3-Axis Reaction Wheel System for CubeSats

Final Design Review

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ABSTRACT

Reaction wheels are a common, but expensive, component used in CubeSats, that can accurately position a satellite using an imparted momentum (or impulse) from a rotating flywheel to adjust a satellite's attitude. This document serves as the final design review and report for the 3-Axis Reaction Wheel Senior Design Project in the Mechanical Engineering Department of California Polytechnic State University, San Luis Obispo. The goal of this project is to produce a functional, low-cost 3-axis reaction wheel system based on previous research done by a master's student at Cal Poly to be implemented in future CubeSats in the Cal Poly CubeSat Laboratory. Since the main components of the reaction wheel are already specified and designed by a published thesis that is the basis of the project, the team focused design efforts mostly on the motor and outer housing of the reaction wheel system as well as how it interfaces with the CubeSat. The manufacturing, assembly, and testing will be done on the entire system of reaction wheels and housings to ensure a successful prototype can be delivered to the sponsor.

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1.0 Introduction

The Cal Poly CubeSat Laboratory needs a way to manufacture reaction wheels in-house to avoid the expense of outsourcing reaction wheels and for students to better understand the inner functioning of a reaction wheel used for Attitude Control Determination Systems (ACDS) in CubeSats and small satellites. Dr. John Bellardo, a faculty member leading the Cal Poly CubeSat Laboratory (referenced as CPCL for the remainder of this document), is the sponsor of this senior design project and represents the desires of CPCL regarding the outcome of this work. This project is a continuation and expansion of a previous CPCL lab member's master's thesis: *Low-Cost Reaction Wheel Design for CubeSat Applications* by Nicholas J. Bonafede Junior [1], which we will reference as Bonafede's Thesis in the remainder of this document.

This document first presents background research on reaction wheels, CubeSats, and Attitude Control Determination Systems (ACDS) to understand the function and design of reaction wheels followed by a description of the Cal Poly CubeSat Laboratory. Additionally, research is presented on existing reaction wheel designs, including two types of reaction wheels that CPCL has used in previous missions. Following the background information, a problem statement is clearly defined. Then, specifications for the project are outlined along with descriptions of procedures to measure these specifications.

The second half of this report focuses on design, manufacturing, assembly, and testing. Design selection was based off of multiple concept designs and was evaluated on the basis of how well they each meet the project goals and specifications. After preliminary analysis and concept design selection, the final design is presented with in-depth description of each component of the assembly. Additionally, a final cost and budget summary is presented. Next, the document outlines the manufacturing process and timeline and is followed by a discussion of the assembly process. Then the design verification tests are presented along with their description and results and recommendations. Lastly, the document defines the overall project management and concludes with recommendations and important takeaways from the project.

2.0 Background

2.1 Reaction Wheel Technical Literature Research

Reaction Wheels are devices that are used in space environments to control the position of a spacecraft. The device is structurally simple, consisting of a flywheel attached to a motor. By applying a torque to the reaction wheel, an equal and opposite torque is applied to the spacecraft [2]. Applying the torque to the reaction wheel over a given period creates an impulse, resulting in a change in the magnitude of the spacecraft's angular momentum. Changing the angular momentum of the spacecraft is balanced by a change in the spacecraft's angular velocity. Thus, by spinning the reaction wheel the spacecraft experiences a change in orientation directly related to the speed at which the wheel is spinning. Each reaction wheel maintains control over a single axis of rotation. To have complete control over the spacecraft's orientation, several reaction wheels can be used in a 3 or 4-axis orientation [3].

Despite being very useful for positioning, reaction wheels have the major drawback of a maximum speed. Even in a space environment there are disturbances, due to factors such as solar radiation, pressure, and aerodynamic drag that cause the spacecraft to lose positioning. As such, the speed of the wheels slowly climbs over time. Since they are limited to the speed range of the motor they use, the reaction wheels eventually are unable to speed up anymore and become saturated. While there are ways to desaturate a reaction wheel, they all involve making use of some alternative means of changing the spacecraft's momentum (such as magnetorquers).

The main benefits of using a reaction wheel system are that they eliminate the need for propellants, they provide 3-axis control, and they are less complex when compared to other methods [1]. Furthermore, reaction wheels are excellent for pointing accuracy. While common methods, such as magnetorquers, can have pointing accuracies of ±5°, reaction wheels can have pointing accuracies below ±1° [4]. Further explanation of technical literature research is explained in a detailed analysis of Bonafede's thesis found in section 2.3 as well.

The primary justifications for using a reaction wheel and specifically this type of active control method in a spacecraft are the following.

Passive control methods are determined to be insufficient and other active control devices do not meet pointing requirements desired. Active control means that the device must be directly controlled by the spacecraft to function properly. However, several methods exist for passive attitude stability. Attitude is a way of defining the orientation of a satellite in a three-dimensional space. The most common being spin stability, gravity gradient, aerodynamic stability, and magnetic stability. These methods incorporated into the design of the spacecraft allow the vehicle to have a natural orientation that it will gravitate toward. The natural orientation for the most part is a very weak one and does not by any means provide precise attitude control and does not allow the spacecraft to change its orientation from the natural orientation it is drawn to [5].

Other methods of active control of a spacecraft attitude as mentioned above are magnetorquers and reaction control thrusters. The drawbacks of using reaction control thrusters are the fact that they are significantly more mechanically complex and more costly. As for magnetorquers they are one of the least complex methods however only provide pointing accuracies up to ±5°.

It is the inadequacies of passive control methods, the complex nature of reaction control thrusters, and the underperformance of magnetorquers that leads to the selection of a reaction wheel as the primary means of attitude control.

2.1.1 Momentum Wheels vs Reaction Wheels

The same device is characterized by different terminology based on its use: a reaction wheel and a momentum wheel. Reaction wheels implement the rotation mechanism to be able to rotate an entire spacecraft to achieve the desired attitude. However, momentum wheels are used to stabilize spacecraft, constantly running to provide extra balance and maintain positioning for the spacecraft [3]. In the production of a direction change, the spin in one direction of a wheel can induce an attitude shift for the satellite until the reaction wheel is at its capacity, and the reaction wheel must be discharged. In the action of discharging the wheel, unless alternative attitude control determination systems are used in conjunction [6], the satellite turns back to its original attitude. This is due to the reaction momentum forces that occur once the applied momentum ceases. In contrast, the momentum wheels do not function in their saturation region; instead, they spin for long durations at lower speeds to offer stability to the position, therefore avoiding as much of a need to be discharged. This need for discharge is the main drawback of reaction wheel devices for attitude control. Therefore, lies the contrast with devices that do not need to be discharged but instead offer less precise positioning, such as magnetometers or other ADCS, as will be discussed in the next section.

2.1.2 Attitude Control Determination Systems (ADCS)

Currently, the satellites designed and launched from CPCL use basic attitude control actuators. These mechanisms need to be able to control the orientation of the satellite, commonly using sensors and actuators with respect to an inertial frame of reference, the main body of interest (i.e., earth), or the sun. Within the control of attitude, there are two main focuses: both spin stabilization and 3-axis stabilization [7]. For spin stabilization, a less common method, the gyroscopic action of a rotating spacecraft provides a stabilized orientation. However, in the more common 3-axis stabilization, the spacecraft is held fixed in the desired orientation without rotation. Within this 3-axis stabilization, there are other sub-categories: using small thrusters, solar sails, or as in our case, powered reaction wheels. The most common of these attitude control devices which is widely implemented within Cal Poly CubeSat Labs is a magnetorquer. A magnetorquer or magnetic torquer implements small permanent magnets to induce a local magnetic field, reacting against the magnetic field of the body it orbits around [6]. While for many payloads, current attitude control actuators are acceptable, for payloads that require high-precision scientific measurements, magnetorquer positioning is not accurate enough, and a 3-axis reaction wheel mechanism is required. The 3-axis reaction wheel system is an industry trend for ADCS systems and is most commonly used on more sophisticated missions.

2.1.3 Patent Research

We investigated various patents to be able to have a base understanding of what limitations were placed on our design. There were very few patents about the direct reaction wheel design; instead, most of the patents were specifically focused on detailed modifications to the basic design of a 3-axis reaction wheel.

The most relevant of these patents was a mathematical analysis and design of a potential 4-axis reaction wheel design, which was even touched on when talking with our sponsor. For many of the current implementations of reaction wheels for large-scale space projects utilize the 4-axis design so that if there were to be a failure in any one wheel, that the entire system would not be incapacitated, instead it would still be able to function [8]. However, under careful consideration, this potential is outside the scope of the project, so avoiding the details in this patent is unnecessary. The general design of a reaction wheel is not patented, as its patents are not allowed to include elements, theoretical plans, laws of nature, physical phenomena, and abstract ideas [9].

Table 1. Patent Research Table

Title	**Description**
Reaction wheel friction compensation using dither [10]	A reaction-wheel stabilized spacecraft reduces attitude errors at wheel reversals by application of a dither component to the wheel torque command signal.
Reaction sphere for spacecraft attitude control [11]	Hydraulically and spherically supported inertial reference, a frictionless gyroscope to function as an alternative to typical reaction wheels.
Back-Up Wheel for 3-Axis Reaction Wheel Spacecraft [8]	The backup wheel is mounted on an axis which is skewed with respect to the axes of the three mutually perpendicular wheels, so if only one of the perpendicular wheels fails, the backup wheel rotates to maintain spacecraft attitude.
Reconfigurable reaction wheel for spacecraft [12]	This patent is of a reconfigurable reaction wheel for a spacecraft, comprising of a reaction wheel housing, a flywheel rotatably disposed in the housing, and an electric motor operably coupled to the flywheel.
Attitude control system for small satellites [13]	An attitude control system (ACS) for use with a pico- or a nanosatellite comprising of a flywheel assembly or gimbal assembly.

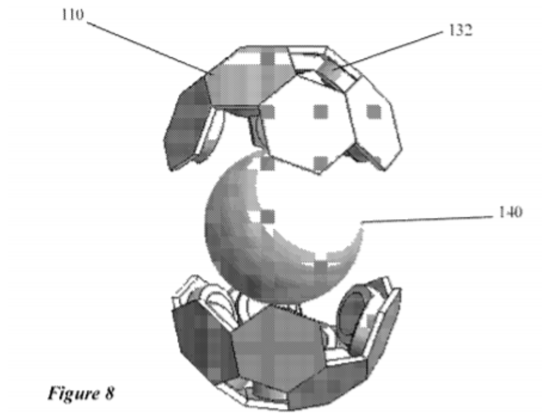


Figure 1. Patent for Reaction Sphere for Attitude Control [11]

One of the other notable patents is pictured in the figure above of a novel reaction wheel design [11]. Creative designs like these reaction "wheels" would be more influential if we were to be creating the reaction wheel design from scratch. However, since we are using the existing work as a jumping-off point for the design, it has limited these design freedoms, therefore focusing our energies on the housing, manufacture, and build process instead of theoretical propositions.

2.2 Cal Poly CubeSat Lab Background

Cal Poly CubeSat Laboratory (CPCL) is a student-run collaboration and development team on Cal Poly's campus, focused on creating small satellites, namely along with the CubeSat standard. A CubeSat is a 10cm x 10cm x 10 cm unit of space, which is a 1-U standard, as will be referenced as a measurement of size later in this document. Increments of this size are utilized for various research payloads, in measurements of this 1-U standard [14]. As a part of NASA's initiative to encourage students in space, CPCL developed P-PODS; these are a launch housing utilized to deploy CubeSats into orbit once past the atmosphere, and they typically hold 3-U increments [15]. That is why the most common CubeSat sizes are 1-U (the most common for basic busses) or 3-U (for larger payloads). Embodying Cal Poly's "learn by doing" philosophy, the lab gives students an ability to design, build, and operate CubeSats. Not only does the lab give students a chance to work together on small interdisciplinary project teams, but it trains them and gives them experience necessary to be valuable once working in industry careers [16].

2.2.1 PAST CAL POLY CUBESAT LABS REACTION WHEEL MECHANISMS

In the history of the Cal Poly CubeSat Laboratory, there have been 2 flight missions that have integrated a form of ADCS (Attitude Determination Control Systems). These flight missions were ExoCube I and II which both used a combination of deployable booms with brass tip masses, magnetorquers, and a single momentum wheel a 3U size CubeSats. There were also two other missions that tested de-tumbling with B-dot (the magnetic flux induced by current in a magnetorquer interacting with the earth's magnetic field) that is a basic form of ADCS. The ExoCube missions are a research project in collaboration with Scientific Solutions, NASA Goddard, California Polytechnic State University - San Luis Obispo, the University of Wisconsin, and the University of Illinois. The primary objective of the ExoCube missions is to acquire global knowledge of the in-situ densities of [O], [H], [He], [N_2], [O+], [H+], [He+], [NO+] in the upper ionosphere and lower exosphere. The necessity for reaction wheels on these missions in particular was the need for accurate positioning of the miniaturized mass spectrometers and ion sensors onboard the spacecraft. Data acquisition of reaction wheel performance on-orbit for the ExoCube I, is unfortunately is non-existent due to some issues with the spacecraft's antenna when launched on January 31st, 2015. ExoCube II is slated to launch sometime in 2020 or early 2021. Each spacecraft used a different reaction wheel from a different supplier to reduce the cost of the mission for ExoCube II. Cost is a driving motivator for CPCL to develop a student made reaction wheel system at a substantially lower cost.

2.2.2 CURRENT CAL POLY CUBESAT LABS REACTION WHEEL SUPPLIERS AND EXISTING PRODUCTS

Sinclair Interplanetary by Rocket Lab RW-0.01 Reaction Wheel

The Sinclair Interplanetary Reaction Wheel (RW-0.01) was used by CPCL on the aforementioned ExoCube I mission; unfortunately, CPCL was not able to gather any valuable flight heritage on the mechanisms because of an anomaly on the antennae of the spacecraft. Regardless, Rocket Lab claims heritage on 10 units on-orbit 4 satellites. The Table 2 shows key characteristics of the reaction wheel provided by Sinclair Interplanetary [17]. The housing of this reaction wheel is particularly interesting because it does not fully enclose the flywheel but rather just forms an X-shaped bracket for mounting and structural stability. This is a viable option when considering how to house the reaction wheels in this project because it uses less material while still protecting the wheels and allowing for adjustments to be made.

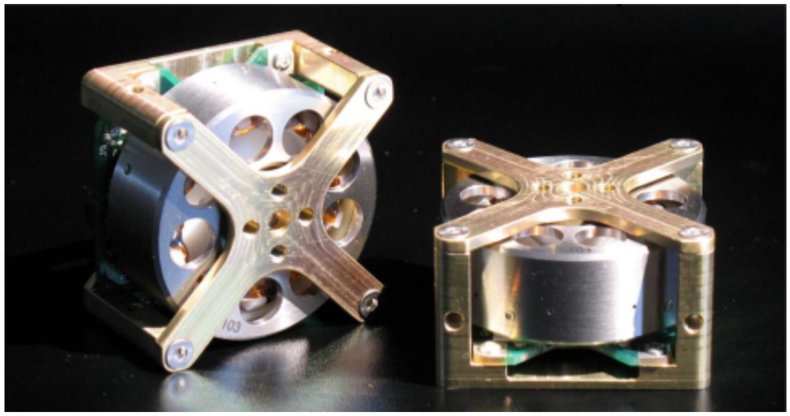


Figure 2. Sinclair Interplanetary Reaction Wheel RW-0.01 [17]

<u>CubeSpace CubeWheel Medium</u>

The CubeSpace CubeWheel Medium was used by CPCL's ExoCube II mission it was selected as opposed to ExoCube I's Sinclair Interplanetary Wheel because it achieves relatively the same performance at over less than half of the price [18]. Table 2 summarizes

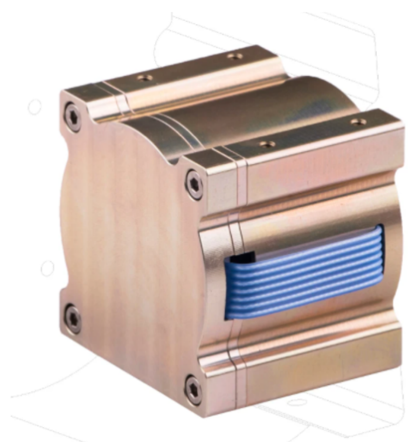


Figure 3*.* CubeSpace Cube wheel Medium [18]

<u>Blue Canyon Technologies RWP015 Reaction Wheel</u>

The Blue Canyon RWP015 has never been used by CPCL, however Blue Canyon Technologies (BCT) is an industry leader when it comes to "off the shelf" CubeSat components and kits which is why a comparison and analysis of this reaction wheel is a valuable endeavor. The specs of BCT's reaction wheel can be seen in Table 2. The housing for this reaction wheel is box-shaped but has slots for the circuit board and flywheel which allows adjustments to the board and wheel to be made if necessary.

