fixture lacks some features (cut-out corners on base plate and clamp spines) due to time constraints.

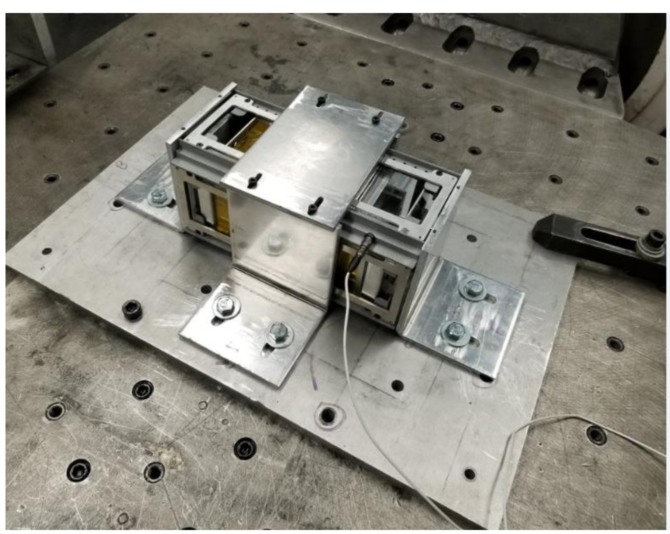

Figure 66 - CubeSat Fixture on Slip Table

The fixture consists of a ¾" base plate, 4 angled aluminum clamps, and a cross plate that connects to the top of the two side clamps. The CAD files for this fixture can be found in the zipped file included with this report. The clamps, which were bent on a 40-ton press in UMS, have M8 diameter slots that allow them to be slid tight against the CubeSat body. The cross plate fastens to the tops of the side clamps with M3 screws, which pass through slots. To fixture the CubeSat, it is placed on the baseplate, and M8 screws are loosely threaded. It was then held tight by one user who would press on it with a pry bar, and the other would fasten the screws down with an impact driver. When all 4 clamps were installed, the cross plate was fastened down with a hex bit. Once the CubeSat was installed, the base plate was fastened to the slip table using M10 bolts and an impact driver.

Upon arrival at Litens, some issues with hole alignment between the clamp and base plate existed. In order to make the holes and slots concentric, the slots had to be filed down manually. A second issue was also discovered while installing the cross plate, as the M3 holes in the side clamp had stripped. To resolve the issue, a Litens machinist drilled M4 holes, and Litens provided new hardware. Finally, when mounting the base plate to the slip table, there were more hole misalignments. This was resolved by using a mill clamp, visible in the top right of Figure 66, above. All of these issues were due to the lack of experience of the group in terms of manual machining. The lack of experience, paired with last minute manufacturing meant less time was spent measuring and misalignments were created.

Procedure

The expected procedure for this testing was that a pre-test sinusoidal sweep would be performed, followed by the random vibration test profile, and finally a post-test sinusoidal sweep. Litens advised that the sinusoidal sweep is much more time consuming and returns similar results to a constant power spectral density (PSD) test. Based on their advice, the pre- and post-test sweeps were instead performed as a random vibration, constant PSD test profile.

Power spectral density is an analytical representation of the vibrational "force" at each specific frequency during the test. It has units of [g^2/Hz], or mean square acceleration per unit frequency. The PSD plot (PSD vs. Hz), allows for the calculation of the accelerations root mean square, as the area beneath the line is the signals mean square, with units g^2 [4].

For the CubeSat Opportunity, random vibration testing was performed with a vibration amplitude along the X-axis, and the repeated along the Z-axis. Testing along the Y-axis was not performed as it was relatively redundant for this stage of the CubeSat's design process. Originally, the CubeSat was planned to be tested with dummy masses representing the subsystems installed. It was decided that due to the higher mass (estimated at 6-7 kg, instead of 3.6kg), that the masses would not be included in order to avoid unnecessary damage to the structure.

The following is the step by step procedure used to test the CubeSat Opportunity:

1. Fasten the CubeSat to the fixture
    a. Place CubeSat in center of base plate
    b. Loosely fasten all angle pieces (backs against the CubeSat) to the base plate
    c. Align the clamps with the CubeSat, ensuring it is parallel to the X and Z axis.
    d. Tighten a side and top clamp with the impact driver, and then tighten the remaining two while someone holds them tight
    e. Set the cross plate on top and tighten it down with a screwdriver
    f. Fasten the base plate to the slip table with the impact driver and a mill clamp where needed, ensuring clamping forces are approximately even across the plate.

g. Clear everything from the slip table aside from test objects.

2. Attach the accelerometer parallel to the direction of vibration at a location of interest (the rails).
3. Set the test frequency envelope in the control laptop in the control room, selecting constant PSD and random vibration. Start recording on the DAQ laptop and run the pre-test for 60 seconds.
4. Inspect the CubeSat and fixture for critical failure after the pre-test. This includes broken parts or large cracks, as well as lost fasteners. If failures occur, evaluate the CubeSat and fixture structural integrity and determine if the test-profile is still feasible and safe. If not, end the test.
5. Load the full test profile (random vibration, random PSD) into the control computer. Start recording on the DAQ laptop and run the test profile for 60 seconds.
6. Repeat step 4. If the CubeSat and fixture are safe, repeat step 3 for the post-test profile (same setup and parameters).
7. Shut down the slip table and remove the CubeSat and fixture. Collect data from DAQ computer
8. Repeat the process for testing along a different axis by rotating the fixture, and repeating steps 1f – 7.

Results

The resulting data from the DAQ provided by Litens is a plot of acceleration in terms of gravity (g) versus time. The results for the X-axis and Z-axis testing are presented below, in Figures 67- 72. The graphs are in the order: pre-test, test profile, post-test. Discussion of the results follows these Figures.

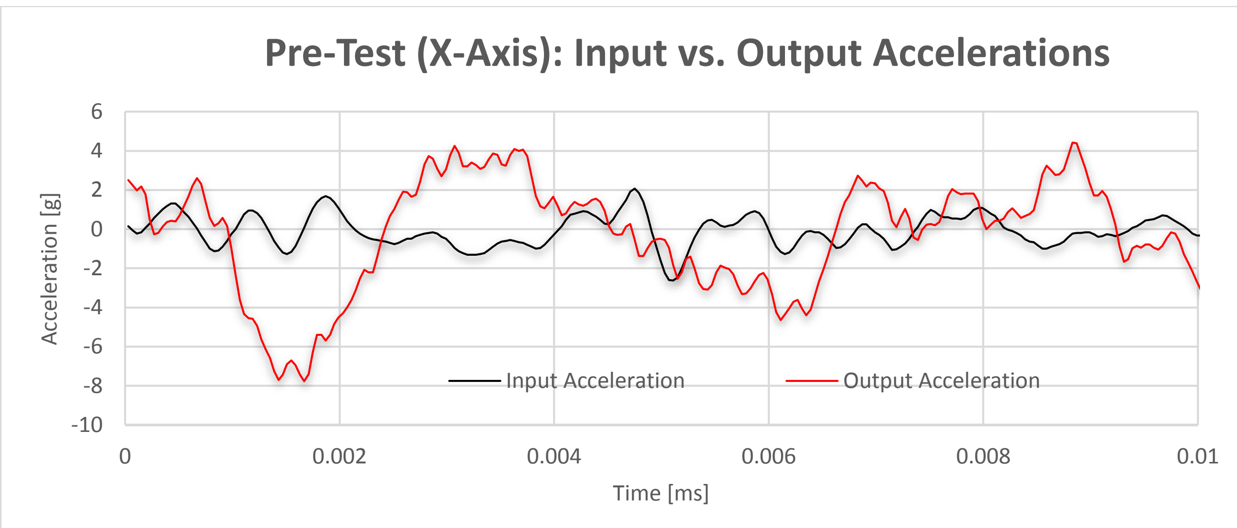

Figure 67 - X-Axis Pre-Test

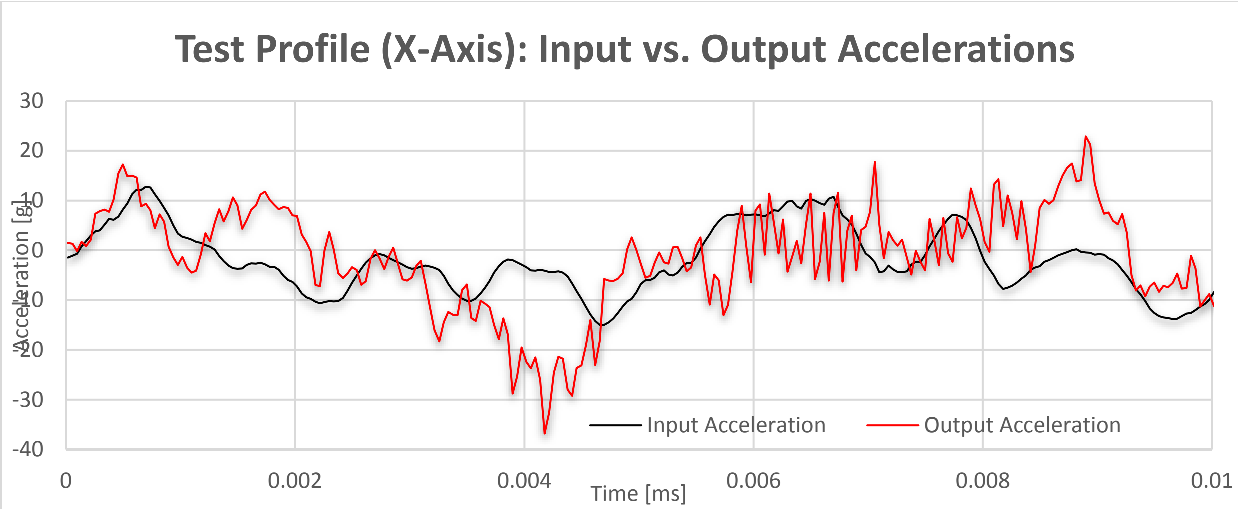

Figure 68 - X-Axis Test Profile

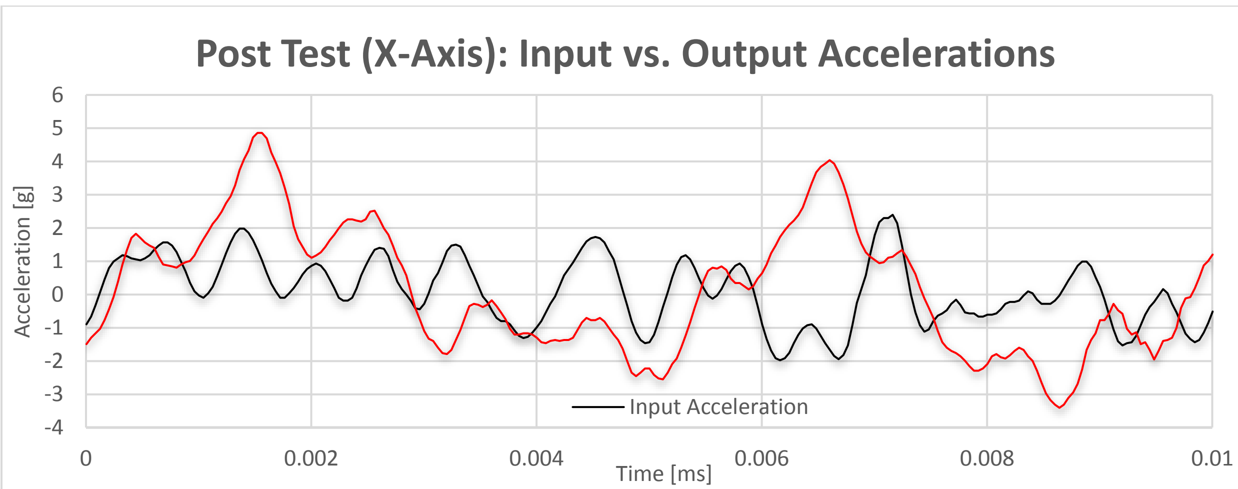

Figure 69 - X-Axis Post-Test

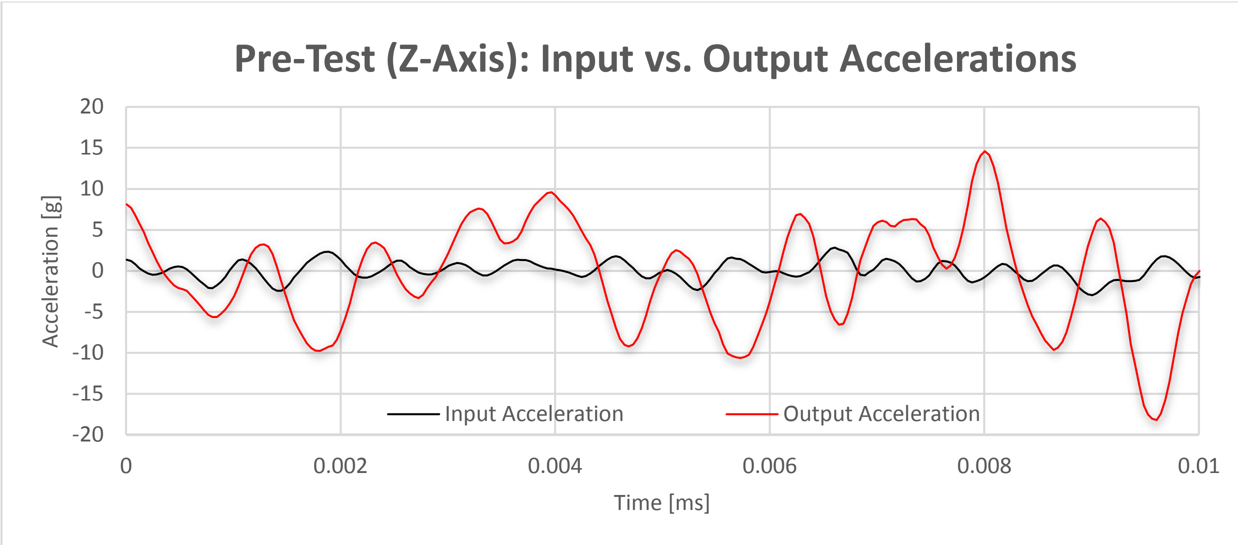

Figure 70 - Z-Axis Pre-Test

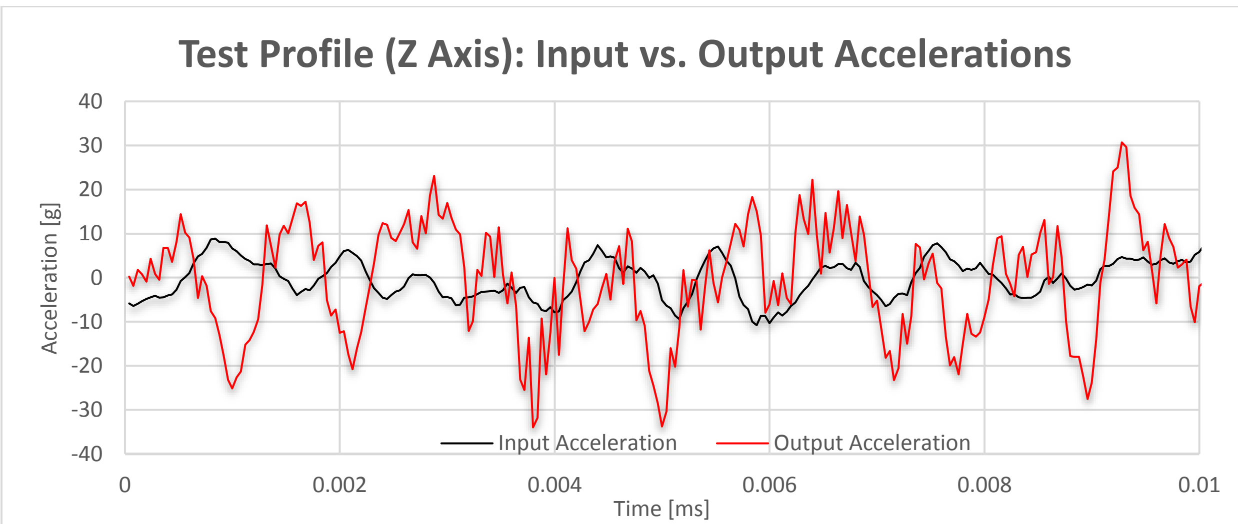

Figure 71 - Z-Axis Test-Profile

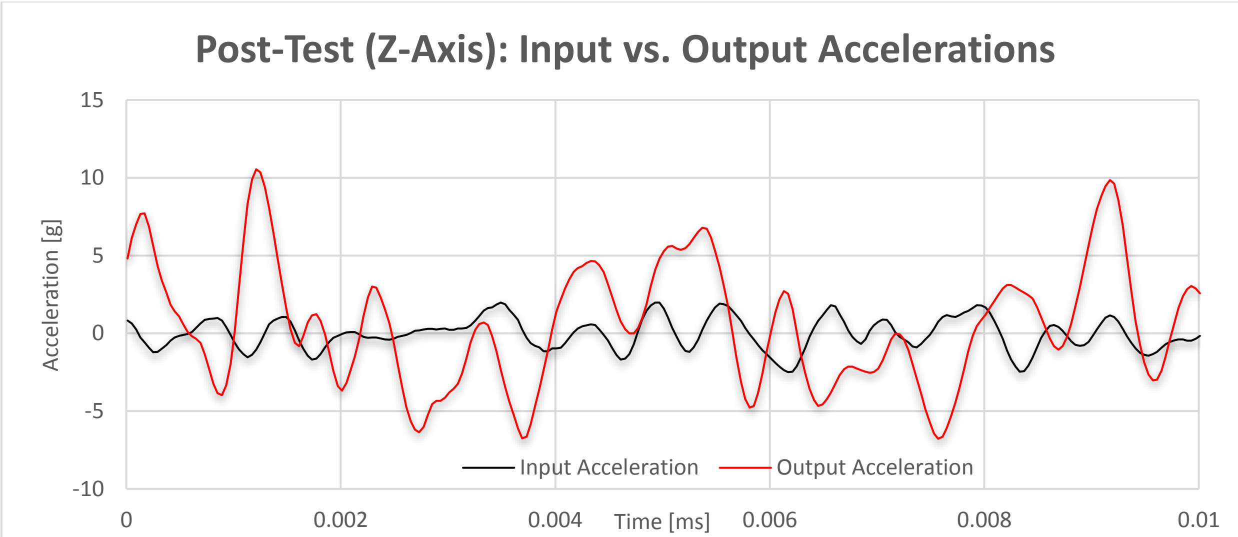

Figure 72 - Z-Axis Post-Test

The graphs output by the DAQ represent the acceleration forces experienced by the CubeSat over a time range of 60 seconds. The DAQ took readings at a rate of 25,000/second, so it is important to note that the x-axis of the figures represents only 0.01 milliseconds of the test. Due to the random nature of the vibration, the 3 runs on each axis will not represent the same vibrational patterns, but the trends can be analyzed. Since the results are quite similar, the X-Axis results will be focused on for the purposes of discussion.