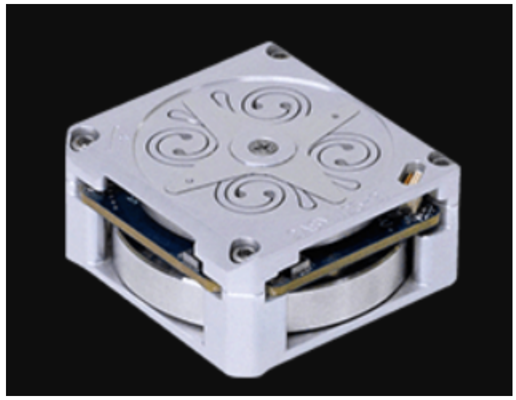


Figure 4. Blue Canyon Technologies RWP015 Reaction Wheel [19]

Tensor Tech Reaction Sphere

The Tensor Tech Reaction Sphere has not been used on CPCL mission either. The device serves as an attitude control system similar to traditional 3-axis reaction wheels for cube satellites ranging from 1.5U, 2U, 3U, and 6U. This reaction sphere differs from other designs of reaction wheels because it functions like a Single-Gimbal Control Moment Gyro as opposed to the reaction wheels which use the rotation of a simple flywheel to impart a change in momentum on the spacecraft. This gyroscope technology allows for control of satellite like a 3 or 4 axis reaction wheel does but with just one single wheel but with lower weight, size, and power consumption. This reaction sphere is expensive costing $20,000 [20]. It has a single cylindrical housing which encompasses the entire sphere. The housing is easily manufacturable since it is a perfect cylinder and is a good option for housing the flywheels in this project.

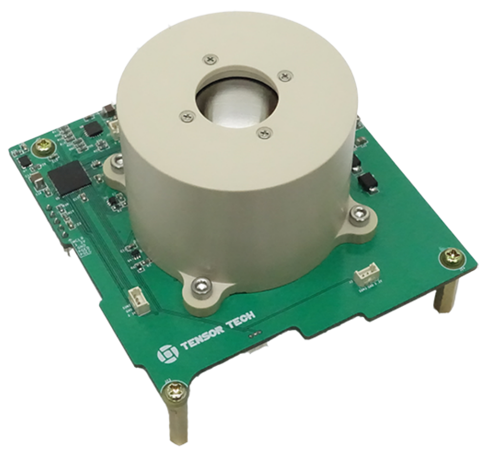


Figure 5. Tensor Tech Reaction Sphere [20]

Table 2. *Various Current Supplier Wheel Specifications*

Supplier	Momentum	Torque	Mass	Volume	Price
Sinclair Interplanetary RW-0.01 [17]	10 mNms	± 1 mNm	120 g	50mm x 50 mm x 30mm	US$20,000 each, + $2,000 for radiation lot-screened parts
CubeSpace CubeWheel Medium Specifications [18]	10.82 mNms	1 mNm	130 g	46mm x 46mm x 31.5mm	US$6,850 each
Blue Canyon Reaction Wheel RWP015 Specifications [19]	15 mNms	4 mNm	130 g	42mm x 42mm x 19mm	Unknown
Tensor Tech [20]	10 mNms	1 mNm	< 400 g	0.4U	$20,000
Bonafede's Low-Cost Reaction Wheel [1]	5.02 mNms	1.61 mNm	130 g	47.15 cm^3	$ 1060 whole system

2.3 Existing Low-Cost Reaction Wheel Design (Bonafede's Thesis)

The primary goal of the project is to develop a low-cost reaction wheel system that has the capability of being developed by Cal Poly Students using the Cal Poly Machine shops. Bonafede's Thesis outlines a preliminary design of a 3-axis reaction wheel system. This system is similar to reaction wheels used in past missions; however, this is a 3-axis system with a reaction wheel on each axis. Bonafede's Thesis report simulated the performance of the system, sourced a high rpm motor, and completed a preliminary design of the flywheel, motor housing, and system enclosure. [1] The next steps for the project outlined in his thesis are to machine, build, and assemble the system. The scope of this project will first be focusing on the detailed selection and design of the housing that will encapsulate the reaction wheel assembly. Questions to be asked are: should there be one single housing for all three wheels, or should each wheel have its own? Does there need to be a housing around the flywheel? How will the reaction wheels be integrated into the satellite bus structure?

Once the housing is designed and assembled with the system, the fly wheel will be sent out to an external shop to be balanced. Following the balancing, benchmark tests will be performed on the wheel and will be compared to his simulation results. This will be an iterative process as small issues in shaft/flywheel interference fits in the design might lead to sub-optimal performance. After all small tweaks have been made to the design, the flywheel will undergo environmental testing to ensure the system will survive on-orbit vacuum and temperature extremes and the vibrational launch environment.

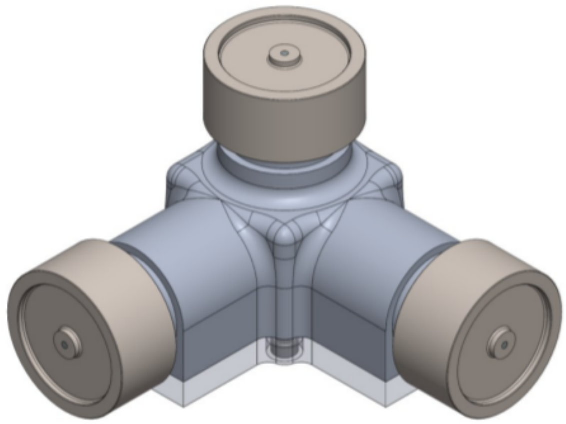


Figure 6. Bonafede's Low-Cost Reaction Wheel Solution [1]

2.3.1 Interview with Sponsor

Through weekly sponsor meetings, the team was able to gain an understanding of the wants and needs of the main customer- CPCL. The main proposed scope of work was building off the work done in Bonafede's thesis on a 3-axis reaction wheel design. By the end of last year, the design was not able to be manufactured, built, and tested. Following more discussions with Dr. Bellardo, it was determined that it is well within the scope of the project to explore other design considerations, namely comparing housing design options. Design freedom of the housing is permitted, on the condition that it is able to build off of the work done in the original thesis, rather than causing a need to start from scratch due to a design decision made. In this, the mechatronics and controls systems of the design will remain intact and functional for the wheels and motors, even if housing or manufacturability changes are made.

3.0 Objective

3.1 Problem Statement

Purchasing reaction wheels from other companies is expensive and difficult to customize. Therefore, the Cal Poly CubeSat Laboratory needs a way to manufacture, assemble, and test their own reaction wheels for satellite positioning which will be integrated into a wide variety of future Cal Poly CubeSats.

3.2 Stakeholder Needs and Wants

Below is a list outlining CPCL's identified needs and wants.

- ☒ Achieving desired performance metrics for reaction wheels (i.e., forces and energy constraints and torque output)
- ☒ Affordable (< $2,000 for total materials and manufacturing)
- ☒ Manufacture a prototype within the Cal Poly Machine Shops
- ☒ Shall survive launch and on-orbit environments
- ☒ Shall meet typical mass budgets provided by launch providers
- ☒ Shall be able to interface with standard CPCL Bus structure
- ☒ Shall be able to fit in less than 1U volume (preferably ½ the volume of a 1U)
- ☒ Completed prototype and build by end of year
- ☒ Can be implemented in a variety of CubeSat projects

3.3 Boundary Diagram

The boundary diagram shown in Figure 7 provides a visual representation of the scope of this project. The orange circled sections of the drawing represent the parts of the project that we will be both responsible for and executing over the course of the year within Senior Project. Outside of these lines are tasks that are outside the scope of the project, however, the steps shown must still be considered when developing our designs.

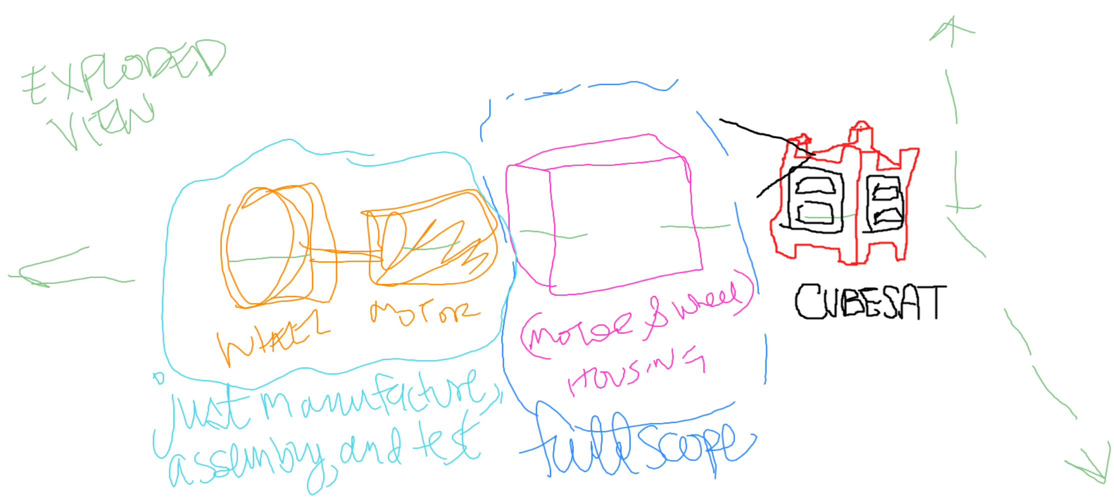


Figure 7. Boundary Diagram

3.4 Quality Function Development (QFD)

Within the process of quality function development (QFD) a house of quality was determined, weighing the various factors that determine customer needs/wants, methods of comparison, and engineering specifications for our design (see Appendix A). Customer needs/expectations were compiled using sponsor interviews, CPCL mission lead input, and largely based on Bonafede's Thesis. These customer needs and wants were evaluated in the context of existing designs which included the design from Bonafede's Thesis (current design) and 3 other competitors including Sinclair, CubeWheel, and Blue Canyon Technologies. Specifications were developed in the "How" sections taking into consideration the customer needs and wants as well as what kinds of requirements are essential for the project to be successful. These requirements were derived from the basic requirements outlined in Bonafede's Thesis and other specifications that are necessary in reaction wheel design, development, and implementation. The specifications correlated with the customer needs and wants to that every specification was fulfilling at least one of the customer needs. At the bottom of the House of Quality (in the "How Much" section) we defined target values which were then used to develop a specification table found in the following section.

3.5 Specifications

Table 3 outlines the project requirements derived from the QFD/House of Quality process. Specification description comes from the "How" section of the QFD and is crossed referenced with customer needs and wants to understand the importance and get the requirement or target value. Our target values were derived mostly from Bonafede's Thesis in which he outlines L standards and target metrics for reaction wheels in CubeSat applications. In some instances, these requirements come from industry standards or specific CPCL standards listed in proprietary documents that cannot be included as appendices, but they are referenced in the "Reference" column. The "Tolerance" column gives the acceptable variation from the target value, which in some cases is marked with "-"to indicate that we must hit the target value. "Risk" is how challenging we think it will be to meet each specification (H = High, M =Medium, L = Low). Finally, the "Compliance" column specifies how we will measure each of these requirements (see below table for key).

Table 3: Reaction Wheel Specifications Table

Spec #	Specification Description	Requirement or Target	Tol.	Reference	Risk	Compliance
1	Mass	660 g total 165 g per wheel	Max	[1]	L	T, A
2	Cost	$2,000 for total system	Max	[1]	M	I, S
3	Machinable	Fulfill CPCL Structural Review Checklist	Check all boxes	CPCL Structural Review Checklist (internal only)	L	I, S, A
4	Size/Volume	10 cm x 10 cm x 5 cm (for total assembly - approx. ½ of a 1U volume)	$\pm$ 1 cm^2	[1]	H	I, S, A
5	Thermal Testing - Bakeout	60 C for 6 hours or 70 C for 3 hours	-	CPCL Standard	M	T, A
6	Vacuum Testing	1 * 10^{-4} Torr	Max	CPCL Standard	M	T, A
7	Torque	1.0 mNm	-10%	CPCL Standard	M	T, A, S
8	Momentum Bit	17.5 μNms	Max	[1]	M	T, A, S
9	Total Momentum	5 mNms	-	CPCL Mission Leads	L	T, A, S
10	Balance Quality Grade	G2.5	-	Balance Quality Grade Table (Appendix B)	H	T, A, S
11	Deorbit Demise	Does not survive re-entry from LEO	-	[1]	L	A
12	Vibration Testing	GEVS Acceptance PSD Profile	Max	NASA GEVS (NASA STD 7000 Table 2.4-3) [21]	M	T, A
13	Compatibility/ Assembly (Mechanical/Electrical Interfaces, Integration into satellite)	Fulfill CPCL Structural Review Checklist	Check all boxes	CPCL Structural Review Checklist (internal use only)	H	A, I
14	Safety	Fulfill Senior Design Hazard Checklist	Check all boxes	Senior Project Success Guide (Appendix C)	L	A, I

Compliance Key: A = Analysis, T = Test, I = Inspection, S=similarity

3.5.1 Specification Measurements

- ☒ **Mass**: Measured using a scale with +/- 0.001g tolerance
- ☒ **Cost**: A budget and spending tracker will be kept by the team in which we will keep track of how much each member has spent and reimbursement status (reimbursements provided by CPCL). Before any parts are ordered, the total will be added up to ensure the budget is not exceeded
- ☒ **Machinable**: Measured by inspection, similarity to machinable parts, and examined for features that are difficult to machine. All of these are outlined on the CPCL Structural Review Checklist (which is for internal CPCL use only).
- ☒ **Size/Volume**: Found by measuring the radius and height of each wheel using a ruler or caliper.
- ☒ **Bake-out Testing**: Measured through testing in TVAC chamber or thermal chamber, analyzing with results from thermocouples and inspection for pass/fail analysis.
- ☒ **Thermal Testing**: Functional testing for survival of launch environment using Cal Poly's thermal chambers.
- ☒ **Vacuum Testing**: Measured through testing in TVAC chamber and pass/fail analysis.
- ☒ **Torque**: The torque spec is based on the desired torque of the wheel and is controlled by the type of motor used in the reaction wheel. This will be measured by inspection of the motor and verification tests (measuring angular acceleration and rotational inertia of the motor shaft) to ensure the motor is outputting the correct torque.
- ☒ **Momentum-bit**: Measured by using rotational inertia of the wheel and the saturation speed of the motor: $dL = I_W \Delta\omega_w$ (Rotational inertia is found by measuring the mass and radius of the motor shaft and rotational speed is by testing)
- ☒ **Total momentum**: Measured by using rotational inertia of the wheel and the max speed of the wheel: $L_{max} = I\omega_{max}$ (Rotational inertia found by measuring mass and radius of motor shaft and rotational speed found using test)
- ☒ **Balance Quality Grade**: Determined with balancing test
- ☒ **Deorbit demise**: Analysis will determine if wheels burn-up upon re-entry using ODAR analysis.
- ☒ **Vibration Testing**: A PSD profile is found by testing the wheels on a shaker table and measuring their output response. The response must be below the acceptance level presented by NASA GEVS (General Environmental Verification Standard) [21].
- ☒ **Compatibility/Assembly**: Measured by inspection and analysis to see if the mechanical and electrical interfaces are compatible and how well the reaction wheel assembly will interface with a satellite using the
- ☒ **Safety**: Measured by inspection/analysis to meet all the guidelines on the *Senior Design Hazard Checklist* (Appendix A).

3.5.2 Discussion of High-Risk Specifications

Some of the high-risk specifications listed in Table 3 are Size/Volume, Balance Quality Grade, and Compatibility/Assembly. These were identified as high-risk specifications because they will be the most challenging to meet. The size/volume requirement, is critical to an effective design, given that most CubeSat missions have a hard time fitting required hardware and payload into a 3U or less space. Additionally, with the balance quality grade requirement this is going to be the most difficult to meet precisely since it requires careful testing and adjustments. If the center of mass of the object rotating is not aligned with the axis of rotation, it will create vibrations perpendicular to the axis of rotation causing rotor imbalance and in result, inaccuracy of the attitude control [1, 22]. This requirement is the most important to meet because it will determine if the reaction wheels are qualified for orbit. The last high-risk specification is compatibility/assembly. This requirement refers to how well the design can be implemented into a variety of future CubeSats (of varying sizes) and how easily the reaction wheels can be integrated and assembled into the spacecraft. This is high-risk because since the design needs to be compatible with a wide variety of bus structures and missions, it must be designed and implemented with flexibility and awareness of its limitations. Additionally, the wheels will be installed onto the spacecraft in a cleanroom environment which means they cannot be welded or soldered so if the wheels are difficult to assemble or integrate into the satellite, this would create a problem. These three high-risk specifications are what are going to be driving this project moving forward.

4.0 Concept Design

After clearly defining the scope of the project with specifications, the concept ideation and design process began. First, a functional decomposition tree was developed to frame the next steps of the process which were ideation, brainstorming, and developing concept sketches and prototypes. Following ideation and prototyping, multiple methods of design selection were used in order to decide on a final design direction. These included Pugh matrices, a morphological matrix, and a weighted decision matrix which were all used to evaluate how well each design performs the desired functions and meets the desired specifications outlined in the QFD.

The design process was mainly focused on the motor and flywheel housing and how they would interface with each other and the outer bus structure. Many different concept designs were formulated considering different configurations, housing shapes, modularity, and accessibility.

4.1 Concept Development – Function Tree

In order to clearly define the desired functions of the housing, a function tree was developed where the main function was broken down into sub functions which occasionally also had sub functions. The main purpose of the housing design is to house the reaction wheel and motor system. Some sub-functions which are necessary to achieve this main function are to transfer torque and momentum from the motor to flywheel and flywheel to bus, ensure safety, protect internal components, mount reaction wheel system to the bus, restrain undesired motion, retain structural integrity, and orient in an effective configuration. The finalized function tree can be seen in Figure 8 below.

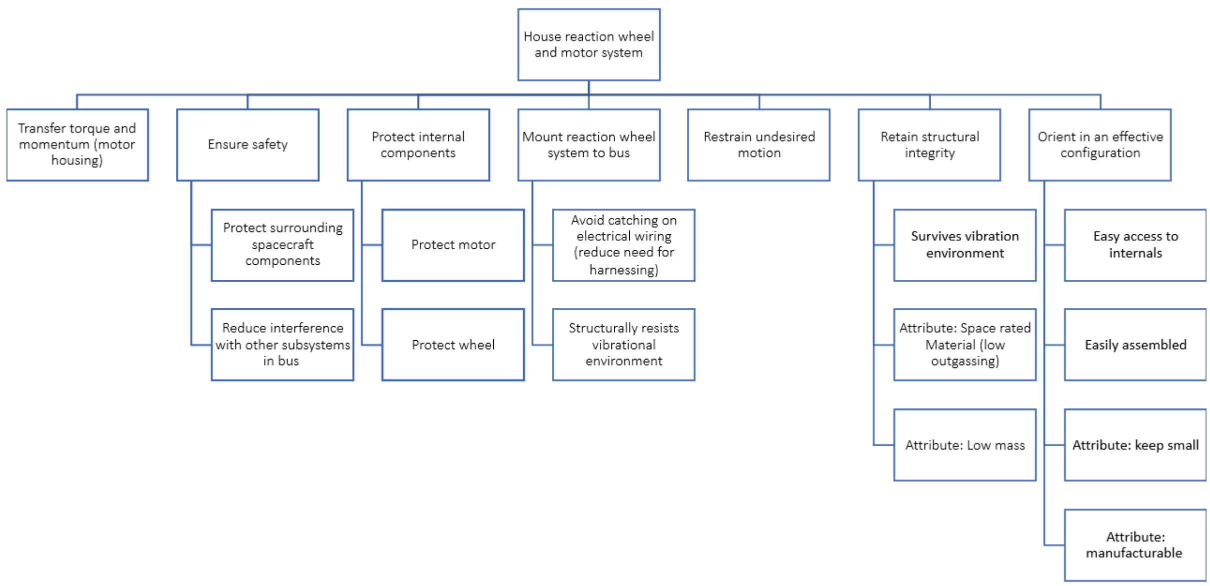


Figure 8. Functional Decomposition Tree

4.2 Ideation

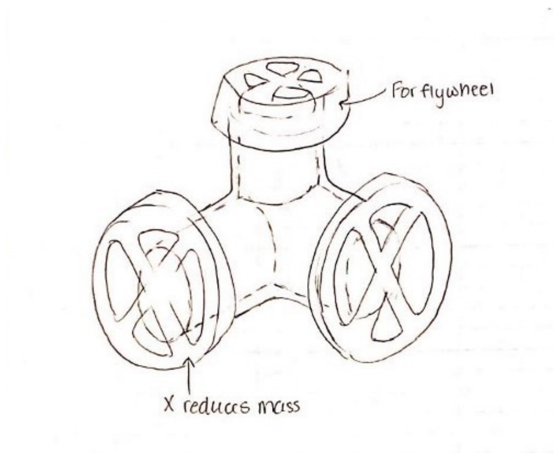
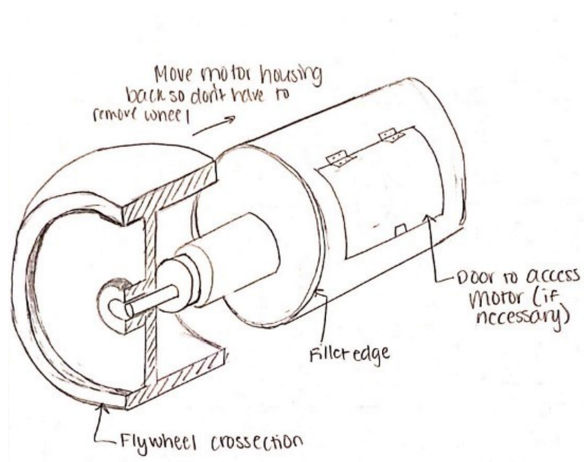
4.2.1 Brainstorming

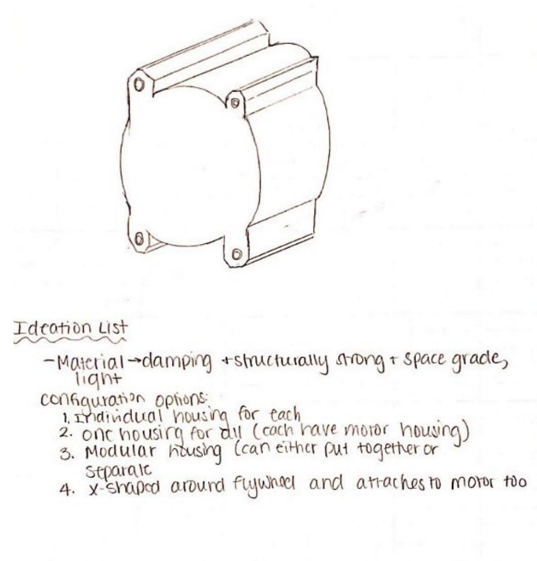
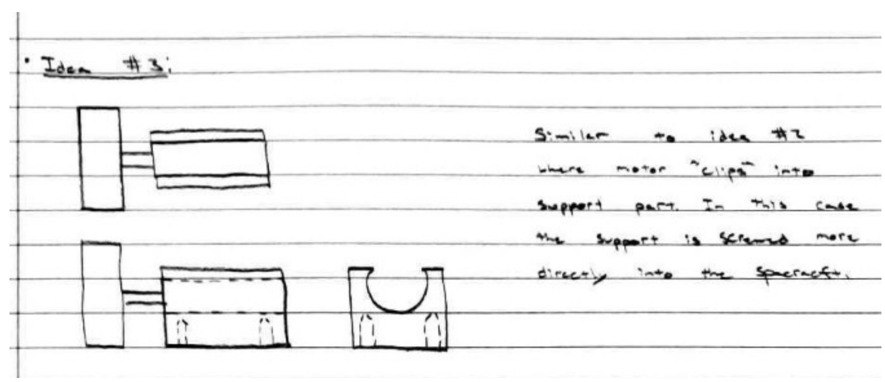
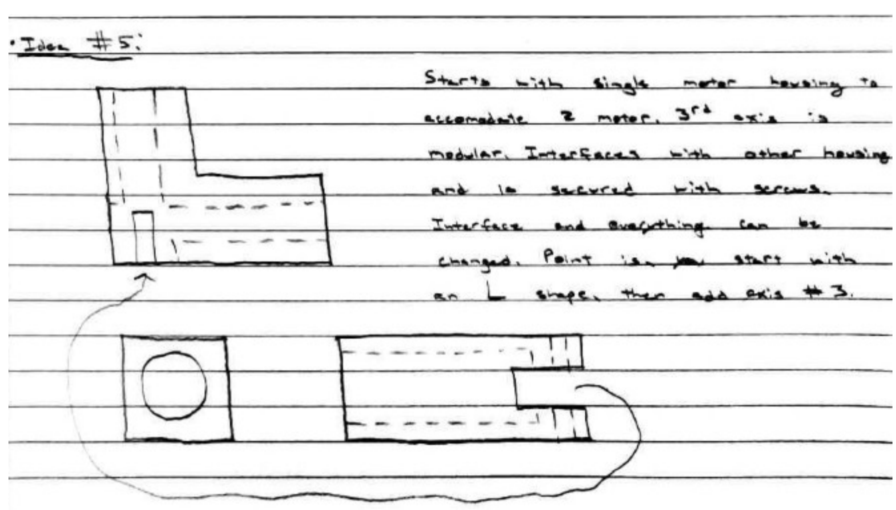
Using the defined functions from the function tree, the team conducted multiple brainstorming sessions using different methods. The first was individual brainstorming. Before meeting as a team, each team member took 30 minutes to an hour to brainstorm solutions to each of the functions outlined in the function tree through sketches or documenting ideas. Then the first group brainstorming session focused on sharing those ideas and brainstorming as a group using Google Jamboard (see Appendix D) to formulate solutions to our desired functions. Following this general brainstorming session, the team applied some more unique brainstorming methodologies such as "How might we?" statements and "Worst Possible Idea." The results of those brainstorming sessions can also be found in Appendix D.

4.2.2 Function Concept Sketches and Prototypes

During individual brainstorming, team members created concept sketches to better convey ideas and capture certain functions. These sketches are all part of ideation and do not represent the final concept ideas. Table 4 below compiles the sketches for reference.

Table 4. Function Concept Sketches

Idea & Function	Sketch
3-axis system all in one housing with x-bracket (protects internal components)	
Motor housing that is not covered by flywheel with latch door to provide ability adjust (protect motor, accessibility)	

<table>
<tr><td>Full enclosure (protect motor and wheel, ensure safety, retain structural integrity)</td><td>
</td></tr>
<tr><td>Single “clip in” motor enclosure with exposed flywheel</td><td>
</td></tr>
<tr><td>3-axis system with two separate housings (one in an L shape, the other integrating perpendicular to the L)</td><td>
</td></tr>
</table>

Each team member individually created concept models using common household items and prototyping materials such as foam core board, hot glue, cardboard, skewers, and rubber bands in order to test the feasibility of designs formulated in ideation. A table of these function concept prototypes can be seen in Appendix E.

4.3 CONCEPT SELECTION

The process of concept formulation and selection began with creating Pugh matrices for the top four functions of the reaction wheel housing. The ideas from ideation and concept modeling were sorted and allocated to a certain Pugh matrix based on the function they perform. Using the top 3-4 ideas from each functional Pugh matrix, a morphological matrix was created where concept system designs could be formulated using different combinations of the top ideas from the Pugh matrices. From these combinations, five were selected as the top ideas and concept sketches were created to picture these ideas. The top 5 concept designs were then evaluated in a decision matrix using the customer specifications in order to select the best design to move forward with.

4.3.1 PUGH AND MORPHOLOGICAL MATRICES

The final concept was developed using Pugh Matrices and a Morphological Matrix. The Pugh matrices were used to evaluate design solutions for specific functions and the Morphological Matrix was used to combine them into one compete design.

As previously stated, Pugh matrices were used as a way to compare possible design solutions for specific functions. The design solutions were compared against a “datum” (the design outlined in Bonafede’s Thesis [1]) based on a set of criteria specific to each function. The datum is assumed to be the control, meeting each criterion appropriately and thus is given a score of 0 for each function (resulting in a total score of 0). Alternative designs are then rated in comparison to the datum. The system used for scoring was based on a scale of “+, S, -”; where “+” indicated better, “S” indicated same, and “-” indicated worse.

As a team we created a total of four Pugh Matrices for each of the major functions of the reaction wheel housing (see Appendix F). The four functions/attributes were the motor housing, the wheel housing, modularity, and Interface between the reaction wheel system and the housing. The design solutions for each of the functions were evaluated against a set of criteria specific to the function. In general, the criteria used were of the following list:

1) Affordability
2) Manufacturability
3) Survivability of Launch/In-Orbit Environment
4) Low Mass
5) Low Volume
6) Compatibility with Bus Structure
7) Versatility with different CubeSats
8) Safety
9) Wheel Protection
10) Assembly

Morphological Matrices were used to establish full designs using combinations of the best function-based design solutions from the Pugh matrices. As shown below, each function/attribute had 4 possible design solutions (with the exception of the modularity function).

Table 5. Morphological Matrix

Function/Attribute	Ideas by Function			
Motor Housing	Cylindrical	Rectangular	Latch/Door	No covering
Wheel Housing	X-Bracket	Complete Enclosure - Rectangular or Cylindrical	Enclosure with Cutouts	No covering
Modularity	One Housing Per Wheel	Removeable Motor and Wheel from Housing	L-bracket	
Interface	Back Plate Glue	Full Body Glue	Set Screw	Press Fit Cylinder

The motor housing concepts are self-explanatory; the outer shape would have been either cylindrical or rectangular. There were also added possibilities of a latch/door for access to the motor or simply no covering at all.

The wheel housing designs consisted of either an enclosure with cutouts or a full enclosure (either rectangular or cylindrical). An enclosure with cutouts would have had the benefit of reduced mass, whereas a complete enclosure would have had the benefit of completely isolating the wheels from the rest of the spacecraft. Options for either no wheel housing at all or an X-bracket cap for the housing were also included for consideration.

The modularity designs were one housing per reaction wheel assembly, a housing that allowed the motor and wheel to be easily removed, and an L-Bracket. Having a single housing per reaction wheel assembly would have provide the most versatility, allowing the wheels to be located anywhere in the spacecraft independent of one another. An L-Bracket housing would have allowed the 3 reaction wheels to be assembled using the least number of parts (hopefully simplifying the manufacturing process).

The concepts for interfacing between the motor and any form of housing consisted of glue (either to a back-plate or to the entire body of the motor), set screws, and a press fit into a cylindrical cutout. Using glue would have been the simplest method as well as one of the most secure. Both set screws and a press fit would have had the advantage of easily allowing the reaction wheel assembly to be removed, though in order to be secure the motor would need to be under compressive forces.

4.3.2 Top Ideas

Following system concept idea generation from the morphological matrix, five top level system concept designs were formulated in detail. Each one is presented and described below.

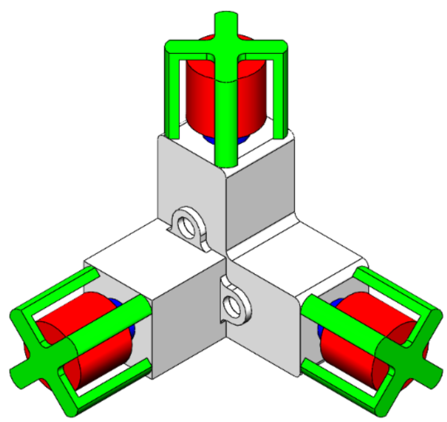


Figure 9. Concept CAD 1

The first system concept design is an L-bracket assembly where two reaction wheels are pre-attached in an L shape and the third can be attached or removed to the interface. This design uses a cylindrical motor housing inside the main housing that is attached by adhesive to the full body and the flywheels are covered by an x-bracket.