Analysis of the results is done most effectively by comparing the pre-test and post-test results, as well as examining the test-profile results individually. The pre-test and post-test results should be quite similar, as their purpose is to indicate changes in structural integrity through a difference in response to vibration. The input vibration (black, slip table) should theoretically match the output vibration (red, CubeSat) closely, as this would indicate the device under testing is vibrating at the same frequency as the input pulse train. Differences between the two indicate some sort of discrepancy.

When reviewing the x-axis pre-test results, some large differences are noticeable between 0.001 and 0.004, and also at 0.008 milliseconds. Based on a PSD plot output by the DAQ (these results were not provided by Litens), it was discovered that the fixture was experiencing a natural resonant frequency. At the end of the pre-test, a constant 258 [Hz] pulse was input to the slip table, and under a handheld strobe light, the fixture clamps along the sides of the CubeSat could be seen resonating. They appeared to be deforming and warping as they matched and amplified the frequency applied to them.

Examination of the x-axis test profile shows that the structure was performing well. There are some discrepancies however, and it was discovered during visual examination after the test that the CubeSat was not responsible for these discrepancies. Presented below in Figure 73 and Figure 74 are images of the fixture clamps after the pre-test. During the test, the fixture itself began to crack on the bends. This is due to the cold hardening effect caused by bending the metal in a press during manufacturing, as well as the resonant frequency that exists within in the test enveloped, discussed earlier, which caused violent shaking of the clamps.

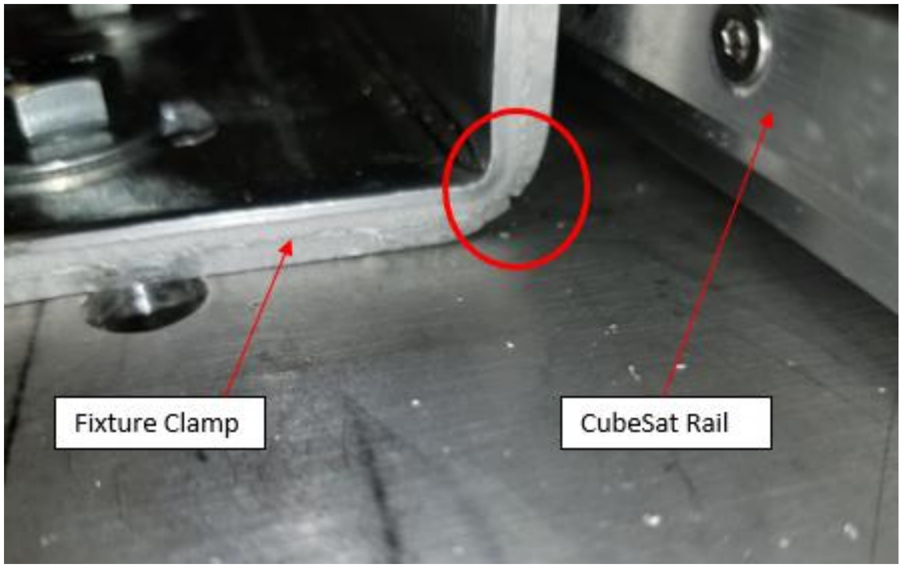

Figure 73 - Side Clamp Cracking on Bend

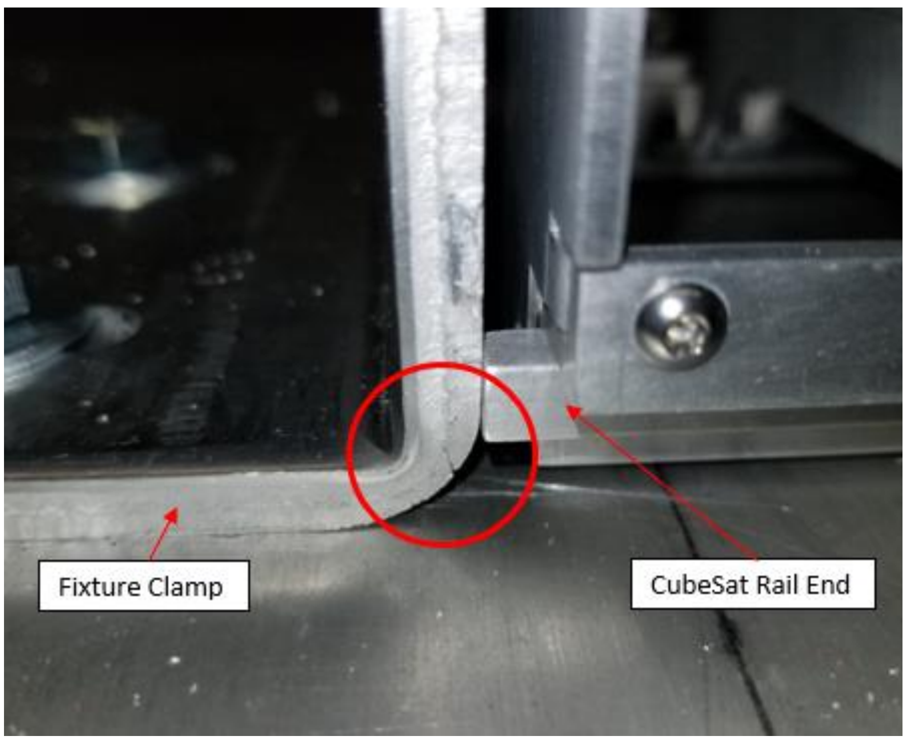

Figure 74 - End Clamp Cracking on Bend

Overall, the CubeSat successfully completed the random vibration testing. Future testing is still required in order to test the structure when it is manufactured based on the final design, as well as testing with the subsystems installed. A stronger fixture must also be designed in order to avoid the fixture causing discrepancies in the results.

Prototype Assembly Results

The prototype assembly was a great learning opportunity and was more challenging than anticipated. The group decided to manufacture the prototype components after receiving many quotes from various suppliers in London. The differences between the final design and the prototype arise mainly due to budget constraints and the manufacturing capabilities available. The prototype components were manufactured in the SEB machine shop by members of the group. As a result, the final prototype had some minor inadequacies and areas for improvement were identified.

The holes on the mounting plates and rails did not line up perfectly causing it to be difficult to screw into the threads. This was due to the tolerance stack up from manufacturing the individual components. The holes on the mounting plates were located on the tabs which were bent to 90° using the 40-ton sheet metal press with custom dies. Although the lower and upper dies were also 90°, the force applied to each tab varied and made it challenging to bend each tab at a perfect right angle. The holes on the rails were drilled using the mill rather than using a drill press which would have been less accurate. However, drilling the holes on the mill still allowed for human error when lining up the part zero and also moving the table to the specified coordinates. The rails were made out of 3 individual components that needed to be fastened together using M3 screws. The error from using the mill to drill the holes combined with the error from fastening separate components together added significantly to the tolerance stack up of the rails. If both the mounting plates and rails were machined from single pieces of aluminum, the holes could then be wire cut on a wire EDM machine to the dimensions of the CAD model. This would reduce the overall tolerance stack-up of the assembly and would line up the holes almost perfectly.

Subsystem Timing

The initial thermal management strategies and structural designs of the CubeSat were based off various parameters provided to us from the different subsystem groups. Canadensys Aerospace Corporation provided the CAD model of the AR/VR cameras along with the specifications early on which was enough to start the preliminary design. Since the subsystem groups were also in the early stages of their designs, many parameters were approximated from existing CubeSats or chosen from commercial off the shelf products. The mounting plates for each subsystem were designed to the dimensions provided by the other groups. The wiring layout for all the components was not yet determined by the subsystem groups and so a general mounting plate was designed that had sufficient room for wires to feed through on all four sides. If the subsystem components were already determined and fully defined, the mounting plates would then have been designed for optimal wire management and to minimize mass. This will have to be done in the next phase of the design process.

Testing Challenges

The CubeSat could not be tested with subsystem components since they were still being designed by the other Capstone groups. In the second year of this project, the subsystem groups will have their prototypes ready for testing and the integration into the CubeSat will begin. The final CubeSat assembly with all of the subsystem components will need to be tested before the CSA conducts their testing to validate the satellite for flight readiness.

The vibration testing of the prototype was the last step in the design process to be completed this year. If the prototype was built and ready earlier in the year, the group would have had more time to design and build a fixture that mimics the NRCD. Although the vibration testing of the prototype was considered a success, the fixture had lots of room for improvement. The fixture will have to be redesigned to mimic the NRCD mounting configuration. The faces along each side of the center rail and the end faces in the z-axis of the center rail are the only contact points that the CubeSat will make with the dispenser. Another possibility for testing is to contact NanoRack's and see if they can supply one of their dispensers. This would be the ideal scenario for vibration testing and would provide the most relevant data for analyzing the CubeSat's response.

Thermal vacuum testing of the CubeSat, including all of the subsystem components, will be necessary before the CubeSat is flight ready. Thermistors are to be placed onto each component to measure the heat of the CubeSat at different locations when subjected to a range of temperatures. The test would simulate the worst-case temperature scenarios in a space environment (no convection) and would identify any areas that are prone to overheating. In addition to thermal vacuum chamber testing with thermistors, the thermal imaging camera (FLIR) could also be used for analyzing the temperature distributions of the final CubeSat. The data collected from testing the CubeSat will be analyzed by all subsystems to ensure their components are functioning correctly.

Final Design Showcase

The Mechanical Engineering Design Showcase was held on March 23, 2018. Professors and Industry Professionals were invited to judge the Capstone projects of all 4th year mechanical engineering undergrads. Starting at 9:30am, tables were set up in the Amit Chakma Engineering Building (ACEB) for all prototypes and information booths that summarized the work done by students in the last 8 months.

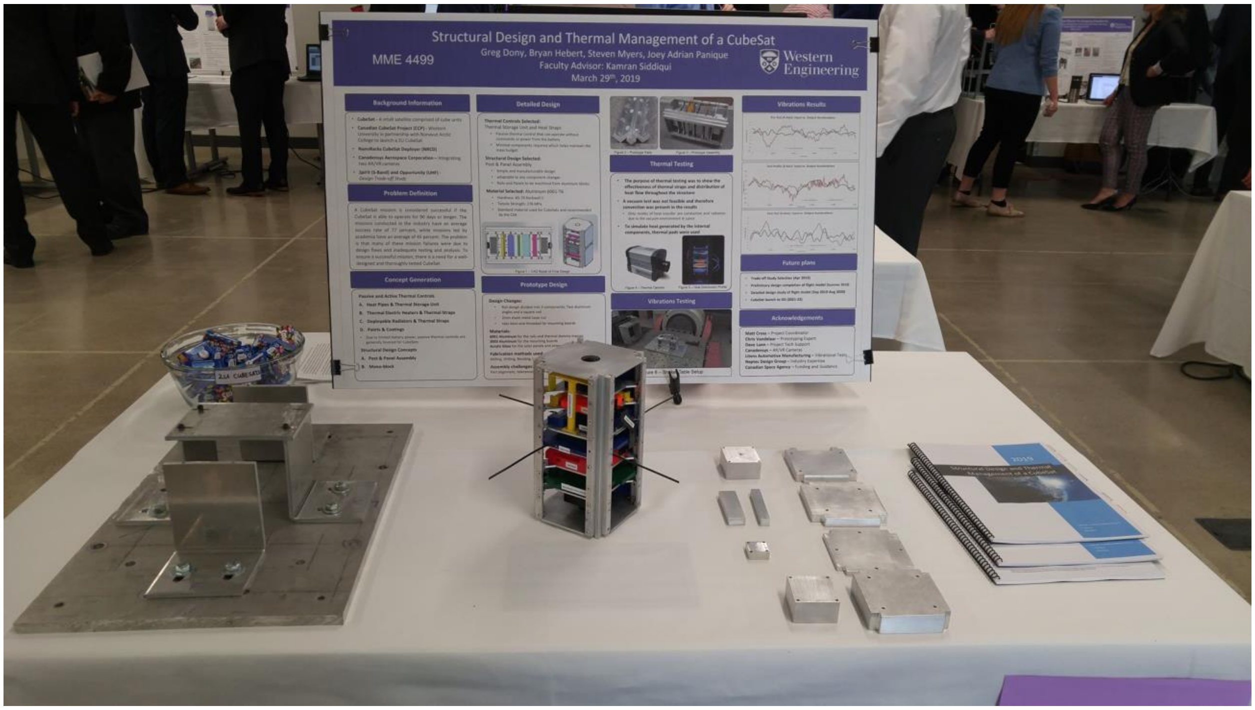

Figure 75- CubeSat Showcase Setup

The CubeSat Showcase consisted of the following components: The Prototype, Testing Fixture, Dummy masses, and Capstone Documentation booklets.

Prototype

The model on display consists of the prototype structure and components. As opposed to the dummy masses that were originally inside the CubeSat during testing, 3D printed parts with labels were installed to better illustrate the various subsystem components and how they would fit in the CubeSat. Transparent acrylic was originally intended for solar panels that would cover the CubeSat, but it was determined that the prototype looks better without them. Sheet metal antennas were glued to the antenna block to show how they would deploy.

Testing Fixture

The original testing fixture made for mounting the CubeSat to the shaker table at Litens was also put on display. The bolts were loosened so that it may move enough to show how the fixture would hold the CubeSats down. The original brackets used during testing are also on display to show the cracks and deformation that occurred during the vibration testing.

Dummy Masses

Dummy Masses were put on display for two reasons, as visual aids to show how the surface area of components was simulated during thermal testing, and to go over a discrepancy that occurred during the project. Thermal pads were also present to help during the thermal testing part of the presentation. The discrepancy regarding the dummy masses which were suitable for thermal testing, but too heavy to accurately portray components during vibration testing, had to be explained during the presentation in order to clarify why the CubeSat in the vibration test pictures did not have any components in it during testing.

Capstone Documentation Booklets

Due to the limited space on the Capstone poster, booklets were made to show additional documentation. Three booklets were made, two picture books and a copy of the NRCSD documentation. This was done so that the judges may view the source of the constraints from the NRCSD. The picture books contained concept generation techniques, relevant CAD models, and pictures of the manufacturing and testing done.

Showcase Judging Results

Overall feedback from the judges was positive. The two judges consisted of one assistant professor and one industry professional. The presentation covered the preliminary design process which included background information, the problem definition, concept generation and selection. A thorough review of the final design, prototype, prototype testing, and future was also covered. Once the presentation was complete, the judges asked the following questions:

Why were the bends of the mounting boards considered weaker/failure points on the structure?