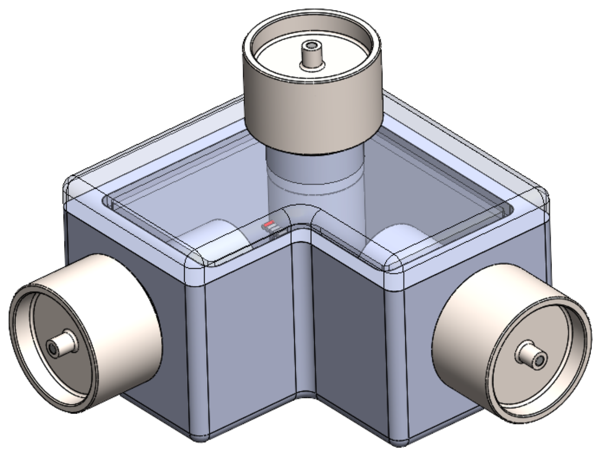


Figure 10. Concept CAD 2

This concept design incorporates the entire 3-axis system with three reaction wheel systems into one square housing which allows for the most containment (no interference with surrounding parts) and easier mounting. Each flywheel/motor system would have a cylindrical housing and a housing around the flywheel with openings. The system would have the ability to remove the flywheels and motors from the housing and when assembled the motor housing will be secured with adhesive on the full body.

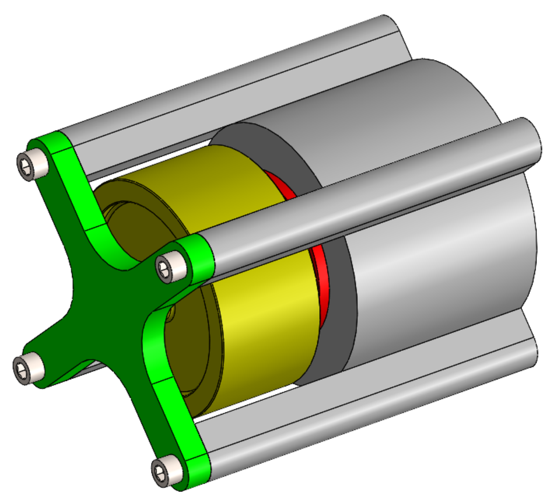


Figure 11. Concept CAD 3

Concept design 3 uses one housing per wheel and motor combination that consists of an x-bracket wheel housing that encloses the flywheel and a cylindrical motor housing that holds the motor and the motor attaches to the main outer housing with adhesive on the back plate.

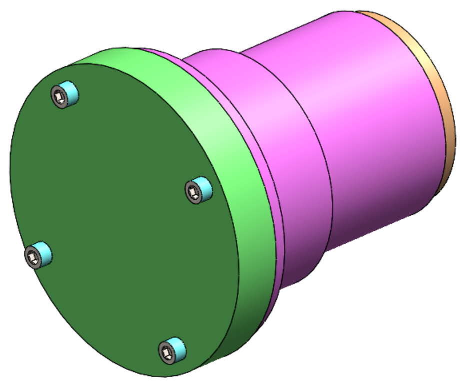


Figure 12. Concept CAD 4

Concept design 4 is a complete cylindrical enclosure for the flywheel and motor system containing a cylindrical motor housing with the motor secured to the housing by adhesive on the full body. Each wheel/motor combination would be separated for greater compatibility with different bus structures.

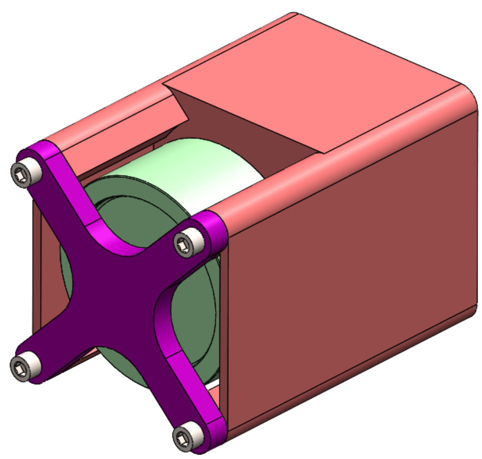


Figure 13. Concept CAD 5

The final concept design has an x-bracket wheel housing for the flywheel attached to a cylindrical overall housing with the ability to slide in the wheel and motor. The motor would have a square housing and would be secured by the back plate to the outer housing. This design would also have separate wheel/motor housing for each reaction wheel.

4.3.3 Weighted Decision Matrix and Design Direction

Taking into consideration the top 5 ideas described previously, a decision matrix was created to evaluate each concept system design against the customer specifications. First, to decide the weight of each specification, a pairwise comparison was used and can be seen below. Each specification was evaluated against each other to determine with ones were more/less important to the customer.

Table 6: Pairwise Comparison of Specifications

Criteria	Affordibility	Manufacturability	Ability to survive launch and on-orbit environemnts	Weight/mass	Volume	Compatibility with Bus	Versitile	Safety	Protects wheel and motor & other components	Assembly
1. Affordability	0.5	1	1	1	1	1	1	0	0	1
2. Manufacturability	0	0.5	1	0.5	0.5	0.5	0	0	0	0.5
3. Ability to survive launch and on-orbit environemnts	0	0	0.5	0	0	0	0	0	0	0
4. Weight/Mass	0	0.5	1	0.5	0	0	1	0	1	0
5. Volume (<1U)	0	0.5	1	1	0.5	1	1	0	0	0
6. Compatibility (with bus)	0	0.5	1	1	0	0.5	1	1	1	0.5
7. Versitile (with different CubeSats)	0	1	1	0	0	0	0.5	1	1	1
8. Safety (stuff in bus outside housing)	1	1	1	0	1	0	0	0.5	0.5	0
9. Protects wheel and motor & other components	1	1	1	0	1	0	0	0.5	0.5	0
10. Assembly	0	0.5	1	0	1	0.5	0	1	1	0.5
Summation	2.5	6.5	9.5	4	5	3.5	4.5	4	5	3.5
Weights	0.05	0.14	0.2	0.08	0.1	0.07	0.11	0.08	0.1	0.07

From the pairwise decision matrix, volume and weight/mass were decided to be the more important specifications. From there, these weights were put into the weighted decision matrix and each concept design was scored on a scale of 1-5 (1 being the worst, 5 being the best) for how well it meets each specification.

Table 7: Decision Matrix

Criteria	Weight Scale: %	System Concept Options									
		Concept 1: L-bracket assembly with cylindrical motor housing, X-bracket wheel housing , and adhesive on fullbody		Concept 2: One square housing for 3-axis system, cylindrical motor housing, wheel housing with openings, with ability to remove flywheel and motor from housing, secured with adhesive on fullbody		Concept 3: One housing per wheel/motor combo, cylindrical motor housing, x-bracket wheel housing, secured by adhesive by back plate of motor housing		Concept 4: Complete cyclindrical enclosure for both wheel and motor, cylindircal motor housing, sepate housings for each wheel, and motor secured to outer housing by adhesive on fullbody		Concept 5: X-bracket wheel housing with slide in wheel and motor, square motor housing, secured by adhesive by back plate, one housing per wheel	
		Score	Total	Score	Total	Score	Total	Score	Total	Score	Total
1. Affordability	0.05	5	0.25	5	0.25	5	0.25	5	0.25	5	0.25
2. Manufacturability	0.14	5	0.7	5	0.7	3	0.42	4	0.56	5	0.7
3. Ability to survive launch and on-orbit environemnts	0.2	3	0.6	4	0.8	3	0.6	4	0.8	3	0.6
4. Weight/Mass	0.08	2	0.16	4	0.32	4	0.32	2	0.16	4	0.32
5. Volume (<1U)	0.1	2	0.2	3	0.3	4	0.4	3	0.3	4	0.4
6. Compatibility between motor and wheel housings	0.07	4	0.28	4	0.28	4	0.28	4	0.28	4	0.28
7. Versitile (with different CubeSats)	0.11	4.5	0.495	1	0.11	5	0.55	1.5	0.165	5	0.55
8. Safety (with other c	0.08	3	0.24	5	0.4	5	0.4	5	0.4	5	0.4
9. Protects wheel and motor	0.1	3	0.3	3	0.3	5	0.5	5	0.5	5	0.5
10. Assembly	0.07	3	0.21	3	0.21	3	0.21	5	0.35	5	0.35
	Total:		3.435		3.67		3.93		3.765		4.35

Decision Matrices are used to compare possible solutions by weighing their contributing variables based on comparable importance. It logically creates a framework to make the decision on the final design based off the weighted number value determined rather than our personal biases towards each of the designs. We went through as a group, implementing the things found from the pairwise comparison and the morphological matrix, to assign scores to each value. There were three winning designs (ideas 2, 4, and 5), where the weighted scores ranked the highest. In actuality, the final design was a mixture of two out of these top three winning designs; the two ideas that were combined for the preliminary concept design were idea number 4 and 5, residing on a complete square enclosure, a cylindrical inner motor housing, full-body adhesive, and an X-bracket wheel housing.

The design selected is highly rated in manufacturability (2) because it does not have unnecessary X-cutouts, which do not save significant mass. Also, the overall safety (8) and protecting the wheel and motor (9) are highly ranked as well because it is fully enclosed. Since each wheel/motor combination is in its own separate housing, this design is more compatible with different CubeSats and easy to assemble (7 and 10).

4.4 Concept Design

The concept design that the decision matrix selected was Concept 4. However, while making the concept CAD and model, some design changes were incorporated from Concept 5 so that the final design concept was a combination of Concepts 4 and 5. Although both these had a cylindrical outer housing, after designing the CAD it was decided that a rectangular outer housing would be easier to machine on a CNC mill because it would have fewer curves and fillets with tight tolerances. Therefore, the concept design was adjusted to reflect this observation and the most updated version of the design that will be moved forward with in design analysis and CDR is presented below.

4.4.1 Concept Model and CAD

A concept model and CAD were created to experiment with the feasibility and assembly of the top design and to visually demonstrate the preliminary design in detail.

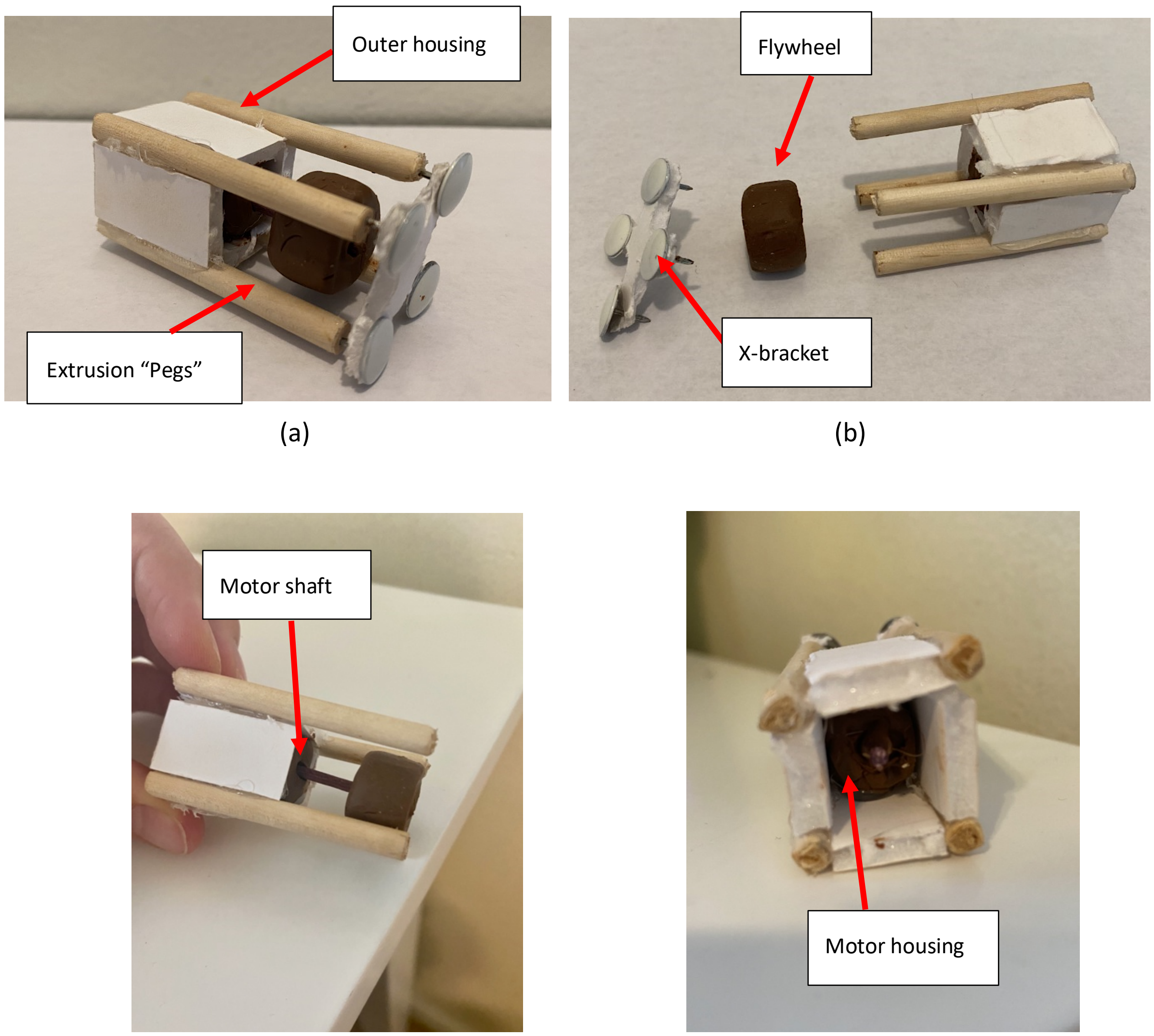
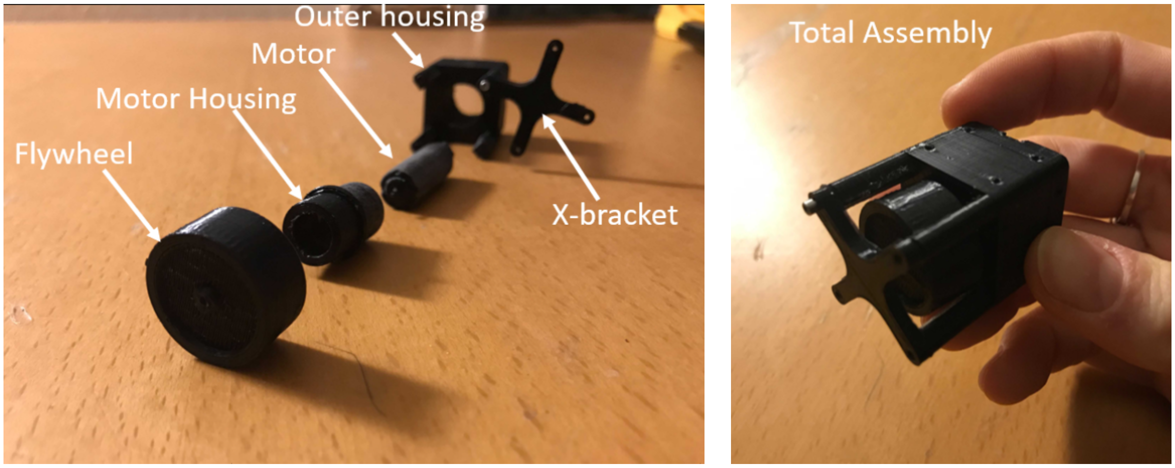


Figure 14. Initial Concept Model

A concept model was created using similar materials as the ideation models except building more to scale. Figures 14a-d show the concept model in different orientations. The outer housing of the reaction wheel is designed as a rectangular enclosure with four “pegs” or extrusions that extend from this enclosure to a x-bracket that can be removed and attached with fasteners demonstrated in Figure 14b and c. Inside the rectangular enclosure will be the motor and cylindrical motor housing which will be attached with epoxy on the entire body to the outer housing, as seen in Figure 14d. The flywheel and motor/motor housing system can be taken out of the outer housing in order to send to the balancing vendor, and then assembled by sliding it in through the front end where the x-bracket is. The flywheel is also shown removed from the shaft in Figure 14b, however, after it is balanced it will not be removed for any more adjustments.



(a) (b)

Figure 15. Secondary Concept Model

A secondary concept prototype was fabricated using 3D printing to further show detail of how the assembly will fit together, shown in the figure above. Due to the small size of our project, it was valuable to have a more accurate representation of the housing and reaction wheel interface. There were various pieces of the housing that did not have the clearance to fit together without some sanding to refine the clearances. Another lesson learned from this prototype is the future difficulty in #0-80 bolts. These bolts require specialty small Allen wrenches (0.050”) not found in many standard sets. Also, most #0-80 taps are relatively short, which begs the question of what the proper thread engagement level is. Both issues with these bolts will be troubleshooted and analyzed in our steps after the preliminary design.

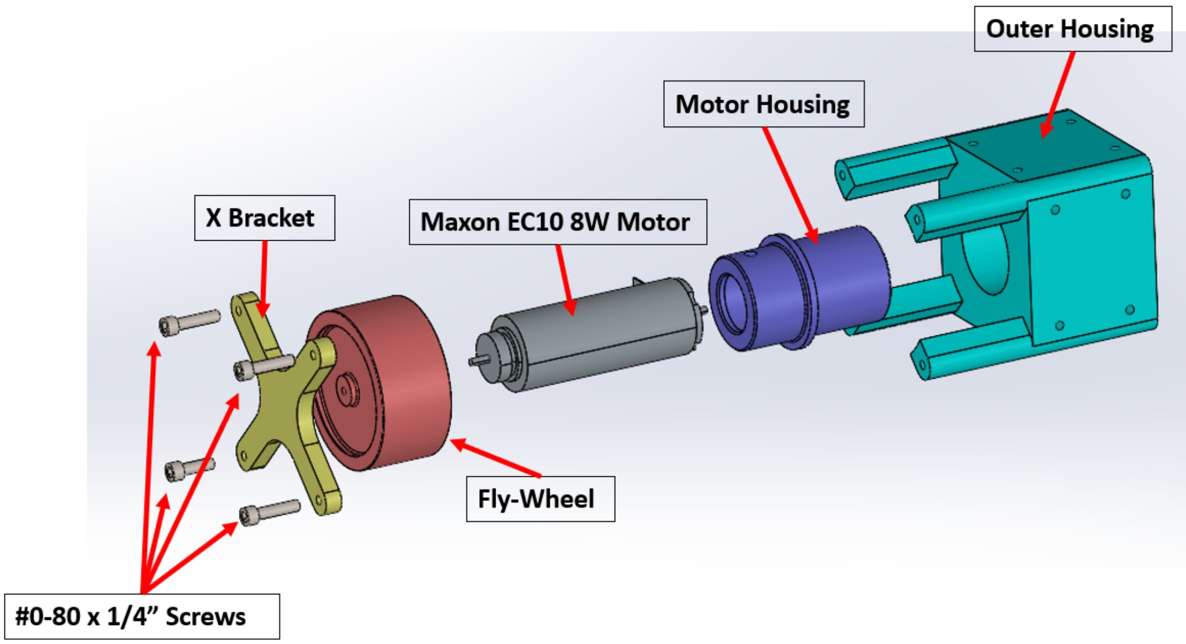
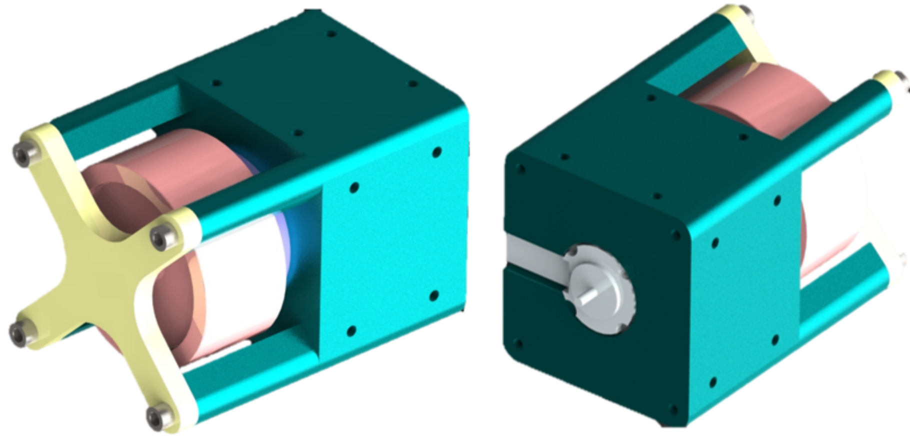


Figure 16. Exploded View of Concept CAD Model

Figure 15 shows a comprehensive overview of the reaction wheel assembly. The x-bracket is attached to the extruded "pegs" that extend out from the main body (outer housing) with #0-80 x ¼" screws. The outer housing contains the flywheel which is attached to the motor by the motor shaft. The motor shaft is then contained by the motor housing which goes inside the outer housing. This design is ideal because it allows the motor/flywheel assembly to be taken out of the outer housing to send to be balanced, and then it can slide back in and the motor housing can be secured will full body adhesive.



(a) (b)

Figure 17. Isometric Views of Concept CAD Model

The system design can be seen in its assembled form in the isometric views in Figure 16. The outer housing serves as a way to house the motor and motor housing as well as protect the flywheel from other components in the satellite such as harnessing (wiring) while still being mass efficient. The back view shows the motor's ribbon cable that will attach to the controller and other electronics in the CubeSat. There is a cutout in the outer housing that allows space for the ribbon cable and it will be removed when the motor assembly is inserted into the motor housing.

The outer housing is attached to the bus through fasteners and can be attached from any one of the 5 sides of the back of the housing. The concept of having the three reaction wheels separate is that they can be incorporated anywhere in the bus structure and be more efficient than putting a block of all three of them together. However, they have the flexibility that they can be bolted to each other to form one system.

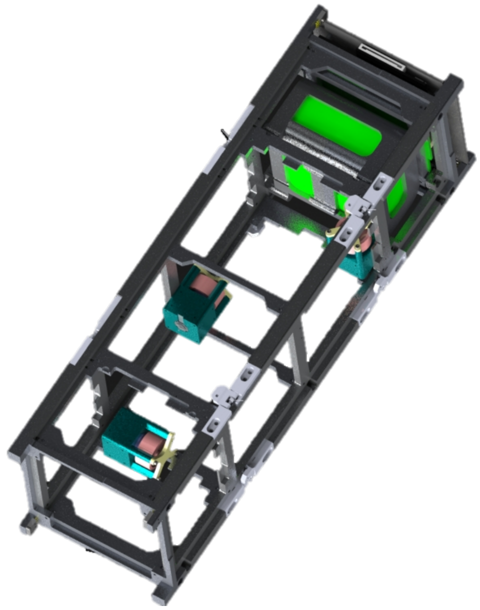


Figure 18. 3-Axis Reaction Wheel Layout integrated into a 3U Size CubeSat

Shown in the figure above is a 3-Axis Reaction Wheel Layout on a typical 3U CubeSat bus structure. The design provides the flexibility to place an individual reaction wherever there may be space in the CubeSat.

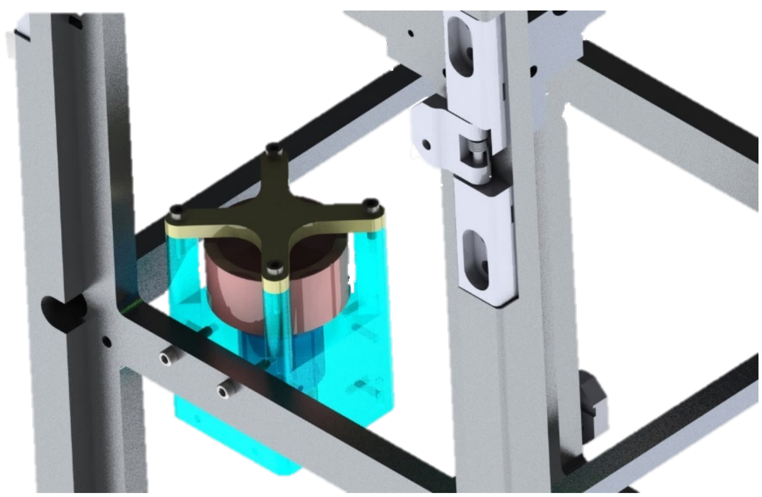


Figure 19. Reaction Wheel and Bus Structure Interface

The Reaction wheel system can be seen interfaced with CubeSat structure via two #0-80 screws that thread into the Blue outer housing. The mounting holes on the other 3 faces of the outer housing allow the system to be oriented in a direction that is favorable for the ribbon cable to be harnessed to the spacecraft and routed to electronics.

Some of the design features that are undefined and that will have to be evaluated and refined before the critical design review are listed below:

1. Modularity
   a. How can we attach 3 wheels together to create an optional 3-axis design while also having the ability to mount each one separately?
2. Assembly
   a. Is the motor wire removeable so that the motor/wheel assembly can slide into the outer housing from the x-bracket side?
3. Symmetry with fastener holes
   a. How can each face have four holes for attaching to the bus/each other without interfering with other holes?
   b. Can the length of the tapped hole be reduced? This will need an analysis of thread engagement
4. Holes for epoxy to seep out when setting
5. Can Larger Diameter screws be used?

4.5 Preliminary Analysis

Prior to any detailed design analysis, preliminary analysis was done to evaluate if the concept design will meet the engineering specifications. It must be noted that not all of the system requirements defined in section 3.5 of the report can be evaluated with respect to the housing design, such as momentum bit, torque output, and balancing grade and have already been evaluated in Bonafede's thesis of the preliminary wheel and motor design [1]. A complete analysis of the relevant specifications is provided on the following page.

Table 8. Analysis of how Concept Design meets Specifications

Spec #	Description	Requirement/Target	Current Concept Design	Pass/Fail/Unable to Specify
1	Mass	165 g per RWA (max)	60.2g	Pass
2	Cost	$2,000 for total system (max)	$1,518.66	Pass
3	Machinability	Fulfill CPCL Structural Review Checklist	-	Pass
4	Size/Volume	(max)	14 cm^3	Pass
13	Compatibility/Assembly (Mechanical/Electrical Interfaces & Integration into Satellite)	Fulfill CPCL Structural Review Checklist	-	Pass
14	Safety	Fulfill Senior Design Hazard Checklist	See section 4.6 Risk Assessment	Pass

Table 9. Cost Breakdown Estimate of Concept Design

Item	qty [-]	Cost [USD]	Subtotal [USD]
Controller	3	$83.22	$249.66
Motor	3	$323.00	$969.00
Wheel	3	$22.21	*$22.21
Motor Housing	3	$4.15	*$4.15
Outer Housing	3	$65.43	*$65.43
X Bracket	3	$13.43	*$13.43
Screws	12	$3.54	*$3.54
Balancing per Wheel	3	$100.00	$300.00
*= Cost for Stock for qty of 3(or qty >12)		Total	$1,518.66

Table 10. Mass/Volume Budget Estimate of Concept Design

Item	qty [-]	Material [-]	Mass [g]	Mass Subtotal [g]	Volume [cm^3]	Volume Subtotal [cm^3]
Controller	3	-	-	-	-	-
Motor	3	-	13	39	2.13	6.39
Wheel	3	316 Stainless Steel	11.45	34.35	1.43	4.30
Motor Housing	3	6061 T6 Aluminum	2.52	7.56	0.93	2.79
Outer Housing	3	6061 T6 Aluminum	24.81	74.43	9.19	27.57
X Bracket	3	6061 T6 Aluminum	1.54	4.62	0.57	1.71
Screws	12	18-8 Stainless Steel	0.11	1.32	0.01	0.12
			total	161.28	14.26	42.88

4.5.1 Balancing Plan & Specifications

The rotor balancing process is one that this team is familiar with through the Cal Poly ME 318 Mechanical Vibration course. However, the equipment needed to achieve a residual imbalance within the tolerance of around the width of single grain of salt is not something that the Cal Poly Facilities possesses. Therefore, the team has selected an outside vendor to balance the flywheel on the motor shaft. The team has selected Electronic Balancing Co. located in Wilmington, CA for reaction wheel balancing. This Balancing process was deemed a scheduling risk for manufacturing and testing on time and because of this risk, the team decided to select a balancing vendor before PDR.

The minimum residual imbalance (balance grade) the flywheel will be balanced to is a G2.5 quality grade at 5 Krpm max service speed corresponding to a permissible residual imbalance of 0.5 g-mm/kg rotor mass. This specification was selected through the *Balance Quality Grade for Rigid Rotors Table* in Appendix C.

The Balancing Specifications and Vendor was selected with the guidance of Cal Poly CubeSat Lab's connection, Aerospace Corporation, located in Los Angeles, CA. Aerospace Corp. has balanced hundreds of small reaction wheels for Picosatellite applications with Electronic Balancing Co. which is why they are a trustworthy vendor to balance the wheels.

The price for a single wheel's balancing is $85-$95, with a lead time of 1-5 days within receiving the parts. Given this information the team conservatively budgeted $100 per wheel and 5 days of lead time.

The process involves the shipping the assembled motor, wheel, and motor housing assembly to the vendor and emailing a detailed drawing of the flywheel to the balancing engineer indicating where material can be removed.

The team learned from the Chief Balancing Engineer (Lance Kouchi) at Electronic Balancing Co. that many companies tend to bend the motor shaft when pressing the wheel onto the shaft on their first couple batches of wheels (including Aerospace Corp.). Knowing this additional schedule risk, the team has allocated time to test press fitting techniques on machined "practice" shafts instead of the motor shafts. These press fitting tests will save the team both time and money.

4.6 Risk Assessment

As referenced by the Design Hazard Checklist (Appendix B) there are various hazards to our design that must be considered. Some of these are unable to be avoided, such as the potential for pinch points in the assembly when press fitting the shaft to the wheel. This press-fit will be a definite challenge, not only for its tight tolerances, but also in maneuvering such small components. When running the spinning wheel no one will have hands near it, so this is not a great concern or hazard under continual use.

Furthermore, there are both a flywheel and stored energy in the design as stated in the checklist as a risk. However, this risk is again accounted for because this spinning will not be occurring during either assembly or testing phases and be of no risk to the people handling assembly. To reduce the risk of the flywheel detaching or forming a projectile, an outer wheel housing was designed. In this design choice, it not only reduces risk to the mechanism itself, but also the risk posed where the wheel could damage other parts of the CubeSat.

One more hazard that was accounted for in the design is that it will be exposed to extreme environmental conditions, as observed in both the high energy launch environment and in the cold vacuum of space. To account for this hazard, TVAC and vibrational testing is used. Another unknown that must be approached is how the fixture for the testing will be designed. Again, this challenge occurs due to the size of our project being much smaller than most things that are tested using the TVAC chamber and vibes table.

There were quite a few hazards on the checklist; however, most do not occur in our design as a result of its small size considering it has no large moving masses, no overhanging weights, low noise levels, and no flammable or toxic substances. All sharp edges are filleted, so they are not a danger to either the personnel in assembly or the other components of the CubeSat. Therefore, by referencing the hazard checklist closely, along with our own personal judgement, the design was made to account for any dangers it would encounter, and the team is aware of the unknowns yet to solve for.

5.0 Final Design

5.1 Post-PDR Final Design

Following feedback from the project's sponsor, Dr. John Bellardo, the senior project class, and CPCL Mechanical Team, the reaction wheel design was updated and finalized. Some of the updates include adding a slot on all four sides of the back face of the outer housing (Green) for the motor wire to be routed, improving hole symmetry and screw selection on two sides and the back face, refining spacing in between the housings for epoxy, adding a motor end cap, and changing the material that the motor will be machined from. These design changes will be discussed in further detail later in this section.