Answer: The bends on the mounting boards were cold hardened during bending which made them harder but also produced some coining and made the bends more brittle which means they are more prone to fracture.

Was the fixture itself validated prior to vibration testing?

Answer: The fixture was made in order to be compatible with both CubeSats. Due to time and resource constraints the fixture was not validated by the CubeSat team. Instead, suggestions from Litens Automotive's engineers regarding the creation of a fixture was followed to ensure compatibility with their shaker table.

Can the data collected from testing be used later?

Answer: Yes, the data can be used for the next phase of the project, detailed design. With the rail design validated they can move forward with a similar structure. Data collected during the thermal and vibration testing can also be used as a base for more sophisticated forms of testing.

What are the next steps that could be taken regarding the thermal control?

Answer: The next steps are integrating a thermal control system with thermistors and a dedicated thermal plc, or integrating a thermal control system into the on-board data handling system.

Would you use white or black thermal coating to produce ideal emissivity?

Answer: The method that produces ideal emissivity is a combination and white and black thermal coatings inside and outside the CubeSat.

Have you considered doing a transient thermal analysis for the outer temperature?

Answer: A transient thermal analysis was attempted but lack of information regarding heat produced by the components made the analysis redundant.

Where is the control accelerometer during vibration testing?

Answer: Litens never specified where the control accelerometer was. It was assumed that it was inside the shaker generator itself, but the judge was not impressed with the answer.

Why did you choose Aluminum 6061 as the primary material?

Answer: Aluminum 6061 was strongly advised by CSA/NASA. The material met the required stiffness/weight ratio, conductivity, and other material qualities. It could also be hard anodized to meet NRCSD constraints. 6061 was both cheap and common in metal vendors which made it ideal for staying within the Capstone budget.

The critique and criticism from the judges revealed many areas where the project could improve, this information was noted and will be readily available for the next year's capstone team who oversees the CubeSat's detailed design.

What would you do differently should you start over again?

Stronger and well documented research literature

There were several times throughout the project where information was inconclusive and had to be reviewed and confirmed. If the project was repeated extra care must be taken to ensure that any specified data is recorded and firmly established to avoid confusion down the road.

Thorough and maintained plan of action, schedule, and timeline

Scheduling, planning, and a strategic timeline was not followed as best as the team could have throughout the project. The result was often rushed decisions and iterations that were made for the sake of time and a product as opposed to prioritizing design and engineering. If the project was repeated planning must be done and followed beforehand to ensure that time is spent effectively.

Team Design Sessions

The conceptual design process eventually leads to the creation of the detailed design, but it was not fully ratified by the team. If the project was repeated the whole team must be together when designing the CubeSat and everyone must have an input. The SolidWorks design was delegated to one member of the group and as a result the other members had limited knowledge of the design and depended on the one member to get everything right.

More Design and Prototype Time

The design and prototype has some glaring flaws in terms of heat strap placement, geometry, tolerances, and other details that affect the final product. These inconsistencies had to be addressed in detailed design phase, but due to time constraints, they were neglected instead. If the project was repeated more time must be made for the final design and prototype fabrication in order to ensure a quality finished product.

Better planning and test process

The test process was highly dependent on outside resources that the team could not control. This made producing test results difficult, and sometimes impossible, which led to certain tests like the thermal testing having to shrink its goals into more feasible forms of testing. If more time was invested in planning and calling for the test process, more valuable test methods could have been conceived and the data produced would've been more useful for future iterations.

Conclusion

Although this was just the first stage of a three-year project, the most important steps of research, planning and preliminary testing are vital for a project's success. While this project did offer some freedom of choice in the ability for design, many requirements and constraints were set in place by NanoRacks and CSA to ensure safety during launch, orbit and re-entry into the Earth's atmosphere. After an in-depth literature review of the requirements and constraints, as well as successful and unsuccessful past launches, many commonly used structural designs and thermal controls were noted and then turned into to an organizational chart to later assist in choosing our conceptual designs. A comprehensive analysis on each concept using a Go/No-Go screening and quality function deployment chart revealed feasible and non-feasible designs which resulted in our final design being a combination of parts from each concept. Finite element analysis through SolidWorks had its limitations for performing preliminary thermal tests but was found to be effective for vibrations testing on the structural aspect of the design. Although the thermal testing wasn't able to be achieved on SolidWorks, a thermal model was still accomplished to observe the CubeSat's equilibrium temperature during worst case hot and worst-case cold situations. With these findings the design was reiterated to perform better before moving on to prototype development.

Prototype assembly presented its own problems due to machining parts without any 3D printing. While this did aid in a learning experience it resulted in a few minor design changes. Ideal thermal testing on the prototype wasn't able to be achieved due to not having access to a vacuum chamber. This resulted in convection being present in our thermal tests which greatly affected the results. Because of this, the thermal tests were primarily to observe the temperature distribution throughout the CubeSat's structure and the effectiveness of the thermal straps. It was found the thermal straps were effective in transferring heat from the internal components to then radiate out in space. The vibrations testing was also found to be successful with the CubeSat surviving random vibrations throughout the entire frequency range that it would experience during launch. The desired results were achieved as accurate as possible with the testing equipment available and although this is still the first of three stages, it lays down a solid foundation in which the latter stages can expand upon and perform further testing.

Cumulative References

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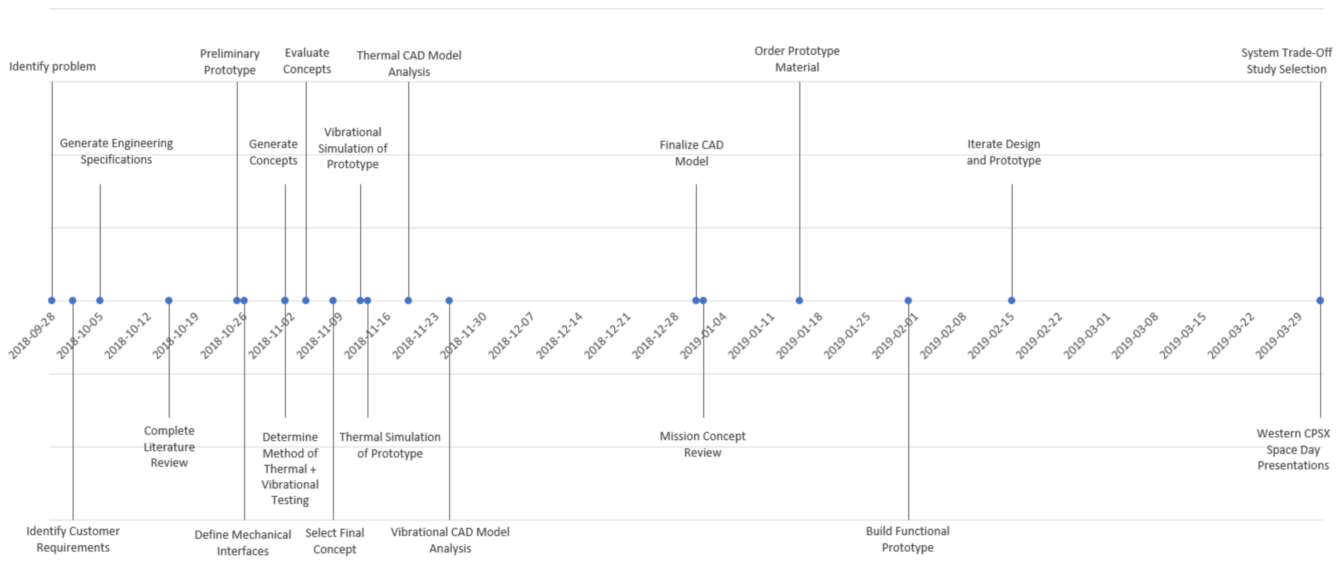
Appendix A – Specification Design

A-1: Canadian CubeSat Project Design Specification

Sent to Project Advisor as a separate attachment.

A-2: Project Timeline



A-3: Previous CubeSat Mission Details

Mission name	Organisation	Nation	Type (U/mass)	Launch date	Mission description	Photo
Ex-Alta 1 (Experimental Albertan #1, EXALTA-1, CA03)	University of Alberta	Canada	3U	2017-04-18	Serve as a platform for the In Orbit Demonstration (IOD) of a digital fluxgate magnetometer designed at the University of Alberta. Address multi-point space plasma physics with data from the QB50 constellation using the Langmuir probe common payloads and the digital fluxgate magnetometer. Promote education of space science and engineering through all levels of the educational sector of Alberta. Provide a foundation on which to begin a space engineering, space science and/or cube satellite program at the University of Alberta. Promote the development of an Albertan commercial space industry and augmentation of current staple industries with space technology. The QB50 multi-Needle Langmuir Probe (mNLP) experiment will study variations in ion densities. These measurements can be used to better quantify how the Earth's atmosphere expands and contracts into low Earth orbit. Will also enable the collection of information to study the effects of re-entry. A Digital Fluxgate Magnetometer (DFGM) developed will be deployed at the end of a 60 cm boom and will study the Earth's magnetic field in low Earth orbit. Finally, a radiation dosimeter will measure variation in radiation levels thus giving insight into average electron and proton flux during the mission. Include the Athena on-board computer. This on-board computer for cube satellites is a fully open source system designed and built by senior undergraduate students at the University of Alberta. It will be tested and qualified on the Ex-Alta 1 mission.	
SwissCube	Swiss Federal Institute of Technology (EPFL)	Switzerland	1U	2009-09-23	The main objective is educational and to show the students how to build a complex engineering system from A to Z like a satellite. Carries a small telescope which will allow to obtain images of the nightglow, a luminescence phenomena occurring at 100 km of height above the Earth surface. Since the nightglow takes place in a very limited region in the high layer of the atmosphere and at well-know locations, it might be possible from the measurements to retrieve the direction towards the centre of the Earth and therefore enabling the design of a new generation of Earth sensor.	

Appendix B – Concept Design

B-1: Quality Functional Deployment (QFD)

CubeSat "OPPORTUNITY"

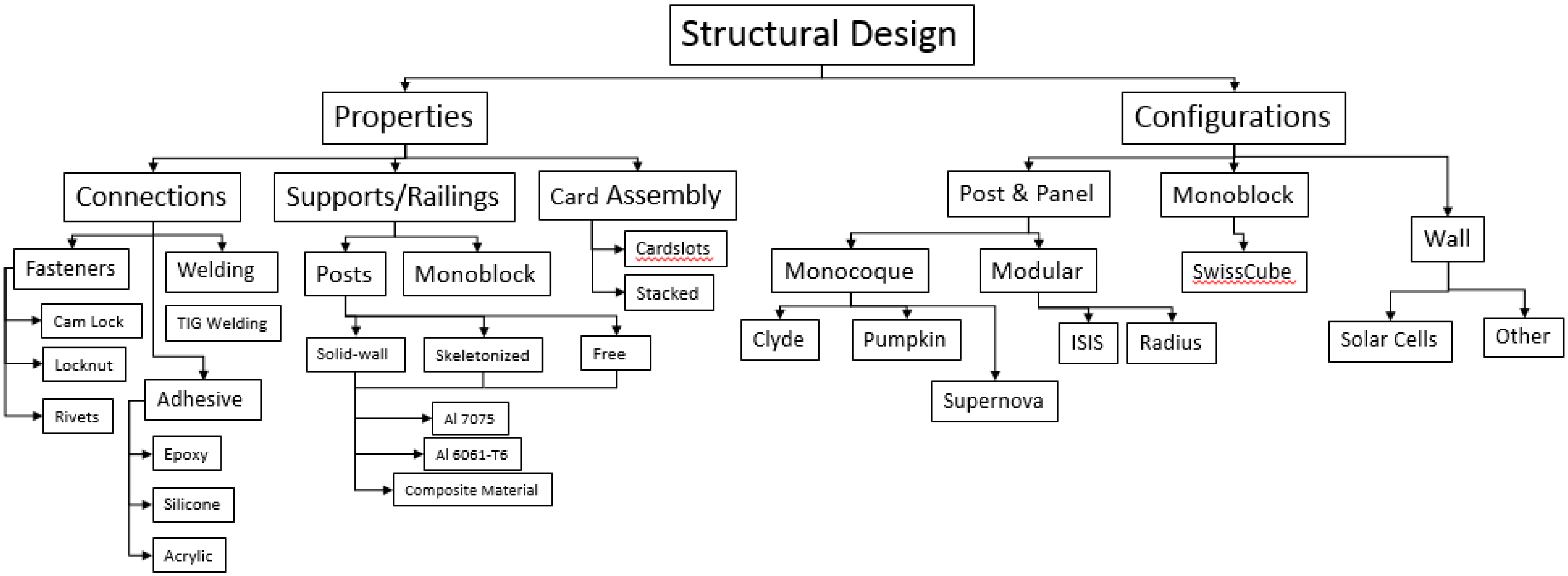
	Mass (Kg)	Volume (m^3)	Mechanical Properties	Thermal Properties	Rotational Speed (RPM/Axis)	Coefficient of Static Friction
Mass (Kg)						
Volume (m^3)	7					
Mechanical Properties	8	3				
Thermal Properties	4	7	4			
Rotational Speed (RPM)	3	4	2	1		
Coefficient of Static Friction	1	2	8	2	6	
Cost	7	8	7	8	1	3

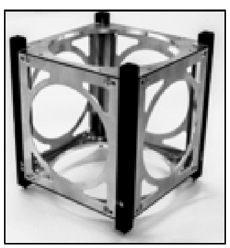
	Weight / Importance	Mass (Kg)	Volume (m^3)	Mechanical Properties	Thermal Properties	Rotational Speed (RPM/Axis)	Coefficient of Static Friction	Cost	Ex-Alta 1	SwissCube
Thermally Regulated	5	1	2	1	9	1	2	8	5	5
Can withstand strong vibrations	4	2	1	7	1	1	2	5	4	5
Structurally Reliable	5	5	2	8	2	6	2	7	4	5
Environmentally Friendly	2	1	1	5	7	1	1	5	4	3
NRCSD Compatibile	5	9	9	7	2	2	9	1	5	N/A
Easily Manufacturable	2	1	3	7	4	1	3	9	4	3
Easy to Handle	3	4	4	2	3	2	2	5	4	3
Payload Integration	4	7	7	4	7	2	1	3	4	4
Absolute Importance	839	127	117	154	128	67	91	155	130	82
Relative Importance	100%	15%	14%	18%	15%	8%	11%	18%		
Units		Kg	m^3	-	-	RPM / Axis	-	$		
Ex-Alta 1		4.00	3.40E-03	variable	variable	0.83	variable	N/A		
SwissCube		1.00	1.10E-03	variable	variable	2.70	variable	N/A		
Our Targets		3.60	2.27e-3	variable	variable	0.83	variable	<$30,000		

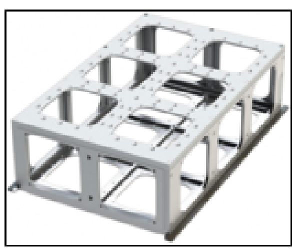
Thermal Properties
-Absorptivity (m^2/mol)
-Reflectivity (%)
-Emissivity (ε)
-Heat Flux ($W.m^{-2}$)
-Thermal Conductivity λ (W/m.K)
-Thermal Expansion Coefficient α (10^{-6} / C)
Mechanical Properties
-Yield Strength (MPa)
-Tensile Strength (MPa)
-Youngs Modulus (GPa)
-Shear Modulus (GPa)
-Hardness (Rockwell C)
-Fatigue Strength
at 10^7 cycles (MPa)

B-2: Functional Decomposition and Morphological Analysis

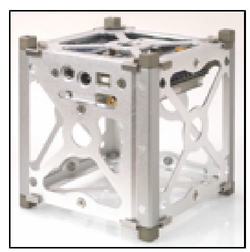
B-2.1 - Structural

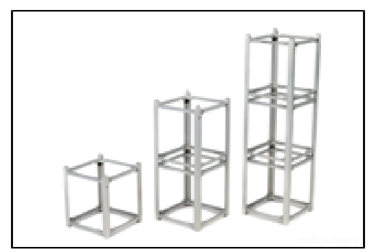



Clyde


Supernova

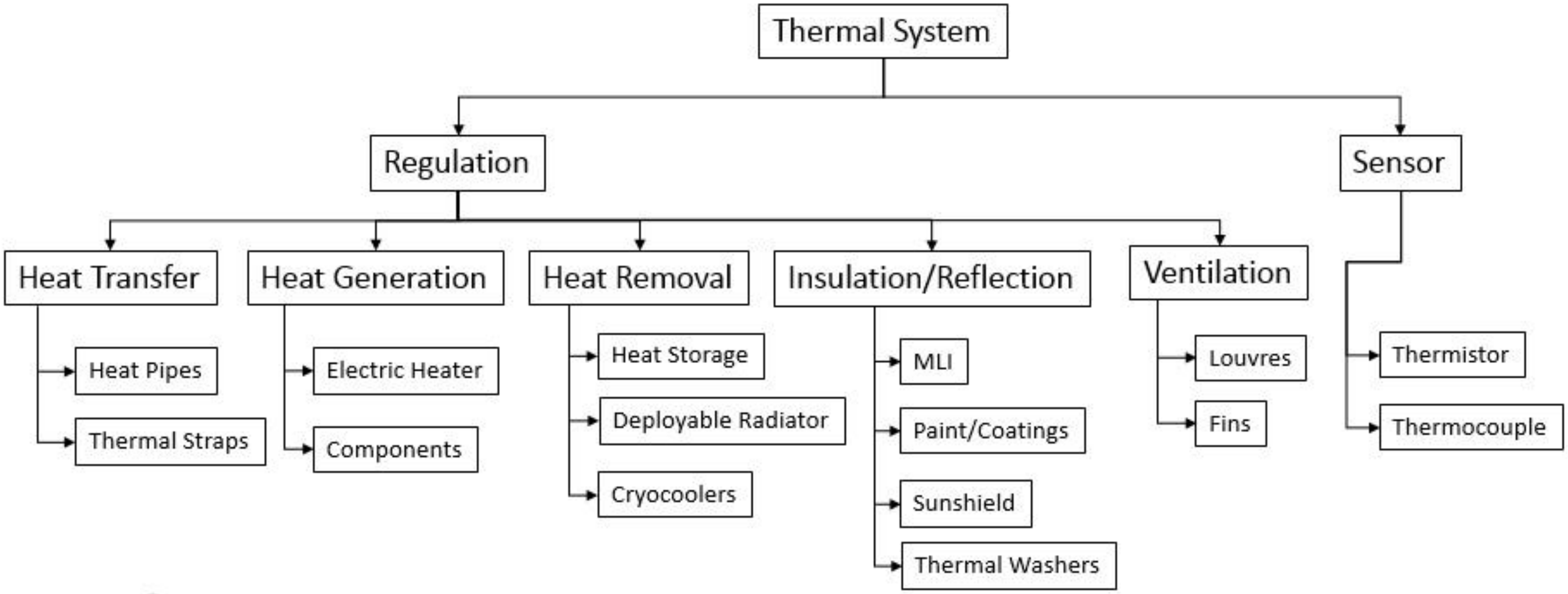

ISIS


Pumpkin

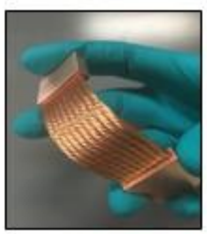

Radius


SwissCube

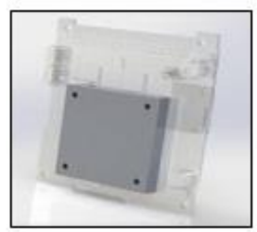
B-2.2: Thermal



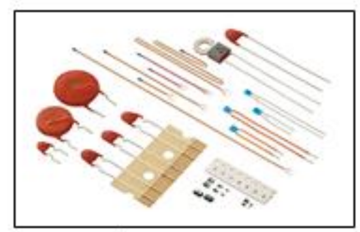

Heat Pipes


Heat Straps


Electric Heater

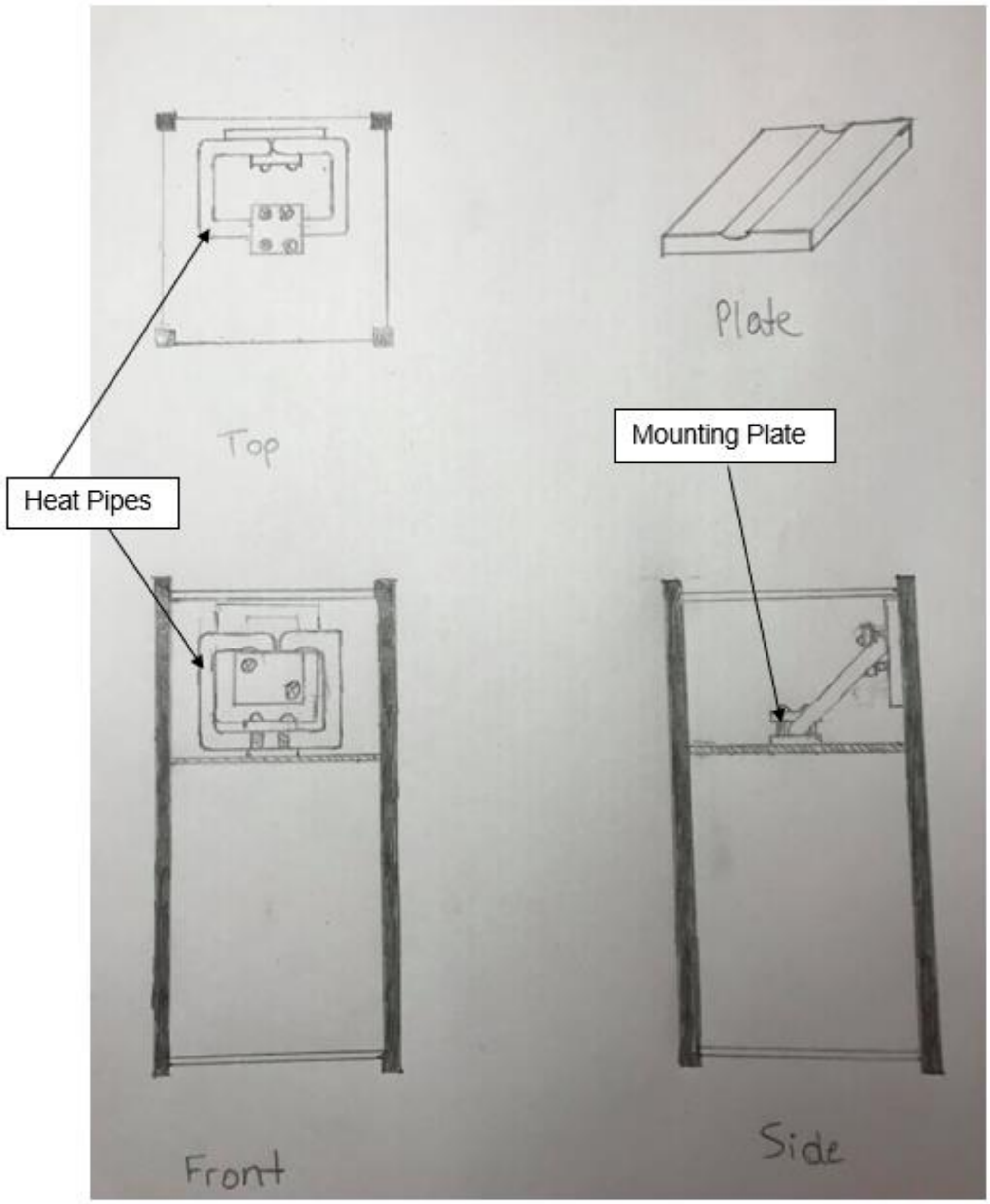

Heat Storage


Sunshield

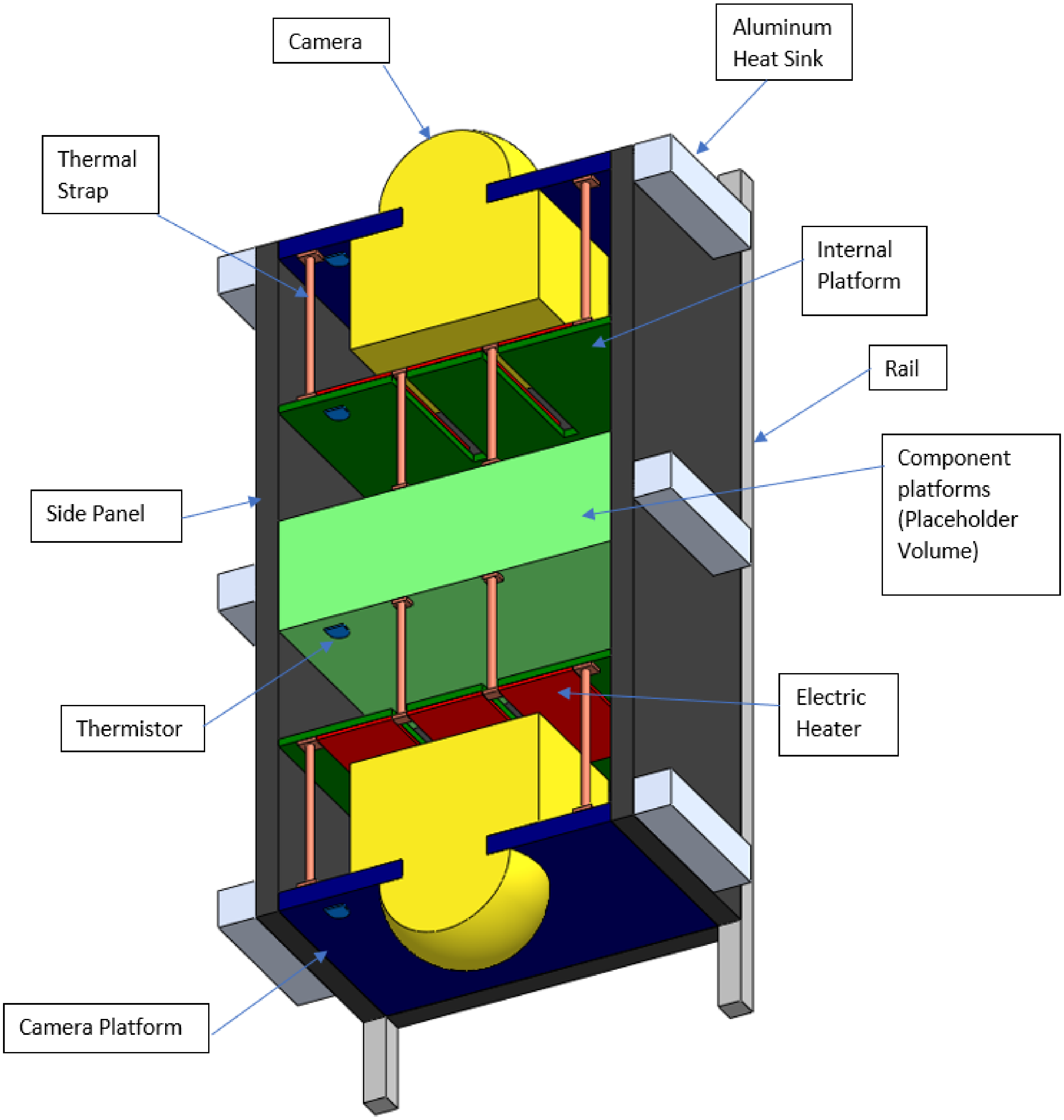

Thermisters

B-3: Conceptual Design Models

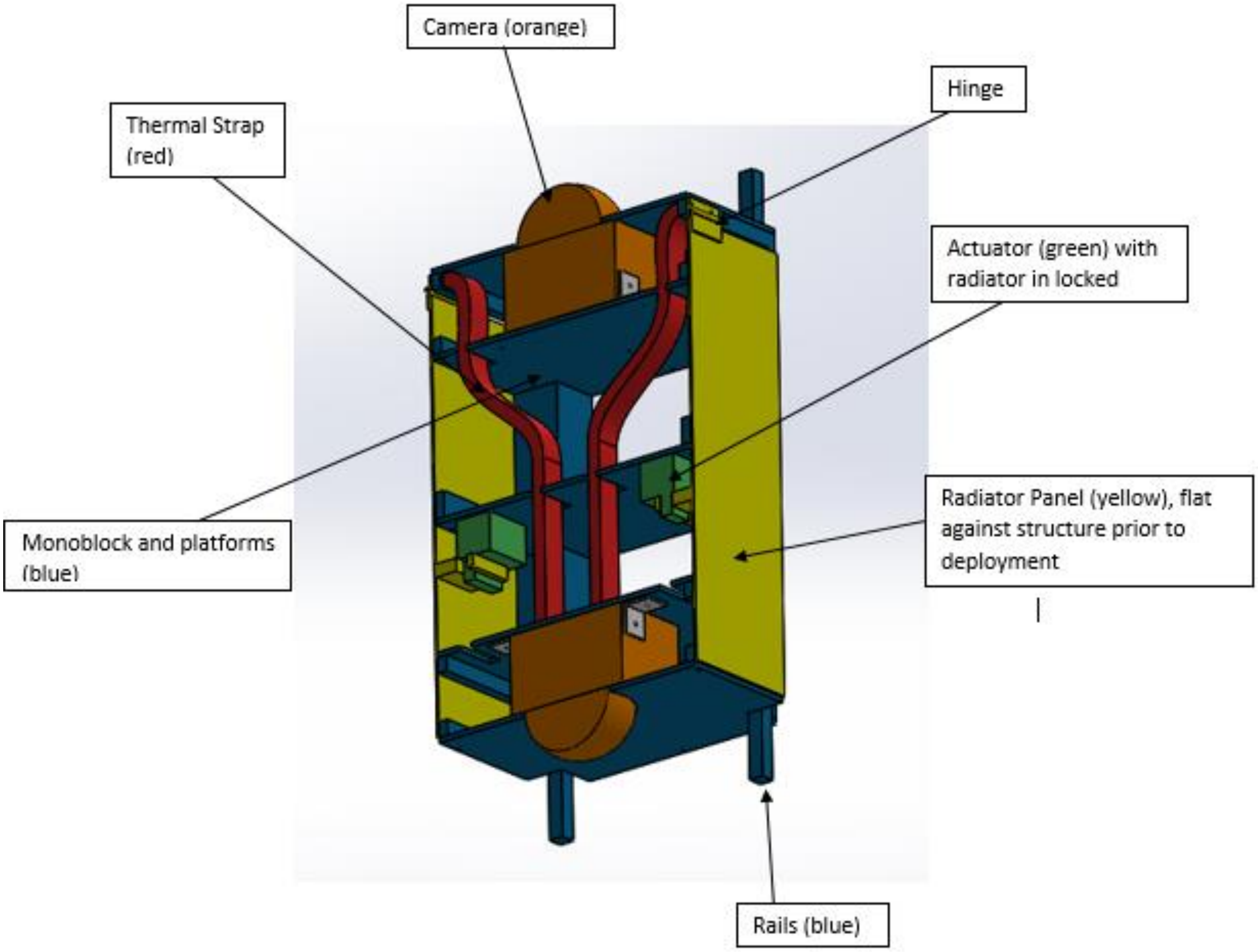
B-3.1: Concept A – Heat Pipes + Thermal Storage Unit



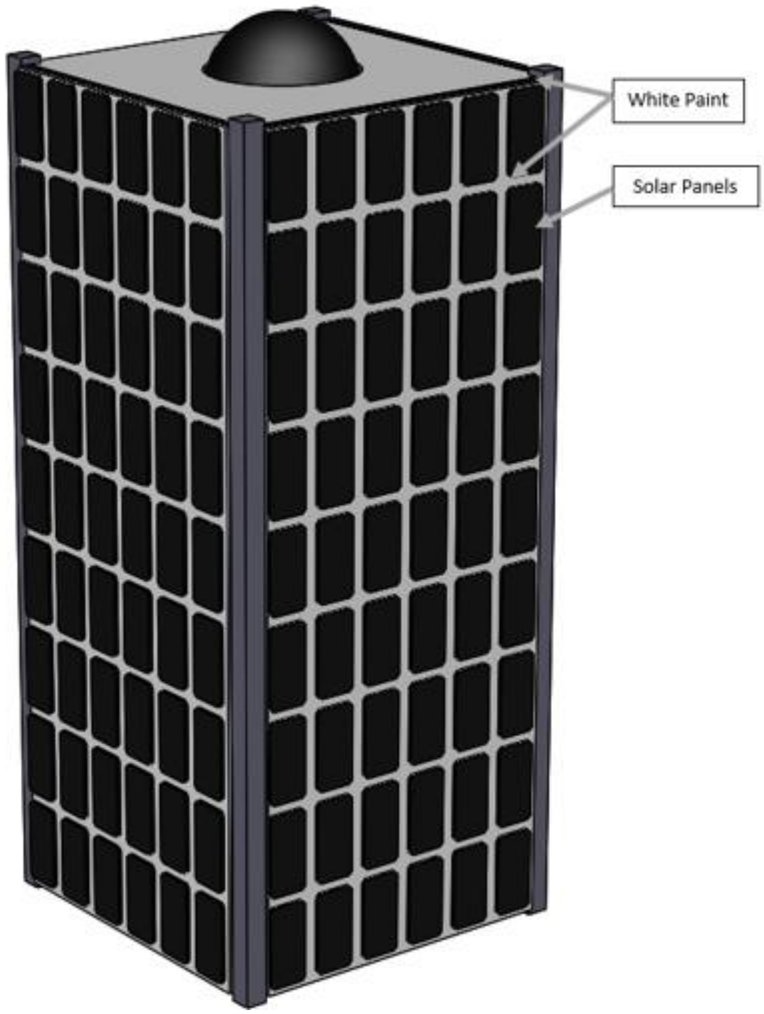
B-3.2: Concept B – Thermal Electric Heaters + Thermal Straps (Section View)