The final design consists of three identical reaction wheels, each with three subsystems. The subsystems are the motor system, flywheel system, and outer housing system. Within the motor subsystem is the Maxon EC 10 mm diameter motor, the motor housing made of HyMu 80 alloy, and the motor end cap also made out of HyMu 80. The flywheel subsystem only consists of the 316 Stainless Steel flywheel which will be press-fitted onto the motor shaft. The final subsystem is the outer housing which will consist of the main housing and the x-bracket that will be attached with #2-56 screws. A detailed description of the assembly plan will be discussed in later sections.

The reaction wheel system in Figure 20 shows the integration of all the subsystems and components into the top-level final assembly.

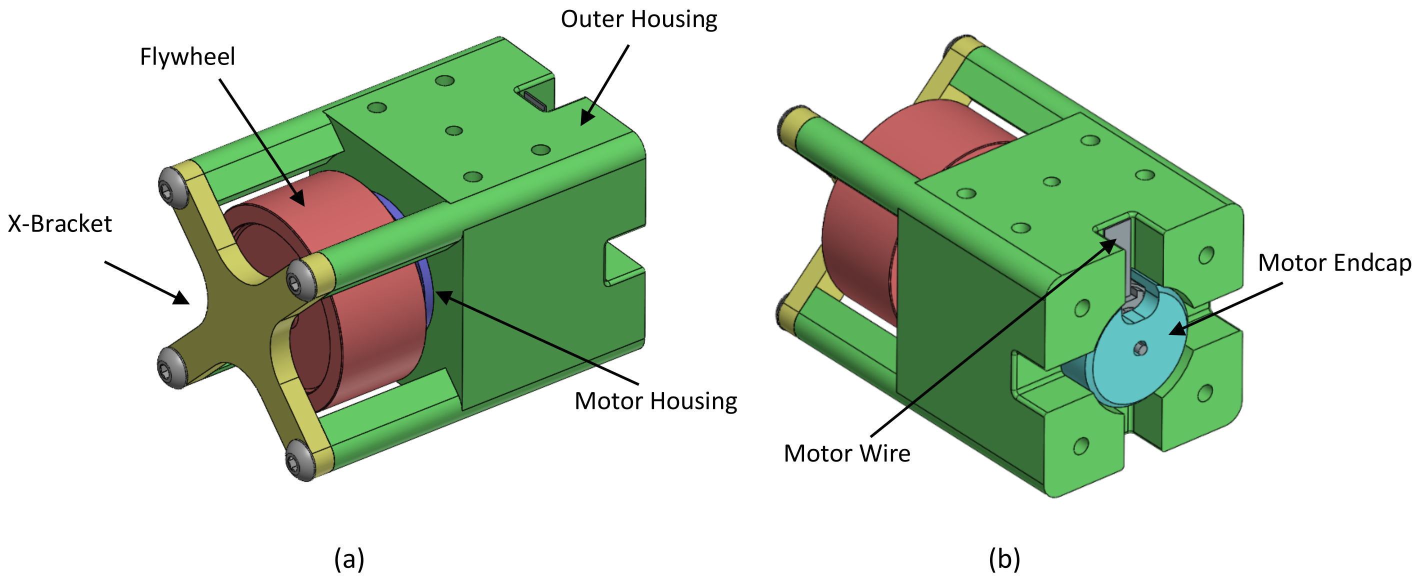


Figure 20. Reaction Wheel System Assembly

Figure 20 shows the newly added motor end cap that will fully cover the motor along with the original motor housing. The motor wire can also be seen routed out of the back of the reaction wheel system noting that the full length of the wire has been removed for clarity of the reaction wheel design.

Figure 21 shows an exploded view for a more detailed understanding of the integration of each component.

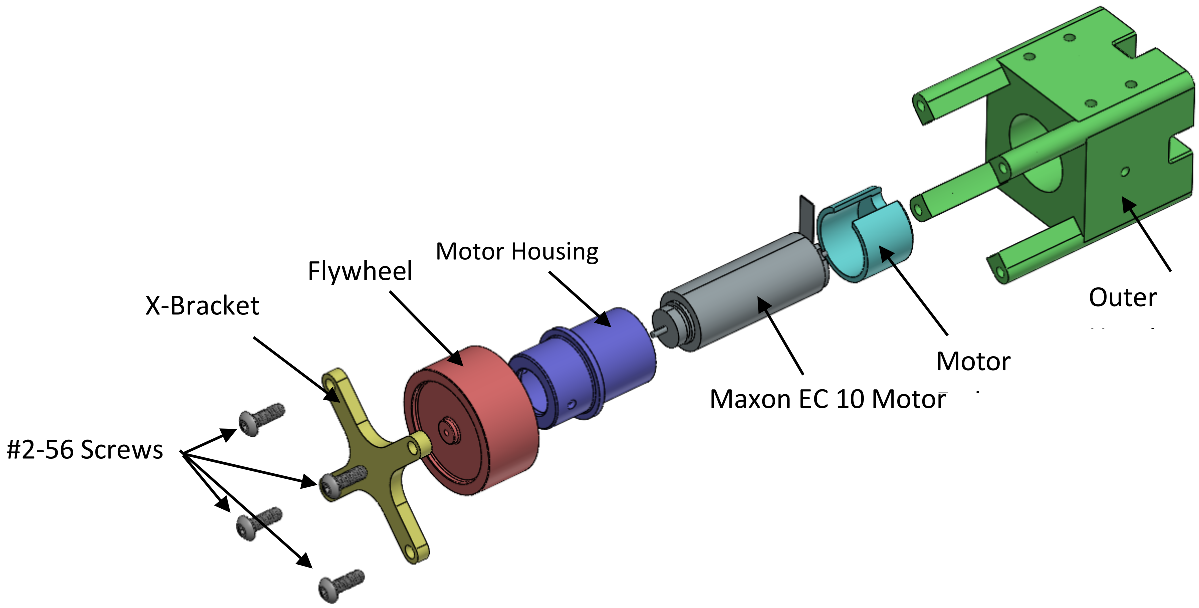


Figure 21. Exploded View of Reaction Wheel Assembly

In Figure 22 below, a detailed image of the outer housing shows the mounting holes both on the side and the back of the housing that are threaded #2-56 holes. The holes are located on both the side and the back for options when mounting the reaction wheel assembly to the spacecraft bus structure. Additionally, the slots for the motor wire exist on four sides to also allow for versatility in mounting since the mounting of the reaction wheels will depend highly on how easily the motor wire can be routed to the main electrical circuit board stack. A hole for epoxy leakage was added to the side face to allow for extra epoxy to seep out during assembly instead of seeping out the back our front of the housing.

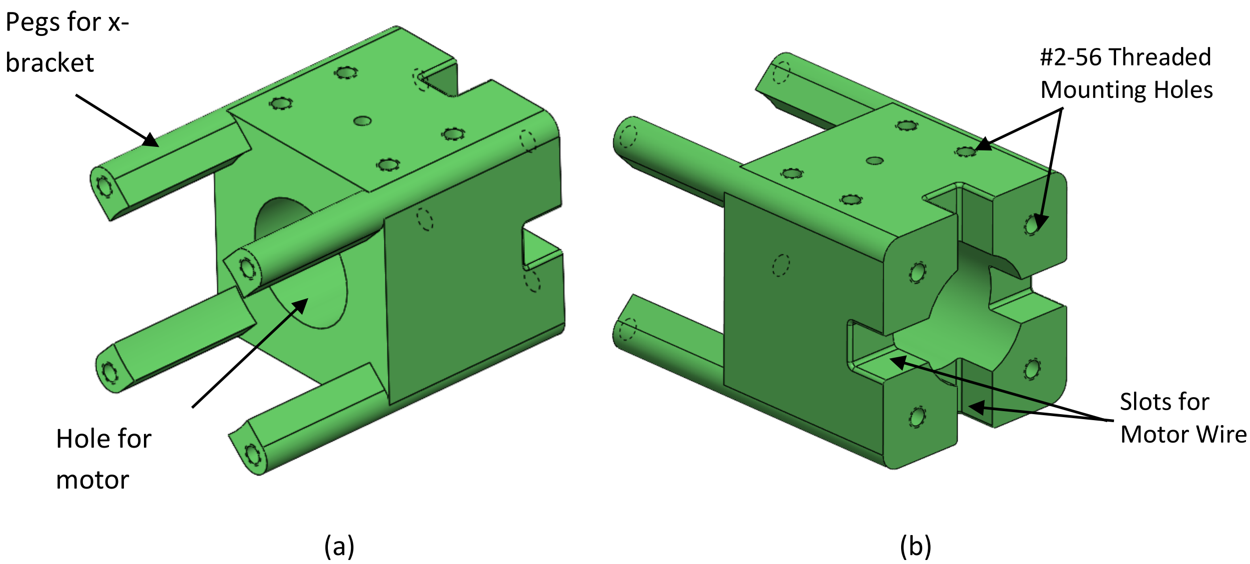


Figure 22. Outer Housing

Figure 23 shows the motor housing, which will be made of high permeability HyMu 80 alloy that protects the motor from emitting harmful magnetic fields. Its thickness is ideal for protecting the electric components inside and the outer ridge allows for proper placement into the outer housing.

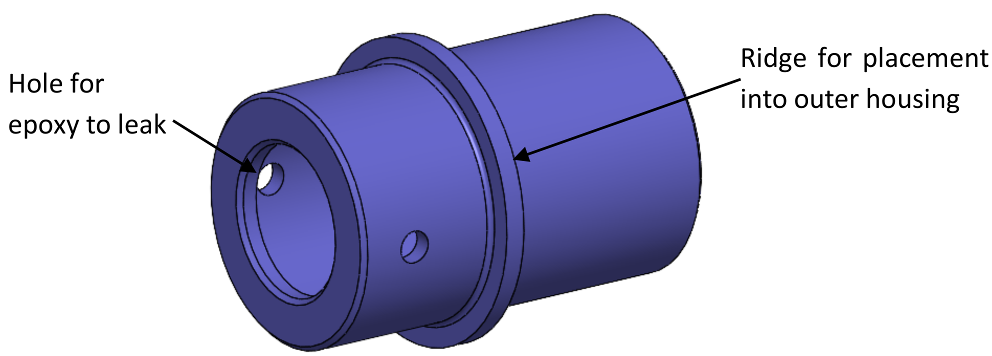


Figure 23. Motor Housing

The motor end cap is shown in Figure 24 and will also be made out of HyMu 80 alloy. It features a slot for the motor wire to be routed through in assembly and a hole for the motor end shaft to protrude through.

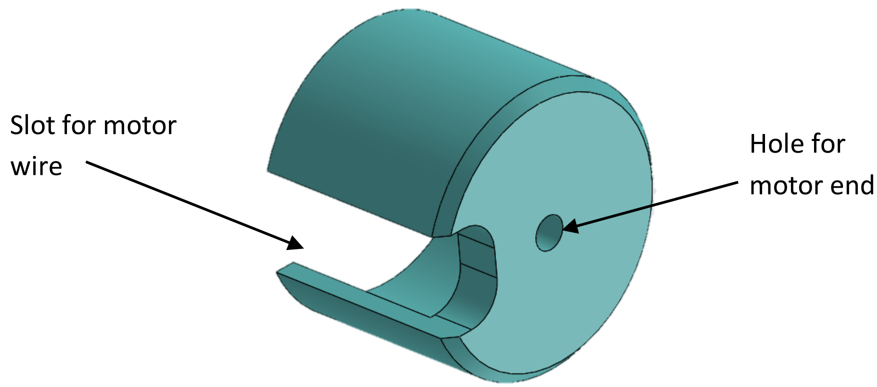


Figure 24. Motor Housing Endcap

The final component is the x-bracket that will be attached to the end of the pegs of the outer housing in order to protect the flywheel from interfering with other components. It features 4 holes for each #2-56 screw to attach to the pegs.

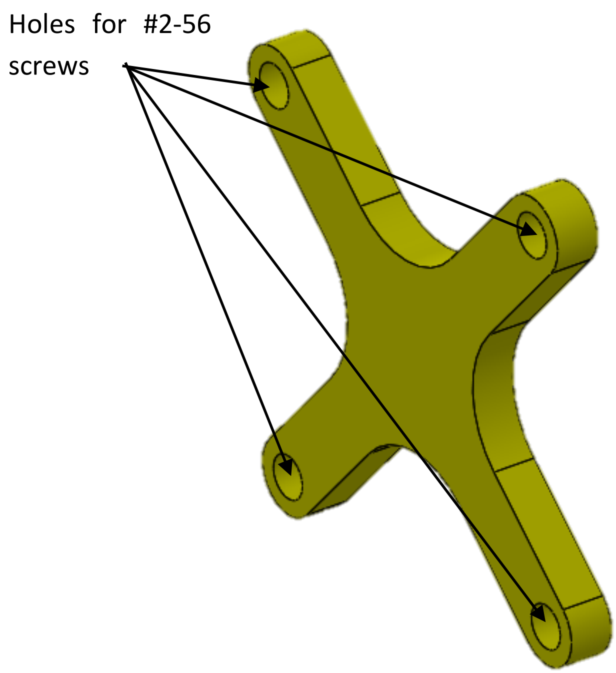


Figure 25. X-Bracket

The design will function by a pre-programmed controller sending instructions to the motor via the attached wire to specify the rpm. The motor will then spin the flywheel up to the specified rpm (performance characteristics will depend on controller selection and design, as specified in Bonafede's thesis) in order to produce a momentum impulse on the spacecraft to orient its position. The reaction wheel system's main performance will be in space, but testing will occur under normal atmospheric conditions and in a vacuum TVAC chamber to simulate space conditions.

The purpose of the inner (motor) housing is to protect the surrounding electrical subsystems in the spacecraft from the electromagnetic induction produced by the motor. The material used is HyMu-80 which is a magnetic shielding alloy whose main characteristics is high permeability used to shield against static or low frequency magnetic fields such as that produced by the motor. For more information on the HyMu-80 shielding alloy, refer to Appendix H.

The first design change made after PDR was to add more slots to the back face of the outer housing. This was to address the issue of symmetry and versatility when mounting the reaction wheel system to the spacecraft bus structure. Adding more slots to the back face allows the wire to be routed in any direction depending on the location of the reaction wheel. The motor will just have to be installed according to the mounting configuration needed because the motor wire is not removable. Additionally, because the slots were added, some of the holes on each side were removed to only leave mounting holes on one side because the versatility with mounting can be adjusted based on the motor configuration. This eliminates the hole interreference that occurred when there were mounting holes on each side face of the outer housing. The hole sizes were also increased to incorporate #2-56 screws since the #0-80 screws are very small and would have a greater risk for shear and tear out during launch environment. The #2-56 screw size still fits into the design with a distance of two times the diameter to the edge of the housing.

Another design update was increasing spacing between the motor and inner housing and between the inner housing and outer housing for epoxy. After researching the spacing used by Aerospace Corp. for Scotch Weld Epoxy, it was determined that a spacing of 0.3 to 0.5 mm would be enough for the epoxy to properly set.

The final major design change after PDR was adjusting the material that the motor housing will be machined out of and adding a motor end cap. In order to fully enclose the motor, however, an end cap had to be added so that the end of the motor would not be exposed. The end cap must have a slot in it so that it can be inserted onto the back of the motor without interfering with the cable and secured to the end of the motor housing with adhesive.

5.1.1 Electromagnetic Interference Mitigation (EMI)

With the compact packaging constraints that come with developing a picosatellite, the chance that a magnetometer is near a Reaction Wheel assembly is high. As mentioned previously, the motor produces a magnetic field that is not negligible to surrounding electronics. The sensor that is particularly concerning if readings are inaccurate is a magnetometer. A magnetometer is frequently used in conjunction with reaction wheel systems in order to precisely determine a spacecraft's attitude.

Electromagnetic Interference is mitigated on motors by surrounding the motor with a high magnetic permeability material with minimal hysteresis loss.

The team approached this issue by relying on magnetic shielding testing data supplied by an Aerospace Company affiliated with the lab. The material used in the test was the HyMu-80 material mentioned in previous sections. While the team could have chosen their own material, we would not have any sort of testing data on the efficacy of the magnetic shielding properties of the material.

Finally a machined housing was chosen as opposed to sheet metal due to the assembly complications the sheet metal would introduce and the lack of test data that was supplied to us regarding a Hymu-80 sheet metal's efficacy against EMI.

5.1.2 Structural Prototype

After refining the design, plans to manufacture a structural prototype were formulated. The goal of the structural prototype is to get a better idea of how the flywheel and motor shaft will be press-fitted. Since the motor shaft has a basic size diameter of 1 mm and the press-fit must be secure in order to maintain the proper moment of inertia at the center of mass, the tolerances are small and precise (see section 5.2.3 Hole Fit Analysis for a detailed description). Additionally, the shaft is very thin and extra precaution must be taken when press-fitting not to bend or break the shaft. Therefore, our structural prototype will be utilized to test the hole fit and press-fitting, as well as practicing the manufacturing of the flywheel and ordering necessary additional tooling.

The manufacture of the wheel was a learning process, not only to get refamiliarized with the CNC Lathe and Mill but also in the manufacturing operations that would be needed in the first iteration of the CAM (computer automated manufacture file that is how the machines are programmed). One bit takeaway was work holding methods. The first plan was to use the rotary vice on the CNC mill (after the outer diameter was turned and parted on the lathe), however a better method was used. A member of steel bridge graciously lent us her soft jaws (able to hold the smaller diameter of the wheel), but in future iterations it is a good idea for us to make a set of our own. Furthermore, it was a learning experience to utilize the chamfer tool on the CNC, as we had never done that before, so the part had much bigger chamfers than intended for this structural prototype.

The goal of our structural prototype was to learn not only about the manufacturing method but, more importantly, to attempt a press fit onto the wheel. In the manufacture of this, a clearance hole of 1mm was made, as we had not yet purchased the tiny drill bit or reamer necessary to do an interference fit. However, this was a good mistake because even though technically the holes should have fit together, there was still a need to press them together (not by hand). Since the hole was tighter than we were expecting, we reflected this design to do an analysis of a clearance hole and have such begun investigating epoxies needed to secure this clearance fit.

MicroVue Coordinate Measurement Machine for Shaft Measurements

Initial Structural Prototype Hole Test Fit

Figure 26. Initial Structural Prototype Measurements and Assembly Testing

Above is a picture or our first attempt at a press fit using a mini arbor press to make sure that the shaft was perfectly vertical in the hole. Due to the strength of the arbor press, and not using any fixturing, the shaft protruded through the top of the wheel more than it was supposed to. This test was with a shaft diameter of 0.0384” (measured on the optical comparator, see Figure 26). This corresponds to the clearance fit performed in the hole fit analysis found in section 5.2.3. It was discovered that the way that we press fit the shaft caused it to lose its concentricity, so we decided to reattempt the press fit on a second shaft.

Figure 27. Second Hole Test Fit

For the second hole fit test, the other side of the same original shaft was used. Both ends of this shaft provided a clearance fit for the hole created, one side was measured as 0.0381” diameter. For the second press fit, it was performed by hand to see that it was able to be done without an arbor press successfully. When this second press fit was performed, a small wooden fixture was created to be able to align the press end of the arbor press and the top of the flywheel so that it would be properly concentric with the shaft. For our actual design, we decided that it would be a better idea to have a metal fixture for this operation, so that it would be able to be more repeatably positioned. This fixture would be an additional part to manufacture but is still a relatively simple lathe part.

Table 11. Prototype Measurements

Wheel			Shafts			Hole-Shaft Fit	
Measurement	**(in)**	**(mm)**	**Portion of Shaft**	**(in)**	**(mm)**	**Difference (mm)**	
OD	0.829	21.0642	1 left	0.0389	0.98806	-0.010160	interference
ID Hole	0.039	0.9779	1 right	0.0392	0.99568	-0.017780	
	0.038	0.97536	2 left	0.0381	0.96774	0.010160	clearance
Thickness	0.392	9.9568	2 right	0.0384	0.97536	0.002540	

After the assembly was performed, the shaft was spun on a hand drill to accelerate its rotation up to 1600 rpm. When this was successful, the shaft was secured in a lathe to be spun up to 2000rpm for approximately five minutes. This was also a successful test, where the wheel did not fly off the shaft at all. This is proof that even with a clearance fit, it was able to stay on well.

5.2 Analyses

5.2.0 Target Structural Margins/Factors of Safety

To ensure adequate target safety factors were selected we consulted the NASA General Environmental Verification Standard that is widely used by the Aerospace Industry. From the table shown below we are going to be performing Static Structural Analysis on a Metallic material and since we are validated with only analysis and not performing a test in a centrifuge, we will be targeting a safety factor of 2.6 when compared to Ultimate Strength.

Table 2.2-3
Flight Hardware Design/Analysis Factors of Safety Applied to Limit Loads [1,2]

Type	Static	Sine	Random/Acoustic[4,5]
Metallic Yield	1.25[3]	1.25	1.6
Metallic Ultimate	1.4[3]	1.4	1.8
Stability Ultimate	1.4	1.4	1.8
Beryllium Yield	1.4	1.4	1.8
Beryllium Ultimate	1.6	1.6	2.0
Composite Ultimate	1.5	1.5	1.9
Bonded Inserts/Joints Ultimate	1.5	1.5	1.9

1 – Factors of safety for pressurized systems to be compliant with AFSPCMAN 91-710 (Range Safety).

2 – Factors of safety for glass and structural glass bonds specified in NASA-STD-5001

3 – If qualified by analysis only, positive margin must be shown for factors of safety of 2.0 on yield and 2.6 on ultimate. See section 2.4.1.1.1

4 – Factors shown should be applied to statistically derived peak response based on RMS level. As a minimum, the peak response shall be calculated as a 3-sigma value.

5 – Factors shown assume that qualification/protoflight testing is performed at acceptance level plus 3dB. If difference between acceptance and qualification levels is less than 3dB, then above factors may be applied to qualification level minus 3dB.

Figure 28. NASA GEVS Factor of Safety Standards [21]

5.2.1 Critical Speed Shaft Analysis

The motor shaft from the vendor, Maxon, is made of 316 Stainless steel with a specified no-load speed of 57,100 rpm, 12N max force for press-fit (approximately 2.7 lbs.), and 2N max radial load. However, the max speed of the flywheel is limited by the saturation speed of the motor which is 53,400 rpm. The weight of the stainless-steel flywheel is 0.11 N so from initial inspection, the flywheel should not bend or break the shaft. However, since the flywheel is much larger than the shaft and will be spinning at high rpms, a critical shaft analysis was necessary to ensure the safety of the shaft. The operational speed of the flywheel was set equal to 57,100 rpm because even though the flywheel will be operating in a range from 0-53,400 rpm, the maximum case scenario was used for operation speed to ensure a conservative estimate. Using this operation speed and the dimensions specified in the drawings, it was determined that the max shaft displacement under rotational loading was $1.55 \times 10^{-10\,m}$, which is essentially negligible. This gives the shaft diameter a safety factor of 42 which is well within reason. For the detailed analysis, see Appendix K.

5.2.2 Quasi-Static Acceleration Loading for Spacecraft Applications

During the launch of a launch vehicle or rocket various axial and lateral acceleration loads are imparted by the launch vehicle on an on-board spacecraft through a complex mix of vehicle accelerations, pitch maneuvers, aerodynamic buffeting, and coupling of loads. These quasi-static acceleration loads can be typically found in a launch provider payload user guide. Shown below is an Axial-Lateral Acceleration diagram found From Firefly Aerospace's Alpha Rocket and the SpaceX Falcon 9 rocket. As seen in the charts below the maximum axial and lateral acceleration varies from one launch vehicle to another. Since the team aims to design a system that can achieve adequate safety margins for a wide variety of launch vehicles, we conservatively assumed axial and lateral acceleration factors of 10g.

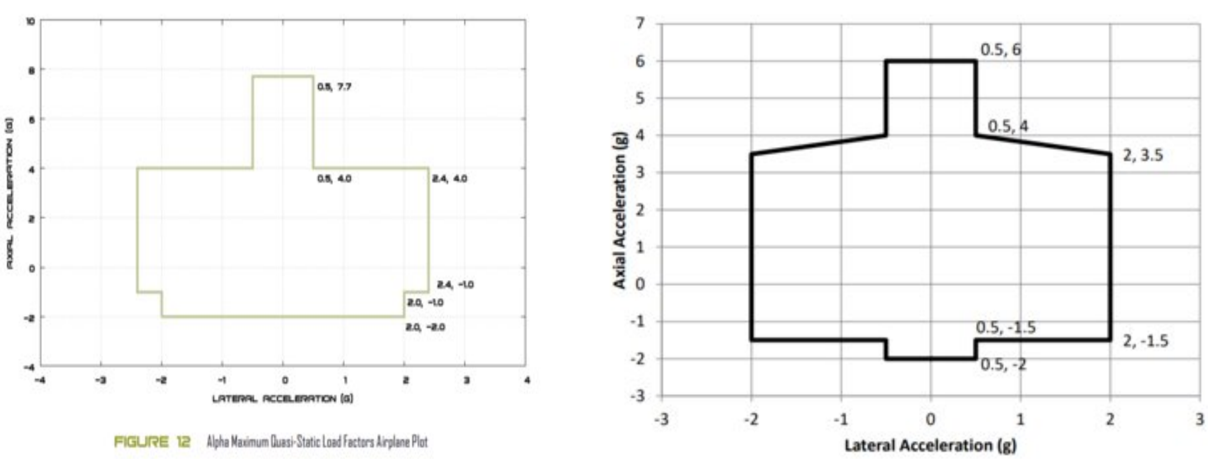


Figure 29. Quasi-Static Acceleration Load Factor Plot for Alpha and Falcon 9

5.2.3 Quasi-Static Acceleration Loading Shaft Analysis

A critical area in the reaction wheel system that we decided to analyze is the shaft bending stress that is induced by the mass of the flywheel. We decided that an appropriate engineering model for the flywheel mounted onto the shaft was a fixed-free cantilever beam. We conservatively concentrated the mass of the wheel to the free end of the shaft. Shown below is a cross sectional view of shaft-flywheel system and the corresponding engineering model we chose for the system. Where l is the length of the shaft, and F is 10 times the weight of the flywheel. This model yielded us a max bending stress of 32.57MPa, which in turn yielded us ultimate strength factor of safety of 19.49 for a Carbon steel shaft. This design margin greatly exceeds our target factor of safety of 2.6. For detailed hand calculations consult Appendix P.

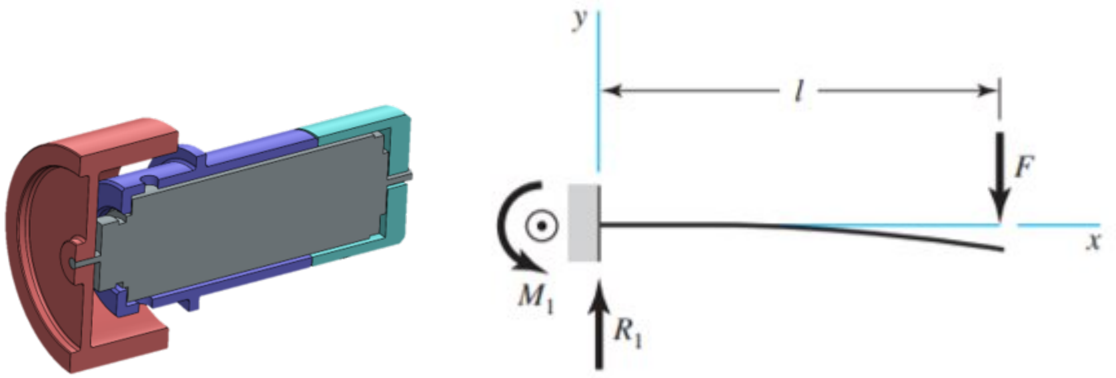


Figure 30. Shaft-Flywheel Engineering Model

5.2.4 Quasi-Static Acceleration Loading Threaded Fastener Analysis

Another critical area in the reaction wheel system that is of concern when accelerating 10g's was the fastened interface that secures our entire Reaction Wheel Assembly to the spacecraft structure. The engineering model that was chosen was to conservatively assume that one critical screw would take the load of the entire reaction wheel assembly. A center of mass was found using a tool available in Solidworks CAD software. We then conservatively analyzed the bolt that would have the furthest center distance. Seen below is the center of mass imposed on the CAD model and the center distance from the center of mass to the furthest screw.

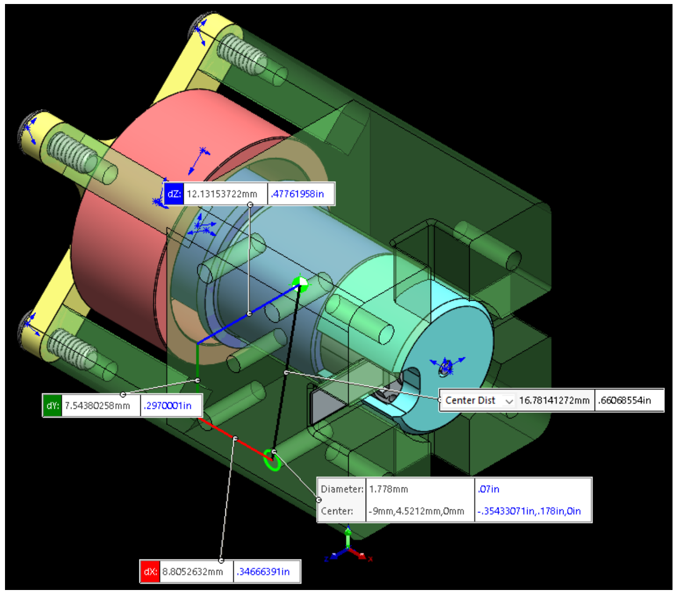


Figure 31. Threaded Interface Engineering Model

The mass of the reaction wheel assembly was conservatively lumped at the center of mass of the assembly. The shear and bending stresses induced by the 10g loading were then analyzed and summarized in a Von Mises stress calculation. The fasteners of concern are #2-56, 18-8 stainless steel screws, and the target factor of safety is again 2.6 as per the NASA GEV Standard. The maximum bending stress induced on the fastener was 74.03MPa and the maximum shear stress was 1.66MPa. It was observed that the major stresses induced on the system were due to bending. The ultimate tensile strength of 18-8 stainless steel is 482.6MPa (70ksi), producing a minimum factor of safety of 3.78, which happens to be well above our target margin.

5.2.5 Thread Engagement Fastener Analysis

It is preferable to have the fastener break rather than strip out the threads if a joint is going to fail. Therefore, an analysis was performed to see the threshold of minimum length of screw engagement was successfully achieved with the length of bolts selected, as shown in Appendix Q. The fastener sizes and specifications are consistent for both the side mounting of the outer housing to the CubeSat Structure as well as the front-face mounting of the X-bracket. In this analysis, it was determined that the minimum length of engagement is much less than the threaded portion of the fastener. This means that the minimum thread engagement was successfully surpassed. From this, it can be concluded that the bolt will break before the threads strip out of the housing, which is a preferable failure mode for the system. So, it was found that the ¼” #2-56 fastener is satisfactory, and this analysis is consistent for all parts of securing both components to the outer housing and the outer housing to the overall CubeSat Structure.

5.2.6 X-Bracket Interface Loading Threaded Fastener Analysis

A simple secondary loading analysis was performed for the force applied to the X-Bracket, shown in Appendix R. This verification attests to the security of our design (as it protects the internal CubeSat components from the event of a failure). It was assumed that all bolts equally share the loading for this analysis, distributed along the four corners of the X-Bracket. The maximum allowable stress that each fastener could retain was determined to be 43.5 lbf, working backwards from the overall yield stress specified. Another basic analysis performed within this was loading the force as a 10 g launch environment, utilizing the mass of the flywheel as 11 g. With these conditions a calculated 10 ksi, which is also well below the 30 ksi ultimate loading stress. Therefore, from this basic overview, the fastener analysis for the X-Bracket showed that these will not be the main point of failure if the flywheel were to become dislodged from its shaft.

5.2.5 Hole Fit Analysis

The mounting of the motor shaft to the flywheel hole must be precisely sized for a press fit. Originally, an interference fit was chosen to assure that the wheel would be properly secured to the motor since it will be spinning at extremely high rpms. However, concerns were raised regarding bending the shaft during press-fitting since the maximum load for press fit specified by the motor vendor is 12N. An interference fit would increase the risk of bending the shaft when mounting the flywheel on the motor shaft. Therefore, calculations were done for a clearance fit as well.