B-3.3: Concept C – Deployable Radiators + Thermal Straps (Section View)



B-3.4: Concept D – Paints + Coatings



B-4: Material Thermal Conductivity and Expansion Tables

Table A.7 Thermal Conductivity, λ, and Thermal Expansion, α

	λ (W/m.K)	α (10^{-6}/C)
Metal		
Ferrous		
Cast irons	29–44	10–12.5
High carbon steels	47–53	11–13.5
Medium carbon steels	45–55	10–14
Low carbon steels	49–54	11.5–13
Low alloy steels	34–55	10.5–13.5
Stainless steels	11–19	13–20
Nonferrous		
Aluminum alloys	76–235	21–24
Copper alloys	160–390	16.9–18
Lead alloys	22–36	18–32
Magnesium alloys	50–156	24.6–28
Nickel alloys	67–91	12–13.5
Titanium alloys	5–12	7.9–11
Tungsten alloys	100–142	4–5.6
Zinc alloys	100–135	23–28
Ceramic		
Glass		
Borosilicate glass	1–1.3	3.2–4.0
Glass ceramic	1.3–2.5	1–5
Silica glass	1.4–1.5	0.55–0.75
Soda-lime glass	0.7–1.3	9.1–9.5
Porous		
Brick	0.46–0.73	5–8
Concrete, typical	0.8–2.4	6–13
Stone	5.4–6.0	3.7–6.3
Technical		
Alumina	30–38.5	7–10.9
Aluminum nitride	80–200	4.9–6.2
Boron carbide	40–90	3.2–3.4
Silicon	140–150	2.2–2.7
Silicon carbide	115–200	4.0–5.1
Silicon nitride	22–30	3.2–3.6
Tungsten carbide	55–88	5.2–7.1
Composite		
Metal		
Aluminum/silicon carbide	180–160	15–23
Polymer		
CFRP	1.28–2.6	1–4
GFRP	0.4–0.55	8.6–33

B-5: Material Heat Capacity Table

Table A.8 Heat Capacity, C_p

	C_p (J/kg.K)
Metal	
Ferrous	
Cast irons	439–495
High carbon steels	440–510
Medium carbon steels	440–510
Low carbon steels	460–505
Low alloy steels	410–530
Stainless steels	450–530
Nonferrous	
Aluminum alloys	857–990
Copper alloys	372–388
Lead alloys	122–145
Magnesium alloys	955–1060
Nickel alloys	452–460
Titanium alloys	520–600
Zinc alloys	405–535
Ceramic	
Glass	
Borosilicate glass	760–800
Glass ceramic	600–900
Silica glass	680–730
Soda-lime glass	850–950
Porous	
Brick	750–850
Concrete, typical	835–1050
Stone	840–920
Technical	
Alumina	790–820
Aluminum nitride	780–820
Boron carbide	840–1290
Silicon	668–715
Silicon carbide	663–800
Silicon nitride	670–800
Tungsten carbide	184–292
Composite	
Metal	
Aluminum/silicon carbide	800–900
Polymer	
CFRP	900–1040
GFRP	1000–1200

B-6: Thermal Electric Heater Properties

Characteristics	NEW High Temp Polyimide
Size Range	Less than 1/2" sq. to 16" X 6+ ft
Temperature Range*	Up to 250C (482F)
Resistance Range	Up to 250 ohms per square inch
Metal Thickness Range	.0005" – 0.0023"
Total Thickness Range	.0035" – 0.010"
Insulation Resistance	5000-6000 V/mil
Example Power Densities	.1 W/in2 to 60 W/in2
Resistance Tolerance	+/- 10%
Standard Coverlay Thickness	.001", .0015, .002, .003
Leads (if required)	Length/AWG/Coating Options
Minimum Bend Radius**	.030"
General Chemical Resistivity	Best
Out gassing / Aerospace	Good
Edge Insulation	.030"
Bond/Peel Strength (to flat plate using PSA)***	101 oz/inch

B-7: Go/No-Go Screening

GO/NOGO TABLE	Concept A Heat Pipes + Storage Unit	Concept B Electric Heaters + Thermal Straps	Concept C Deployable Radiators + Thermal Straps	Concept D Painting + Coatings
Thermally Regulated	G	G	NG	G
Can withstand strong vibrations	G	G	G	G
Structurally Reliable	G	G	NG	G
Conforms to NRCSD	G	G	NG	G
Environmentally Friendly	G	G	G	G
Manufacturable	G	G	G	G
Payload Integration	G	G	G	G
Easy to handle	G	G	G	G

B-8: Decision Matrix

CUBESAT DECISION MATRIX														
	Thermally Regulated	Can Withstand strong Vibrations	Structurally Reliable	Conforms to NRCSD	Environmentally Friendly	Easy to Manufacture	Payload Integration	Easy to handle (ergonomics)	Total	Weighted Value		Concept A	Concept B	Concept D
Thermally Regulated	1.00	3.00	0.50	0.25	7.00	0.33	0.50	6	18.58	0.13801		0	1	0
Can withstand strong vibrations	0.33	1.00	1	0.33	7	0.50	4.00	5.00	19.17	0.14234		1	1	1
Structurally Reliable	2.00	1.00	1.00	0.50	7.00	0.50	5.00	6.00	23.00	0.17081		1	1	1
Conforms to NRCSD	4.00	3.00	2.00	1.00	6.00	6.00	8.00	4.00	34.00	0.2525		1	1	1
Environmentally Friendly	0.14	0.14	0.14	0.17	1.00	0.25	0.20	0.33	2.38	0.01766		0	1	1
Easy to manufacture	3.00	2.00	2.00	0.17	4.00	1.00	0.50	3.00	15.67	0.11635		1	1	0
Payload Integration	2.00	0.25	0.20	0.13	5.00	2.00	1.00	6.00	16.58	0.12309		0	0	0
Easy to handle (ergonomics)	0.17	0.20	0.17	0.25	3.00	0.33	0.17	1.00	5.28	0.03924		1	1	1
							Total:		134.65	1	Total:	**0.72123**	**0.87691**	**0.62255**

B-9: FMEA

FAILURE MODE AND EFFECTS ANALYSIS

Item: CubeSat
Model: Current
FMEA Date : 2018-11-12 Rev: 1

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Action Results: Sev	Action Results: Occ	Action Results: Det	Action Results: RPN
Control Temperatures within Operating Range	Too Hot	Overheat electrical components / Payload past survival temp.	8	Y	Lack of cooling	3	Thermisistors	6	144	Thermal Storage Unit + Thermal Straps / Exterior White Paint	Test thermal devices in vacuum 2018-01-01					0
	Too Cold	Freeze electrical components / Payload past survival temp.	8	Y	Lack of heating	3	Thermisistors	6	144	Thermal Storage Unit + Thermal Straps / Electrical Heaters	Test thermal devices in vacuum 2018-01-01					0
Provide Structure to CubeSat	Structure breaks	Vibrations / Accelerational Loads	9		Poorly Assembled	1	Post and panel with nuts and bolts	1	9	Apply adhesives to final assembly	Test structure on vibration table 2018-01-01					0

Sev: Severity
Occur: Occurrence
Detec: Detection
RPN: Risk Priority Number

Appendix C – Detailed Design

C-1: Part Drawings

Due to the volume, size and detail of the drawings, they will be submitted separately to Group 46 faculty Advisor Dr. Siddiqui as PDF's.

16 PDF documents will be submitted as a .zip via email to Dr. Siddiqui.

Drawing List:

OPP-STRU-001
OPP-STRU-002
OPP-STRU-003A
OPP-STRU-003B
OPP-STRU-004
OPP-STRU-005
OPP-STRU-006
OPP-STRU-007
OPP-STRU-008
OPP-STRU-009
OPP-STRU-010
OPP-STRU-011
OPP-STRU-012
OPP-STRU-013
OPP-EPS-002

C-2: Assembly Drawings and BOM

This document will be included as one of the 16 PDF documents mentioned in Appendix C-1. It will be sent in the .zip via email to Dr. Siddiqui.

Drawing: OPPORTUNITY ASSEMBLY DRAWING

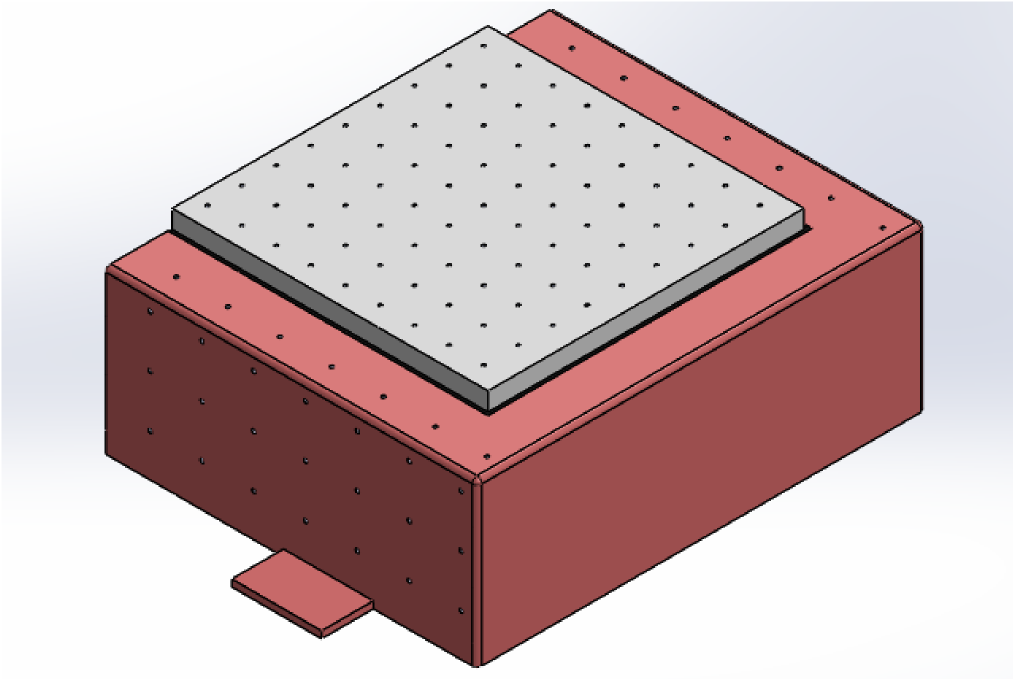
C-3: Design for Manufacturing (DFM) Table

Part Name	Material	Manufacturing Method	Comments on DFM
Rails	Aluminum Alloy 6061-T6	CNC Mill	- aluminum blocks are cut to the box dimensions of the rails - blocks milled for high dimensional accuracy -holes pre-drilled and countersunk from the outside -holes will be tapped to a M3 thread size -sent out for hard coat anodizing (surface hardness between Rockwell 65-70C)
Top Camera Plate Bottom Camera Plate XY-Magnetorquer Plate Z-Magnetorquer Bracket Transceiver Plate Gyroscope Bracket Antenna Plate Battery Plate OBDH Plate	Aluminum Alloy 6061-T6	Water Jet Cutter, Sheet Metal Bender	-3mm thick aluminum sheets will be cut to each unique shape -holes will be drilled to a 3mm diameter -corner tabs for mounting will be bent at a 90° angle to ensure the rails are perpendicular

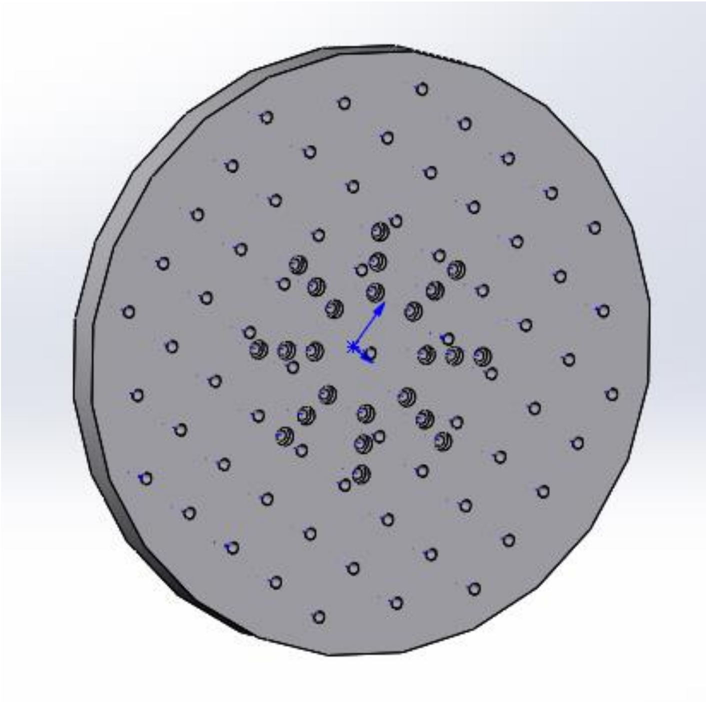
Cover Plate Antenna Slot Bracket	Aluminum Alloy 6061-T6	Water Jet Cutter, Sheet Metal Bender	-3mm thick aluminum sheets will be cut to each unique shape -holes will be drilled to a 3mm diameter -corner tabs for mounting will be bent at a 90° angle to ensure the rails are perpendicular -parts will be painted black on outer surfaces

Appendix D – Prototype Design

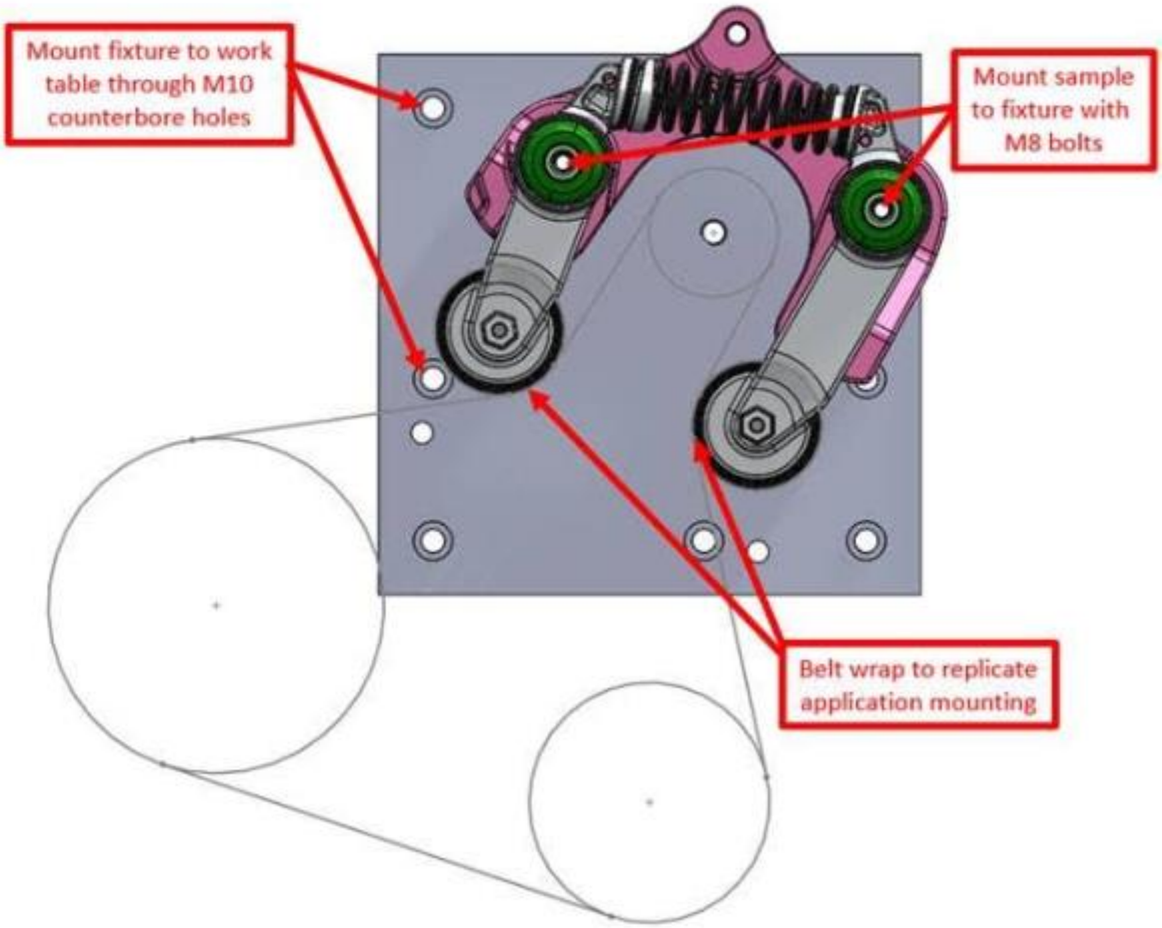
D-1: Shaker Table CAD (Primary Slip Table)



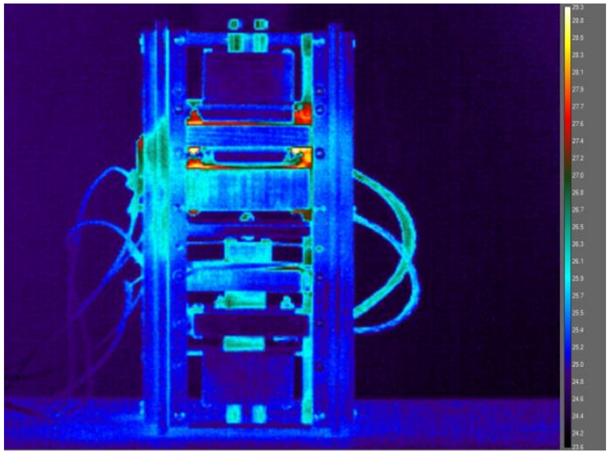
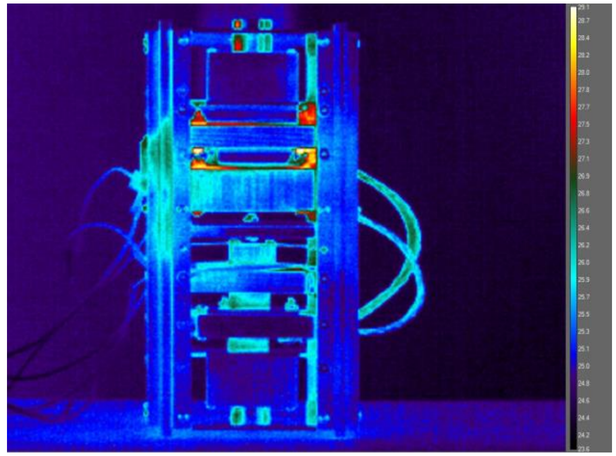
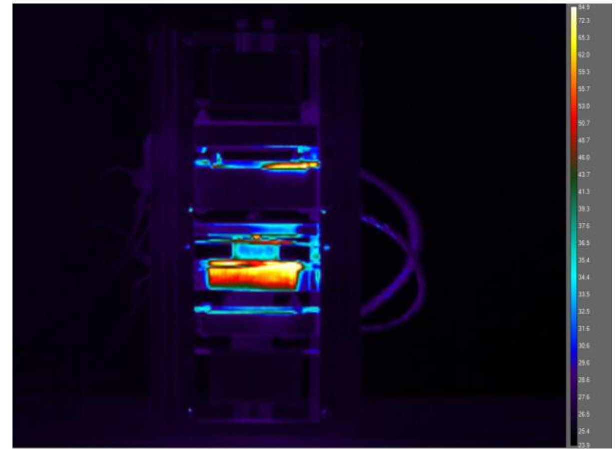
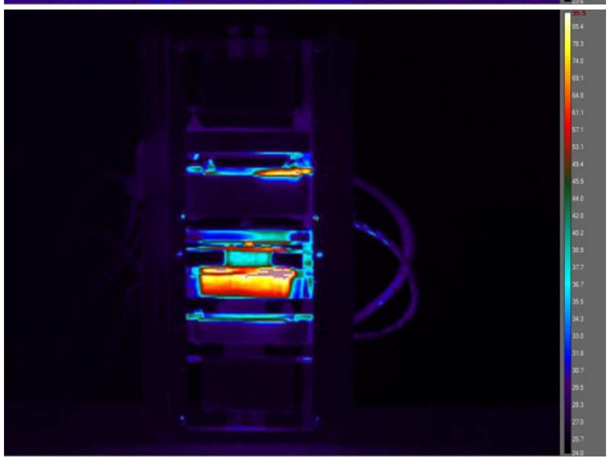
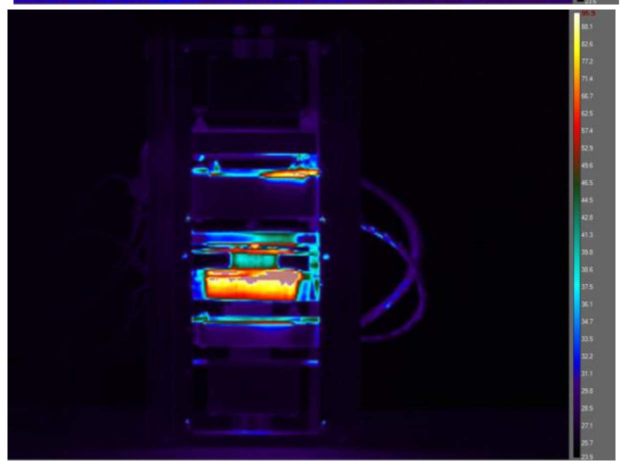
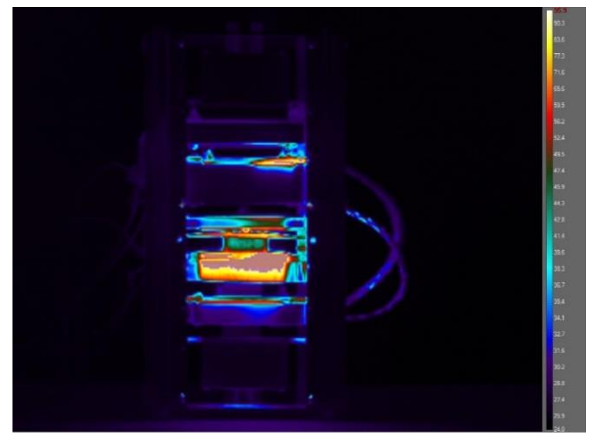
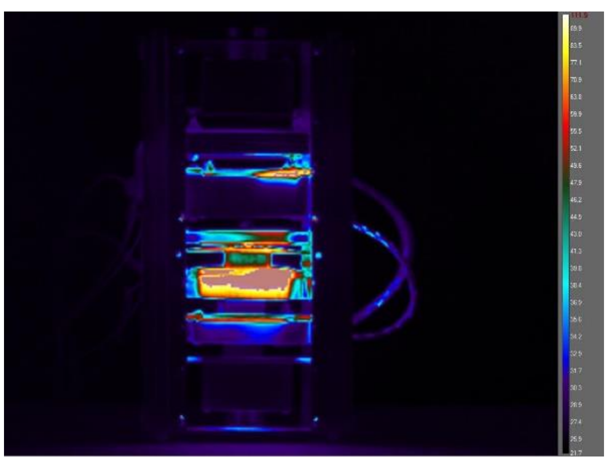
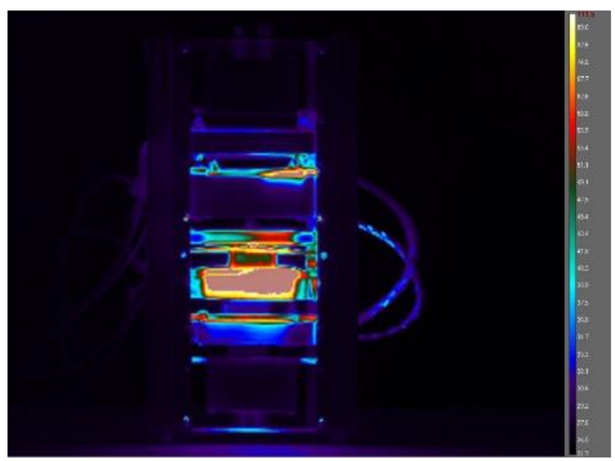
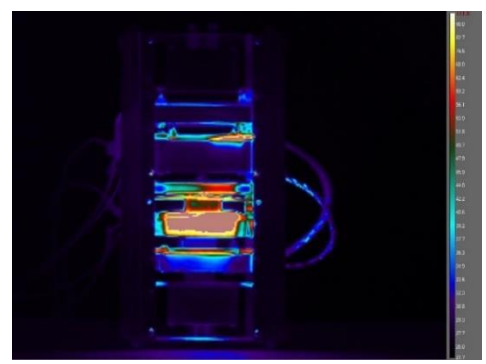
D-2: Shaker Table CAD (Alternative Slip Table top)



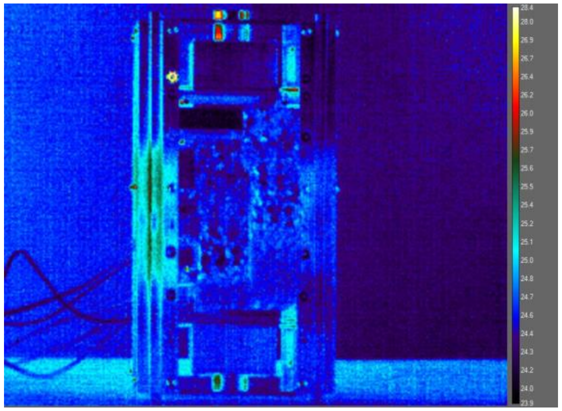
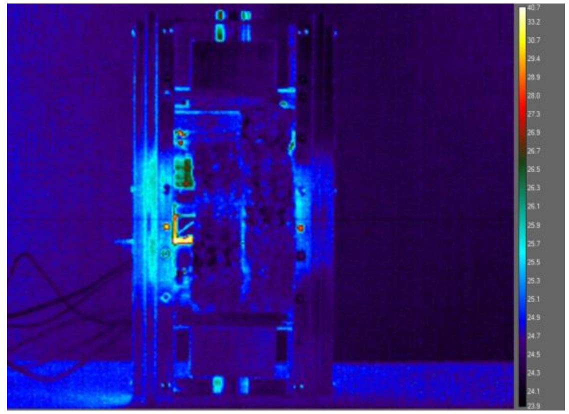
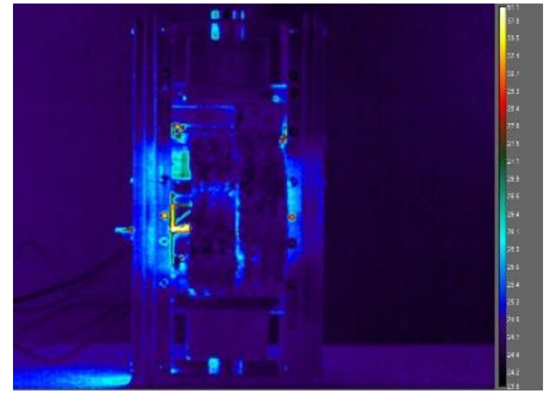
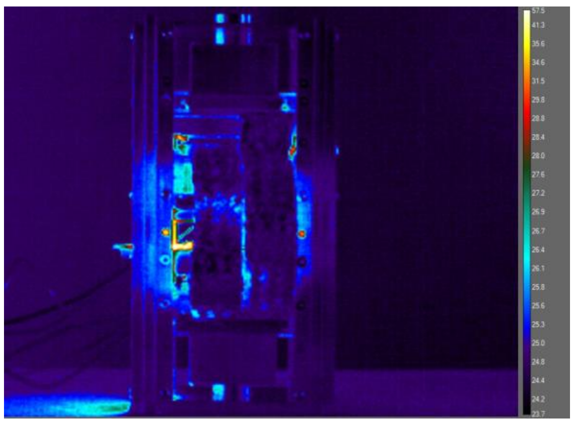
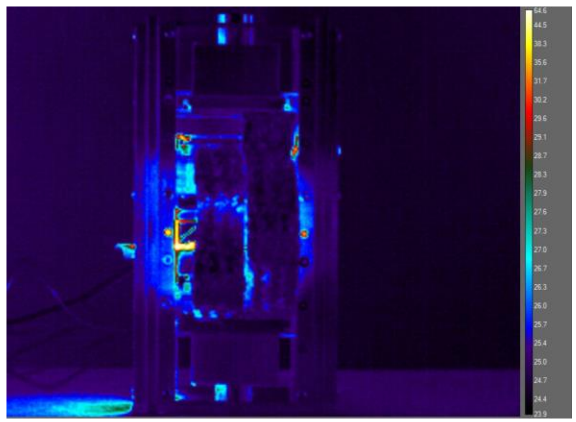
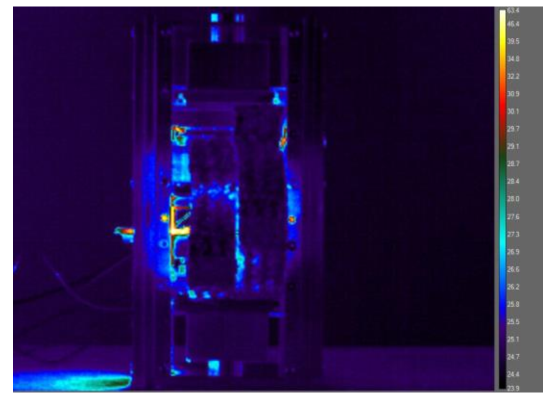
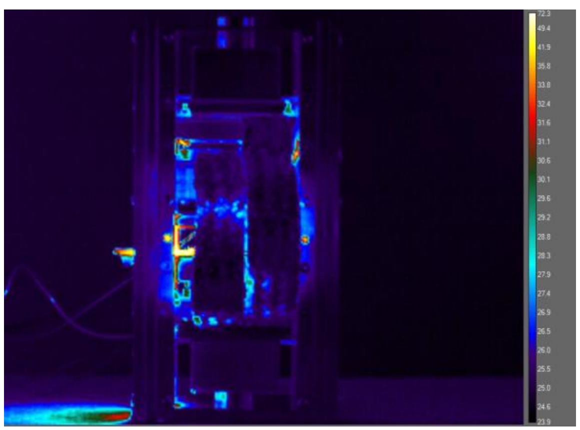
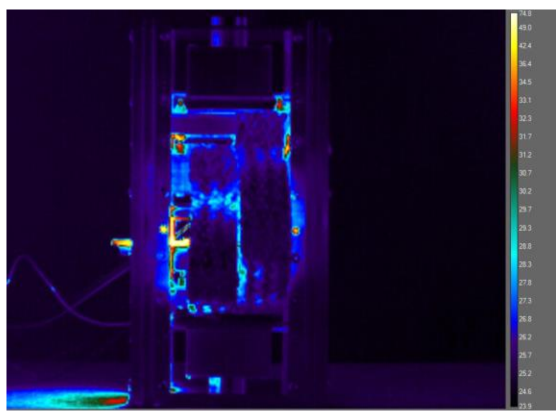
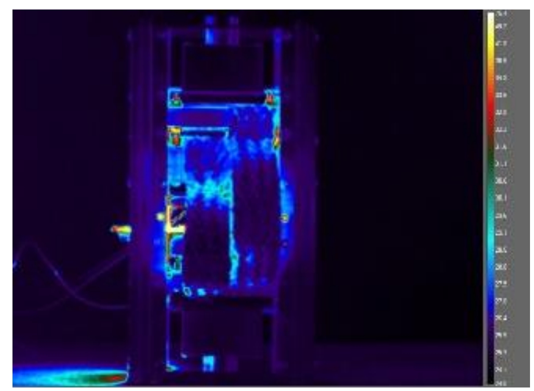
D-3: Shaker Table Sample Fixture



D-4.1: Thermal Testing Results Orientation I

D-4.2: Thermal Testing Results Orientation II

D-5: Quotes

D-5.1: Metal Super Market – Approved & Purchased

The Convenience Stores For Metal™

Page 1 of 3

CUSTOMER QUOTE # 1064587

This is not an ORDER or INVOICE

Bill to UNIVERSITY OF WESTERN ONTARIO 1151 Richmond St. Efs Stores, Teb 40, Dock 59 London, ON N6A 5BA Phone: (519) 661-4276 Fax: (519) 661-3066 **Attention: Attn. Paul Sheller** Contact Phone:	**2257076 Ontario Inc., an independent franchisee dba METAL SUPERMARKETS LONDON** 2100 Oxford Street E., Unit 33 London, ON N5V 4A4 Phone: (519) 659-1212 Fax: (519) 659-1213 E-Mail: london@metalsupermarkets.com Store #: KCL-SO
Ship to UNIVERSITY OF WESTERN ONTARIO 1151 Richmond St. Efs Stores, Teb 40, Dock 59 London, ON N6A 5BA Email: apinvoice@uwo.ca **Attention: Accounts Payable 519-661-2111 X 83024** Contact Phone: (519) 661-2111	Customer Purchase Order # Valid Until: Feb-15-2019 Date: Feb-13-2019 Terms: Net 30 Days Promise Date: Feb-13-2019 Delivery Method: Pickup Customer Rep: Pete Hanvey

Product		Qty	Length	Unit	Unit Price	Dimension	Total
AR6061T6/1	Aluminum Round Bar 6061T6511 1.000						
		2	0.6875	IN	1.71636	2 @ 0.6875 IN	2.36
AF6061/5004	Aluminum Flat Bar 6061T6511 0.500 X 4.000						
		1	4	IN	1.83733	1 @ 4 IN	7.35
		1	3.5	IN	1.83733	1 @ 3.5 IN	6.43
AF6061/500750	Aluminum Flat Bar 6061T6511 0.500 X 0.750						
		1	2.75	IN	0.76364	1 @ 2.75 IN	2.10
AF6061/2504	Aluminum Flat Bar 6061T6511 0.250 X 4.000						
		1	4	IN	1.41250	1 @ 4 IN	5.65
ASQ6061/2	Aluminum Square Bar 6061T6511 2.000						
		2	1	IN	5.08000	2 @ 1 IN	10.16
ASQ6061/1	Aluminum Square Bar 6061T6511 1.000						
		1	0.375	IN	4.16000	1 @ 0.375 IN	1.56
AF6061/3752500	Aluminum Flat Bar 6061T6511 0.375 X 2.500						
		1	2.25	IN	1.43556	1 @ 2.25 IN	3.23

CUSTOMER QUOTE # 1064587

This is not an ORDER or INVOICE

Bill to
UNIVERSITY OF WESTERN ONTARIO
1151 Richmond St.
Efs Stores, Teb 40, Dock 59
London, ON N6A 5BA
Phone: (519) 661-4276 Fax: (519) 661-3066

Attention: Attn. Paul Sheller
Contact Phone:

2257076 Ontario Inc., an independent franchisee dba METAL SUPERMARKETS LONDON

2100 Oxford Street E., Unit 33
London, ON N5V 4A4
Phone: (519) 659-1212 Fax: (519) 659-1213
E-Mail: london@metalsupermarkets.com
Store #: KCL-SO

Ship to
UNIVERSITY OF WESTERN ONTARIO
1151 Richmond St.
Efs Stores, Teb 40, Dock 59
London, ON N6A 5BA
Email: apinvoice@uwo.ca
Attention: Accounts Payable 519-661-2111 X 83024
Contact Phone: (519) 661-2111

Customer Purchase Order #
Valid Until: Feb-15-2019
Date: Feb-13-2019
Terms: Net 30 Days
Promise Date: Feb-13-2019
Delivery Method: Pickup
Customer Rep: Pete Hanvey

Product		Qty	Length	Unit	Unit Price	Dimension	Total
ASQ6061/500	Aluminum Square Bar 6061T6511 0.500						
		2	3.188	IN	0.43287	2 @ 3.188 IN	2.76
ASQ6061/4	Aluminum Square Bar 6061T6511 4.000						
		1	0.875	IN	17.46286	1 @ 0.875 IN	15.28
ASQ6061/250	Aluminum Square Bar 6061T6511 0.250						
		1	40	IN	0.09825	1 @ 40 IN	3.93
AA6063/750750125	Aluminum Angle 6063T5 0.750 X 0.750 X 0.125						
		2	40	IN	0.18988	2 @ 40 IN	15.19

CUSTOMER QUOTE # 1064587

This is not an ORDER or INVOICE

Bill to	2257076 Ontario Inc., an independent franchisee dba METAL SUPERMARKETS LONDON
UNIVERSITY OF WESTERN ONTARIO 1151 Richmond St. Efs Stores, Teb 40, Dock 59 London, ON N6A 5BA Phone: (519) 661-4276 Fax: (519) 661-3066 **Attention: Attn. Paul Sheller** Contact Phone:	2100 Oxford Street E., Unit 33 London, ON N5V 4A4 Phone: (519) 659-1212 Fax: (519) 659-1213 E-Mail: london@metalsupermarkets.com Store #: KCL-SO
Ship to UNIVERSITY OF WESTERN ONTARIO 1151 Richmond St. Efs Stores, Teb 40, Dock 59 London, ON N6A 5BA Email: apinvoice@uwo.ca **Attention: Accounts Payable 519-661-2111 X 83024** Contact Phone: (519) 661-2111	Customer Purchase Order # Valid Until: Feb-15-2019 Date: Feb-13-2019 Terms: Net 30 Days Promise Date: Feb-13-2019 Delivery Method: Pickup Customer Rep: Pete Hanvey

Product	Qty	Length	Unit	Unit Price	Dimension	Total

SUB-TOTAL	**76.00**
Sales Tax 13%	9.88

Description (Special Comments) :

D-5.2: Chandco Mfg. Inc. – Approved & Purchased

CHANDCO
MANUFACTURING INC.
Your partner in business

Pickup Address:
Chandco Manufacturing Inc.
554 Admiral Drive
London, ON, Canada
P: 519 649 4888
F: 519 453 5539
E: info@chandco.ca

Billing Address:
University Machine Services

London, ON N6G 4L2
ATTN: Accounts Payable
P: 519-661 2111
F: 519-661-3066
E: apinvoice@uwo.ca

Shipping Address:
University Machine Services

London, ON
ATTN: Cheri Jenkins
P: 519-661 4276
F: 519-661 3066
E: cheri.jenkins@uwo.ca

Quote: 188

Issue Date: 2/12/2019

Ship Via	Payment Currency	Payment Terms	Quote Valid For	Lead Time
CUSTOMER PICKUP	Canadian Dollar	Net 30	10 days	5-8 days

Qty	Part No.	Description	Price Each	Extended Price
1	OPP-STRU (10pcs)	laser cut 0.080" aluminum	$111.55	$111.55

D-5.3: Attica Mfg. – Approved, Not Purchased

ATTICA MANUFACTURING

Attica Manufacturing Inc.
25 Invicta Court
London, ON N6E 2T4
Canada

Ph: 519-451-5448 Fax: 519-451-4599

Quote
ID: 15311 Date: 08-Feb-19

To
UNIVERSITY OF WESTERN ONTARIO

Quote To
University of Western Ontario

Terms	Ship Via	Salesperson
Net 30		

Quantity	Description	Unit Price	Amount
4	Line: 001 Expiration Date: 22-Feb-19 Part: CENTER RAIL Rev: CENTER RAIL ea	$105.00	$420.00
8	Line: 002 Expiration Date: 22-Feb-19 Part: RAIL A/B Rev: RAIL A AND RAIL B ea	$85.00	$680.00
	PLEASE EMAIL ALL PURCHASE ORDERS TO: ORDERS@ATTICA-MFG.COM	Total:	$1,100.00

D-5.4: Westool Precision Products – Not Approved

QUOTATION

WESTOOL PRECISION PRODUCTS
150 Edward Street
ST. THOMAS, ONTARIO N5P 1Z3
Telephone: (519) 631-3874
Fax: (519) 631-7857

No 23772
PLEASE INDICATE THE ABOVE NUMBER WHEN ORDERING

TO: GREG DONY
ATTN: GREG DONY

Quotation Date	Salesperson
Feb 11, 2019	Alan TUCKER

ESTIMATED SHIP DATE	SHIP VIA	F.O.B	TERMS
	BESTWAY	WESTOOL	

	Quantity	Description	Price	Amount
001	4	RAIL A	$213.500	$854.000
002	4	RAIL B	$213.500	$854.000
003	4	CENTER RAIL	$146.000	$584.000
			TOTAL:	$2,292.000

D-5.5: Mcmaster Carr – Approved & Purchased

McMASTER-CARR.
Order

Line	Quantity	Unit of Measure	Product	Description	Estimate	Unit Price	Total
1	1	Pack of 100 each	92095A179	Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 6mm Long	Ships today	5.06	5.06
2	2	Packs of 100 each	90592A085	Steel Hex Nut Medium-Strength, Class 8, M3 x 0.5 mm Thread	Ships today	0.88	1.76
3	1	Each	91458A112	Threadlocker Loctite® 242, 0.34 oz. Bottle	Ships today	16.03	16.03
4	1	Pack of 100 each	92095A181	Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 8mm Long	Ships today	9.37	9.37
5	1	Pack of 100 each	92095A472	Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 18mm Long	Ships today	6.00	6.00
6	1	Pack of 50 each	92095A187	Button Head Hex Drive Screw Passivated 18-8 Stainless Steel, M3 x 0.50 mm Thread, 30mm Long	Ships today	6.55	6.55
7	1	Pack of 100 each	92125A130	18-8 Stainless Steel Hex Drive Flat Head Screw M3 x 0.5 mm Thread, 10 mm Long	Ships today	5.81	5.81
8	10	Each	94669A107	Aluminum Unthreaded Spacer 4.500 mm OD, 13 mm Long, for M3 Screw Size	Ships today	0.44	4.40
						Merchandise Total	$54.98

D-5.6: DigiKey – Approved & Purchased

2/26/2019 Digi-Key - Print

Reference Information

Salesorder Number: 58636895
Customer Number: 5711195

Submitted: 2019-02-26 2:06:19 PM

Address

Shipping Address:
KEN STRONG
WESTERN UNIVERSITY/ELECTRICAL COMPUTER ENGINEERING
1151 RICHMOND ST
EF STORE TEB DOCK 59 RM 40
LONDON, ON N6A5B9
CANADA
Email: KSTRONG@UWO.CA
Phone: 5196613332

Billing Address:
UNIVERSITY OF WESTERN ONTARIO
ACCOUNTS PAYABLE
1393 WESTERN ROAD
SUPPORT SERVICES BUILDING STE 6100
LONDON, ON N6G1G9
CANADA
Phone: 5196612111

Shipping

Ship Method: FedEx International Priority
Incoterms: DDP (Duty and customs paid by Digi-Key)

Payment

Payment Method: Digi-Key Account 1332666
Purchase Order: P0164673-57

All prices are in CAD

#	Product Details	Quantity	Availability	Unit Price	Extended Price
1	1568-1247-ND SEN-11574 PULSE SENSOR FOR ARDUINO ECE 4416 Group 8	1	Immediate	35.37000	$35.37
2	450-1665-ND 1825966-1 SWITCH TACTILE SPST-NO 0.05A 24V MSE 4499 Group 6	10	Immediate	0.26700	$2.67
3	CT2153-ND 026TB32R500B1A1 POT 50 OHM 5W WIREWOUND LINEAR TS	1	Immediate	7.50000	$7.50
4	F2422-ND 0218005.HXP FUSE GLASS 5A 250VAC 5X20MM [redacted]	5	Immediate	1.40600	$7.03
5	469-1053-ND 8180 MAGNET 0.187"DIA X 0.25"H CYL TS	5	Immediate	0.45200	$2.26
6	1568-1797-ND COM-11288 HEATING PAD 5VDC 750MA 5X10CM MME 4499 Group 45	5	Immediate	5.94000	$29.70
7	283-2733-ND BK/MDL-1-R FUSE GLASS 1A 250VAC 3AB 3AG Stock	20	Immediate	1.21400	$24.28

Summary

Subtotal:	$108.81
Shipping:	$0.00
GST:	$0.00
HST:	$14.15
PST:	$0.00
Total:	$122.96

These commodities, technology or software will be exported from the United States in accordance with the Export Administration regulation. These products may not be re-exported, diverted, or otherwise shipped to another destination that does not fully comply with U.S. laws and the laws of any other applicable jurisdiction.

https://www.digikey.ca/ordering/Submit/Submit/Print?Length=6 1/2

D-5.7: McMaster Carr – Approved & Purchased

McMASTER-CARR.

Purchase Order (optional

Ships today

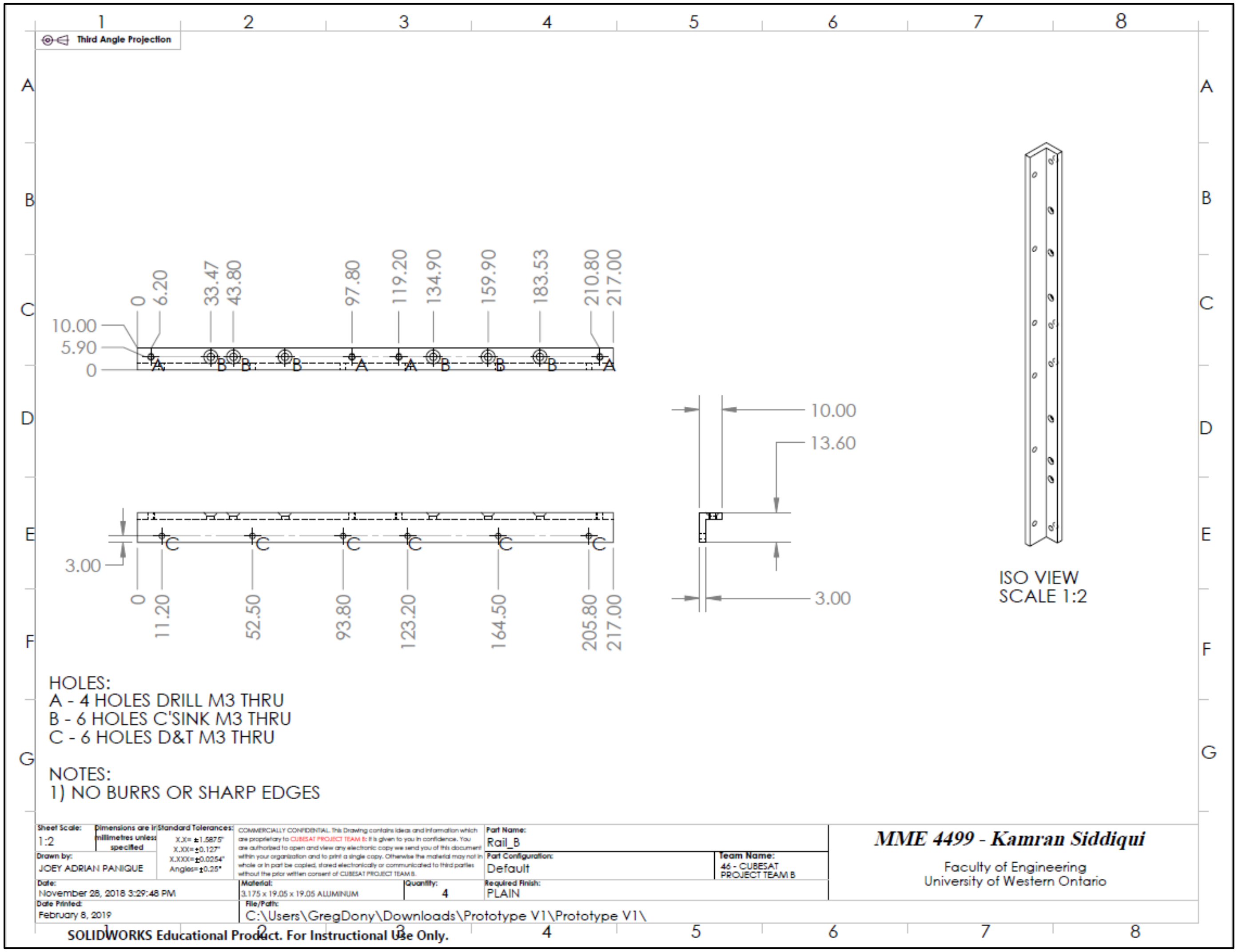
1	**Flexible Grounding Braid** Noninsulated, 1 Wire Gauge Equivalent, 2 ft. length 69925K42	2 Each	$10.30 Each	$20.60
2	**Black-Oxide Alloy Steel Hex Drive Flat Head Screw** M3 x 0.5 mm Thread, 5 mm Long 91294A125	1 Pack of 100 each	5.36 Pack	5.36
3	**High-Strength Steel Hex Nut** Class 10, Zinc Yellow-Chromate Plated, M3 x 0.5 mm Thread 92497A200	1 Pack of 25 each	8.14 Pack	8.14
4	**316 Stainless Steel Washer** for M3 Screw Size, 3.2 mm ID, 7 mm OD 90965A130	1 Pack of 100 each	2.80 Pack	2.80
5	**Threadlocker** Loctite® 242, 0.34 oz. Bottle 91458A112	1 Each	16.03 Each	16.03
6	**Heat-Transfer Sealant for Electronics** 1.69 oz. Cartridge 7548A11	1 Each	46.23 Each	46.23
7	**18-8 Stainless Steel Hex Drive Flat Head Screw** M3 x 0.5 mm Thread, 40 mm Long 92125A150	1 Pack of 25 each	3.83 Pack	3.83
8	**Button Head Hex Drive Screws** Black-Oxide Alloy Steel, M3 x 0.5mm Thread, 5mm Long 91239A110	1 Pack of 50 each	11.50 Pack	11.50
9	**Moisture-Resistant Cushioning Washer** for Number 6 Screw Size, 0.141" ID, 0.25" OD 93650A100	1 Pack of 25 each	7.87 Pack	7.87

Merchandise $122.36

Applicable shipping and tax will be added.

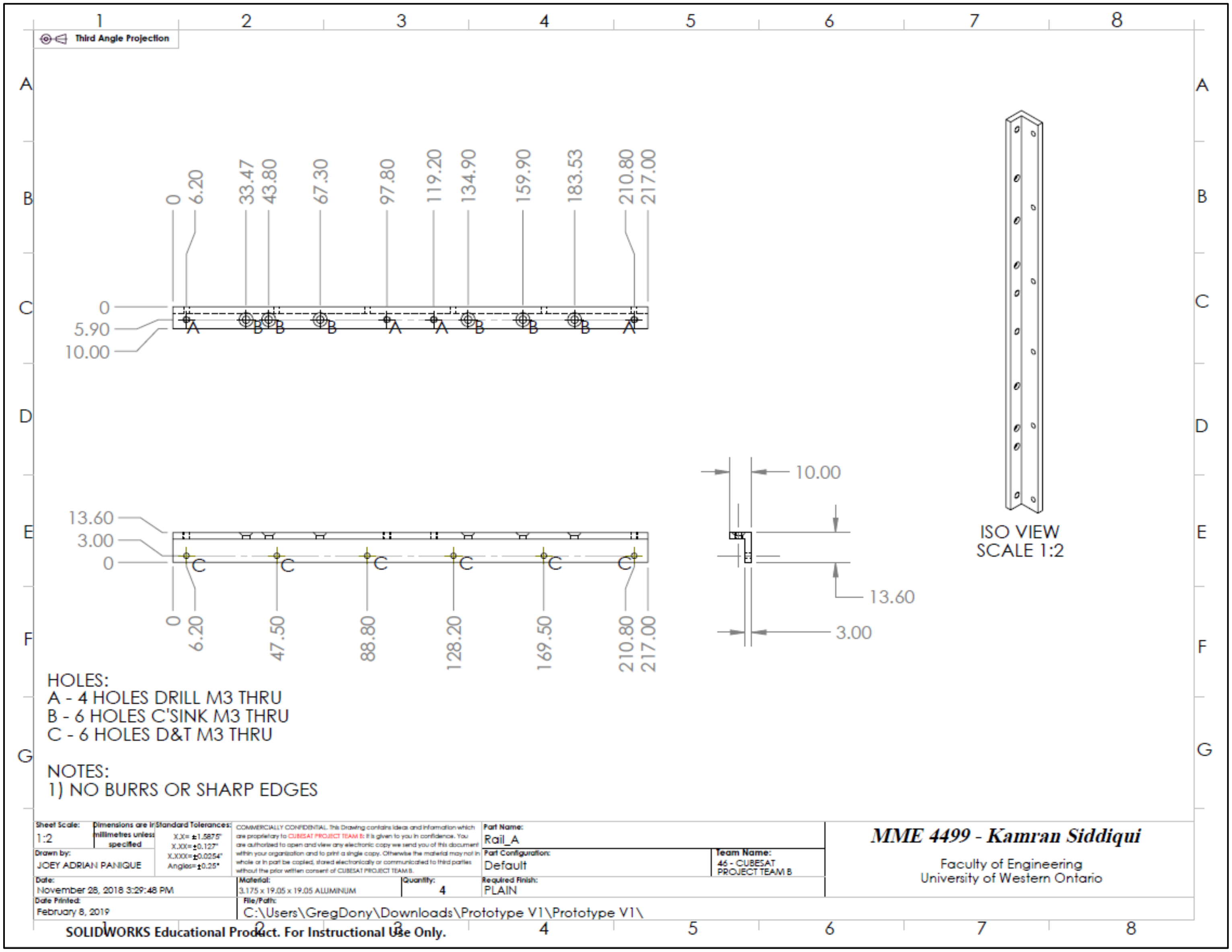
D-6: CAD Drawings and .dxf Profiles

D-6.1: Rail Angle Drawing Side A

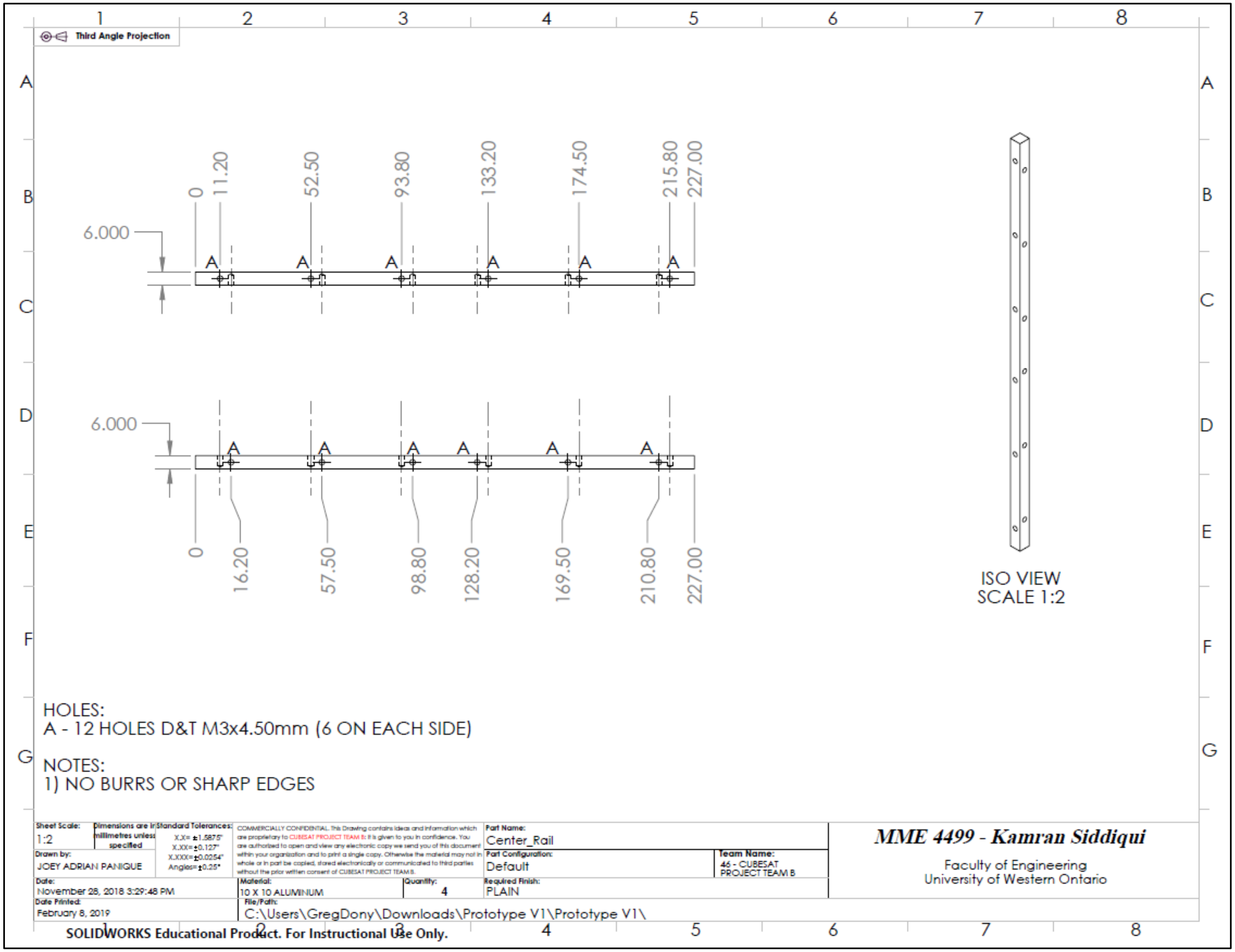


Note: Complete Prototype CAD files were submitted with this report in a separate .zip folder.

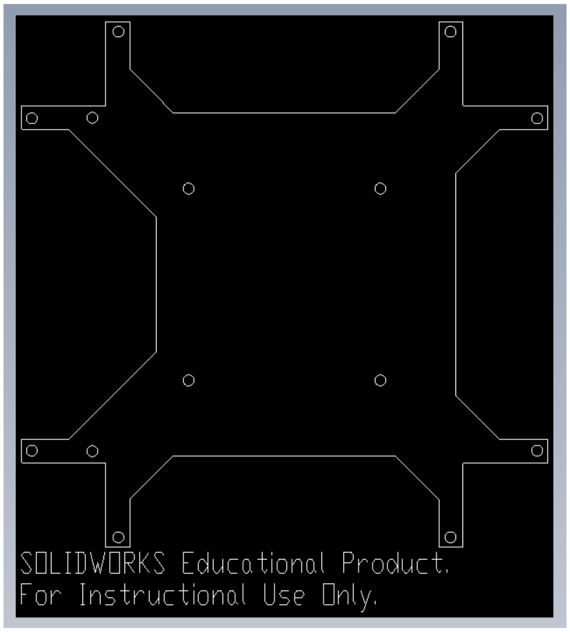
D-6.2: Rail Angle Drawing Side B

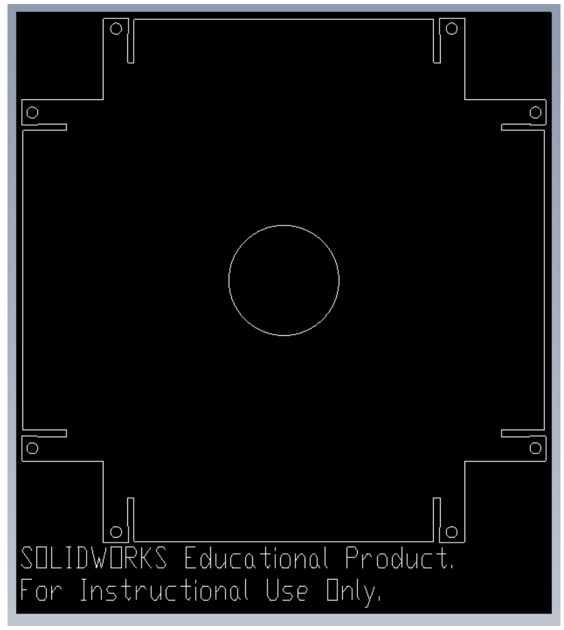


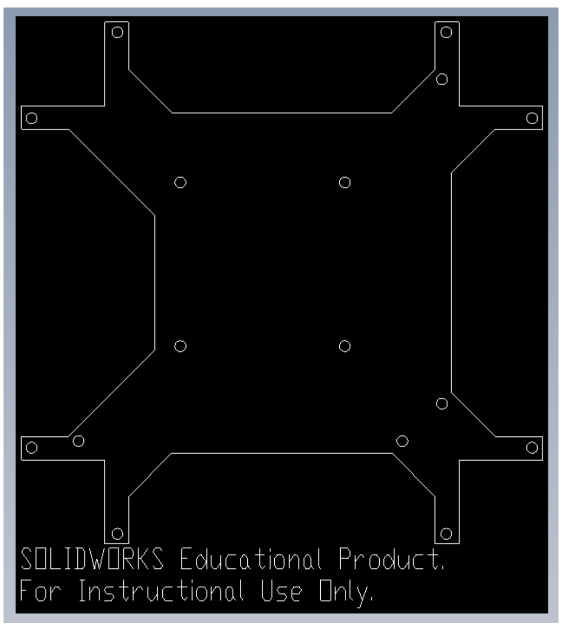
D-6.3: Rail Angle Square Rod Drawing

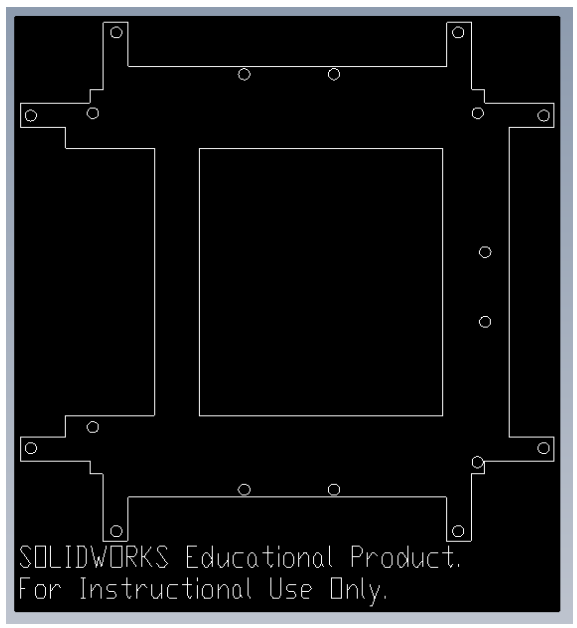


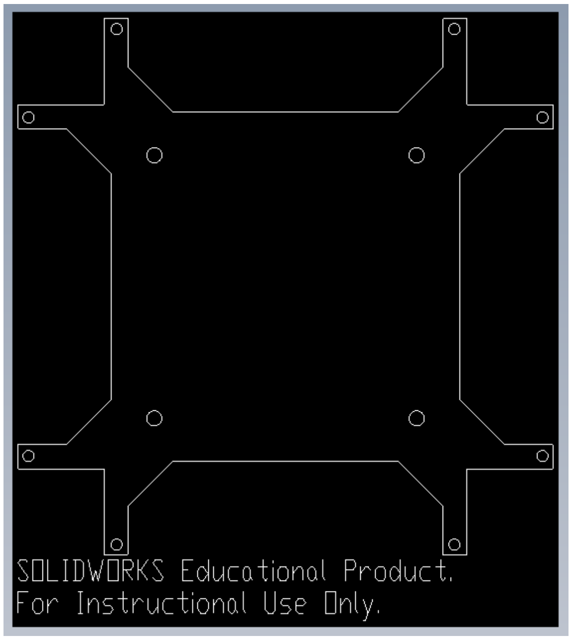
D-7: Prototype Mounting Board DXF Files







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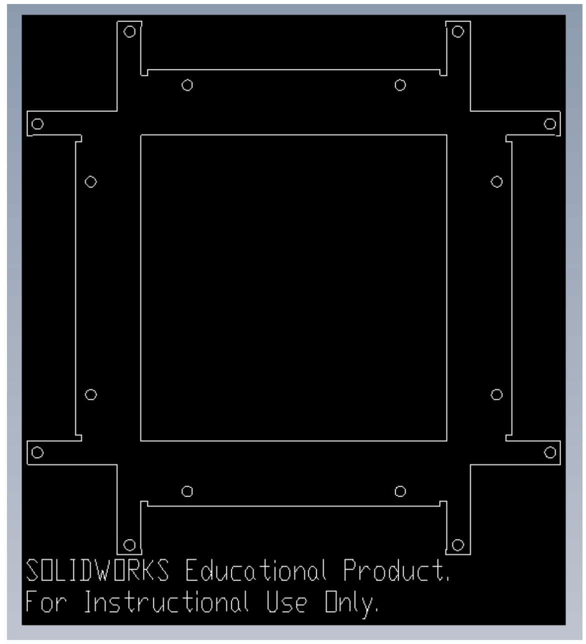
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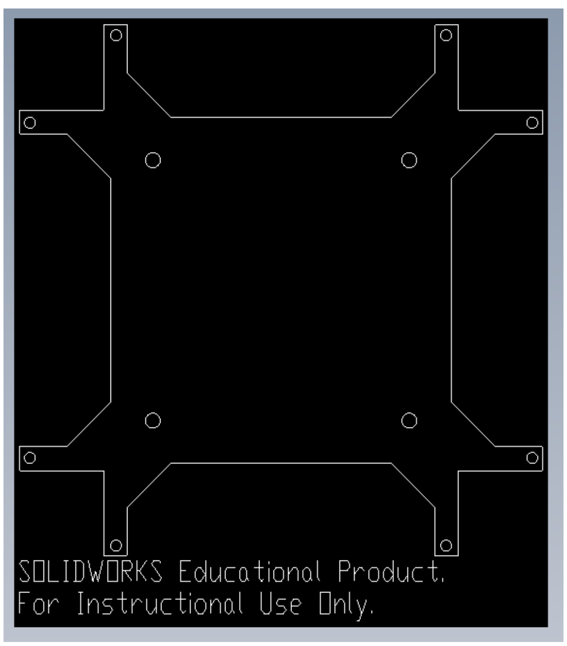
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D-8: Random Vibration Testing Fixture CAD