Referring to Table 7-9 in *Shigley's Mechanical Engineering Design* [25] the optimal clearance fit for this application is *the locational clearance fit* H7/h6 based on ISO standards. The capital letter refers to the hole and the lower-case letter refers to the shaft. Since the shaft tolerances are provided by the manufacturer are predetermined, the denotation "h" for the shaft (meaning no deviation) is satisfactory. In ISO standards, the letters represent the fundamental deviation, and the numbers represent the tolerance grade used to calculate the maximum and minimum dimension of a hole and shaft. For the shaft, the basic size is 1 mm, and the deviations are -0.009 mm and – 0.003 mm. Since tolerance grade is calculated from the difference between the maximum and minimum dimensions, the tolerance grade for the shaft is 0.006 mm, which matches the grade in Table A-11 in *Shigley's* [25] for IT6 and a 1 mm basic size. Table A-12 in *Shigley's* specifies fundamental deviations for shafts based on the letters of the fit (all Shigley's tables referenced can be seen in Appendix N). Since both the hole and the shaft are "h" then their upper and lower deviations are both zero. Plugging this into the fundamental equations yields the following fits and tolerances.

The same process was done for an interference fit, choosing the *medium drive fit* H7/s6. However, since the shaft has given tolerances and cannot have deviations, the lower-case letter must be changed to "h" indicating no deviation making this interference fit H7/h6. The same process was done for the interference fit as described in the clearance fit. The results are presented in Tables 12 and 13 below. For the full analysis of both an interference and clearance fit, please see Appendix M.

Table 12. Hole Fits and Tolerances for Clearance Fit

	Hole	Shaft	
Nominal (mm)	Ø 1.00 +0.007 -0.003	Ø 1.00 -0.003 -0.009	
Maximum (mm)	1.007	0.997	Max Interference -0.00 mm
Minimum (mm)	0.997	0.991	Max Clearance +0.014 mm

Table 13. Hole Fits and Tolerances for Interference Fit

	Hole	Shaft	
Nominal (mm)	Ø 1.00 +0.017 -0.027	Ø 1.00 -0.003 -0.009	
Maximum (mm)	0.983	0.997	Max Interference -0.024 mm
Minimum (mm)	0.973	0.991	Min Interference -0.008 mm

According to these fits, the tolerance for the hole is 0.01 mm for both a locational clearance fit and medium drive fit, which is equivalent to 0.3 thou. This is a very tight tolerance but may still be possible with a specialized reamer. If this tolerance proves to be too tight, a larger clearance fit will be used, and the hole will be filled with a special adhesive to bond the shaft and hole.

5.3 Safety, Maintenance, and Repair

The main concerns for safety of our wheel lie in avoiding damage to other components within the satellite. This safety concern guided a lot of our design in creating an outer housing in the case of the wheel flying off of the motor shaft. Since the flywheel will be spinning at high rpms and accelerating and decelerating to produce an impulse, the x-bracket was created to prevent the flywheel from damaging other components in the spacecraft.

The other safety concern would be in the process of testing for TVAC, vibrational loading, and controller function. This would be the only time that the reaction wheel assembly would be directly running when humans are present. However, during these tests, proper Personal Protective Equipment (PPE) will be worn, so that this safety is handled. Once complete, these designs will have no maintenance or repair, as they will be inaccessible in a launched CubeSat. For a full analysis of other safety concerns, see Appendix B for the Design Hazard Checklist.

5.4 Cost Summary (pre-Procurement)

The total budget for this project was specified as $2,000 and the project remains under the budget at a total of $1,858.04 for components and balancing (not including tax and shipping and handling). However, there will also be additional costs for tooling that will increase the budget over the specified limit. With permission from the sponsor to go over-budget, the project has moved forward with purchasing and procurement.

For the controller and motor subsystem, the total cost includes one Maxon ESCON Module controller at $101.50 and 3 EC 10 motors at $323.00 each. This comes out to be $1,110.50 for this subsystem including estimated shipping and packaging costs.

For the flywheel subsystem, the 316 Stainless Steel stock and cost for balancing each wheel comes out to be $339.97 without tax and shipping for the flywheel stock. The motor housing subsystem will be made out of HyMu 80 which will be $300 for the stock not including shipping and handling. The outer housing subsystem, including the x-bracket will be $79.66 not including shipping and handling.

Extra components such as the scotch weld epoxy, screws, and the 1 mm stainless steel test shafts will come to a total of $67.91.

The tooling cost and breakdown can be found in the manufacturing section and is considered to be longevity investments for CPCL for the project to be produced and manufactured in the future.

5.5 Design Changes Post-CDR

The design was finalized in the critical design review report; however, a few changes occurred following CDR based on new information and feedback. The biggest of these changes was changing the size of the hole in the flywheel from an interference fit to a clearance fit with extra room for shaft-locking adhesive or epoxy. This was changed following a meeting with David Hinkley from Aerospace Corp. who recommended using a clearance fit with shaft-locking adhesive because of the high risk of bending the shaft with a press fit. Even if the press fit is a clearance fit as opposed to interference fit is still tight and would risk bending the motor shaft which would mean the assembly would be rejected from the balancer. Therefore, the diameter of the hole in the flywheel was increased by 1 thou from 0.039 inches to 0.040 inches, again by recommendation of Aerospace Corp.

Another design change that was implemented post-CDR was more clearance between the motor housing and outer housing for epoxy. This was also increased by 1 thou.

The mass-volume budget was updated with the HyMu-80 material for the motor housing and motor endcap, which is denser than the original proposed aluminum and increased the total mass. Additionally, some small tweaks to the design were made to accommodate more epoxy in between the motor and outer housing. The updates to Table 10 are shown in Table 14.

Table 14. Final Mass-Volume Budget

Item	qty	Material	Mass	Mass Subtotal	Volume	Volume Subtotal
	[-]	[-]	[g]	[g]	[cm^3]	[cm^3]
Controller	3	-	-	-	-	-
Motor	3	-	13	39	2.13	6.39
Wheel	3	316 Stainless Steel	11.45	34.35	1.432	4.296
Motor Housing	3	HyMu 80	7.748	23.244	0.886	2.658
End Cap	3	HyMu 80	4.12	12.36	0.47	1.41
Outer Housing	3	6061 T6 Aluminum	27.13	81.39	10.05	30.15
X Bracket	3	6061 T6 Aluminum	1.5	4.5	0.55	1.65
Screws	12	18-8 Stainless Steel	0.11	1.32	0.01	0.12
			total for 3	196.164	15.528	46.674

6.0 Manufacturing

6.1 Material Procurement

A complete analysis of the manufacturing plan was performed to determine the procurement procedure for each component of the design. The entire structure was machined in-house, with the exception of the motors and controller which were purchased from Maxon.

For the flywheel, inner housing, outer housing, and x-bracket that were machined in house, stock was purchased and procured from various vendors. For the flywheel, outer housing, and x-bracket stock was ordered from McMaster-Carr and arrived within four days of purchase. Members of the team split up ordering different parts and then filled out a reimbursement form to submit to the Cal Poly Corporation to be reimbursed from CPCL funds. The inner housing stock (HyMu 80) was more expensive and was purchased by the project's sponsor directly and shipped to the CPCL office in approximately 2 weeks because it was a relatively small order since it was not purchased in bulk. The reimbursement form process was also used for tooling, with Rose ordering all tooling from McMaster-Carr and being reimbursed by the Cal Poly Corporation via reimbursement form.

The other components that needed to be procured besides the tooling and stock were the Maxon motors and controller, #2-56 screws, and 1 mm test shafts. The Maxon motors and controller were more expensive so they were purchased directly by the project's sponsor and shipped to the CPCL lab on campus. The lead time for the three motors and controller was approximately a week and a half. The #2-56 screws were ordered from McMaster-Carr along with orders placed for stock and finally the 1 mm shafts were ordered from Amazon and arrived in three days.

For a full list of components and their stock or material to be procured, see Table 16 below and refer to Appendix J for a more detailed summary on cost.

Table 15. Material Procurement Summary

Item	Qty	Length/ Info	Part Number	Vendor
Controller	1	ESCON Module 24/2, 4-Q servo controller, 2/6 A, 10-24 VDC	466023	Maxon
Motor	3	EC 10 - 10 mm dia, brushless, 8W, w/ hall sensors	315173	Maxon
Wheel Stock	1	316 Stainless Steel 2 ft rod bar stock, 7/8" dia	89325K19	McMaster
Motor Housing Stock	1	HyMu 80 bar stock Circular 0.75" dia x 24" length	n/a	National Electronic Alloys
Outer Housing Stock	1	6061 Aluminum 1" Thick, 2" x 48"	9246K781	McMaster
X Bracket Stock	1	6061 Aluminum 0.09" Thick, 4" x 24"	89015K222	McMaster
Screws	1	#2-56 x 1/4" Socket Head (pack of 100)	92196A077	McMaster
1 mm shafts	2	316 Stainless Steel 7.31" long	1265K11	McMaster
Shaft Locking Adhesive Rite-lock 48	1	3M SCOTCH-WELD RT48 50ML; PRESSURE FIT HIGH-TEMP	054007-99632	rshughes
Epoxy: Scotch Weld Epoxy (Aerospace corp.)	1	3M Scotch Weld Epoxy Adhesive 2216, Translucent, Part B/A, 2 fl oz kit	n/a	Amazon
Soft Jaw Aluminum	1	Scavenged	n/a	All Industrial
TiAlN-Coated High-Speed Steel Drill Bit	2	1/16" Size	3202A244	McMaster
TiN-Coated Carbide Rounded-Edge Square End Mill	3	4 Flute, 1/8" Mill Diameter, 0.015" Corner Cut Radius	2851A211	McMaster
Fast-Cutting Carbide Square End Mill	2	AlTiN Coated, 4 Flutes, 1/8" Mill Diameter, 1/2" Length of Cut	8207A27	McMaster
Fast-Cutting Carbide Square End Mill	2	TiAlN Coated, 5 Flutes, 1/4" Mill Diameter, 3/4" Length of Cut	8207A49	McMaster
Fast-Cutting Carbide Square End Mill	2	TiAlN Coated, 5 Flutes, 3/16" Mill Diameter, 5/8" Length of Cut	8207A489	McMaster
TiN-Coated High-Speed Steel Drill Bit	3	Wire Gauge 63, 1-1/2" Overall Length	29045A821	McMaster
TiN-Coated High-Speed Steel Drill Bit	2	Wire Gauge 62, 1-1/2" Overall Length	29045A822	McMaster

0.0385 HSS Straight Flute Chucking Reamer	2	0.0385 HSS	416-0652	Shars
0.04 HSS Straight Flute Chucking Reamer	2	#60 (0.0400)	416-0222	Shars
TiAlN-Coated High-Speed Steel Drill Bit	2	1/16" Size	2851A212	McMaster

In the budget, due to the various complex machining operations as well as incorporating the machining of a super-alloy (HyMu-80), approximately $500 was allotted for various tooling. The tool breakdown will order one of each tool required, allotting extra money in the budget to replace tools when they did break during the manufacturing process (especially of the MyMu-80 Alloy). The tool breakdown and the stock costs and sizes are included in the following two tables below.

Table 16. Tooling Breakdown

Tool	Component	Cost (ea.)
3/16” Coated Carbide Endmill	All	25.03
1/4” Coated Carbide Endmill	All	31.28
1/16” Drill Bit (x2)	Inner Housing	4.36
.0395” Drill Bit (x4)	Test Wheels	3.25
1/8” TiN Bull Nose Endmill	Outer Housing	18.21
1/8” AlTiN Coated Endmill	Inner Housing and Wheel	24.45

6.1.1 Final Budget Status

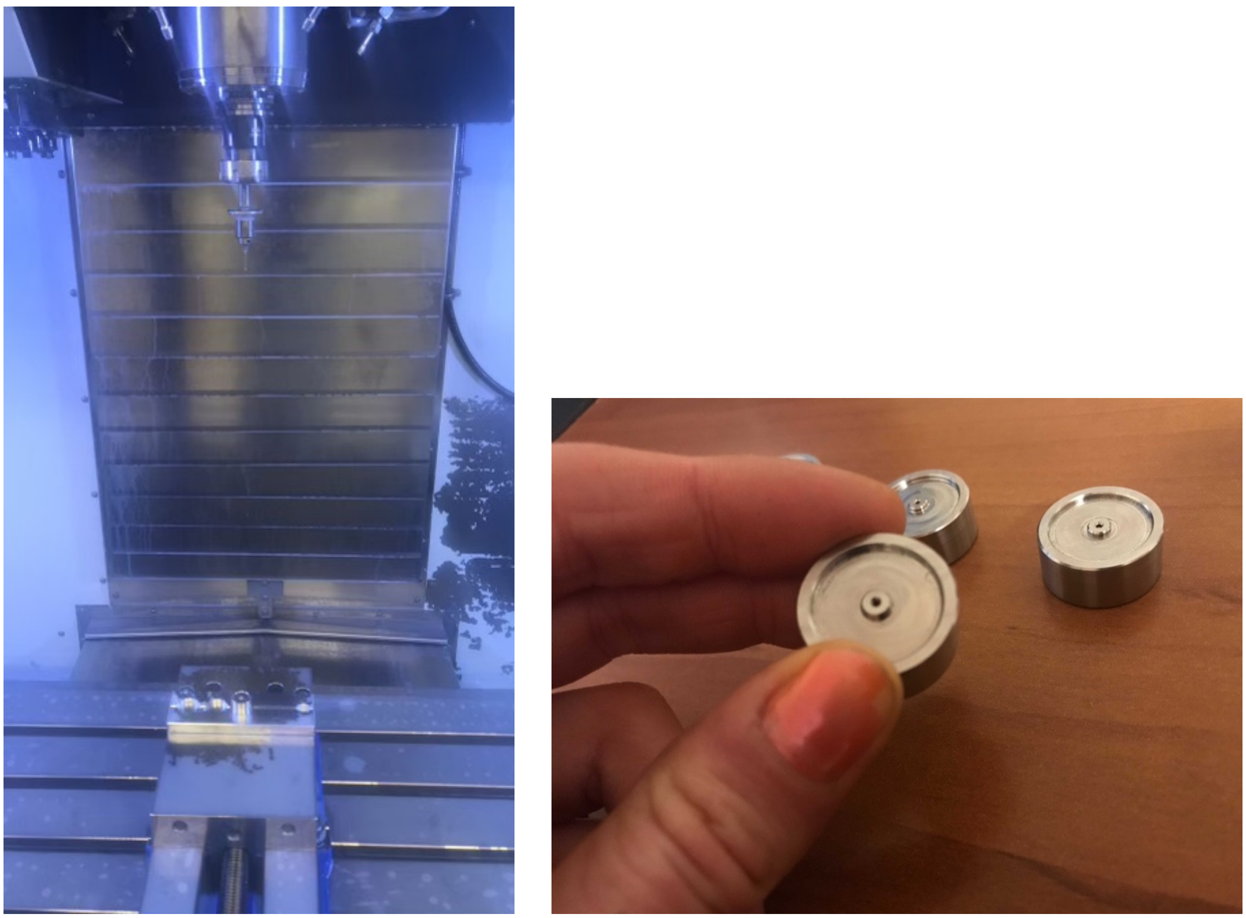
The proposed budget for this project was $2,000 for all three assemblies of reaction wheels. After all expenses were recorded and computed, the project cost approximately $2,140. It is important to note that this is for the senior design project and does *not* reflect the total projected cost of the 3-axis reaction wheel system. The project cost accounts for all stock and tooling and procurement of all parts. The only difference between the total project cost and the projected cost is the cost of balancing. Our project only balanced one assembly and since it was expedited ended up costing $180 for one wheel instead of $100 per wheel (for a three-wheel assembly). ***The proposed final cost of the reaction wheel system that should be referred to when budgeting for the cost of production and procurement in the future can be seen in Table 16.*** Also note that all tooling will not have to be re-purchased every time, so this final budget prediction might be more than required if tools do not have to be re-purchased.

Table 17. Final Cost Summary

Item	Qty	Cost for 1	Subtotal for 3
Controller	1	$101.50	$101.50
Motor	3	$323.00	$969.00
Wheel Stock	1	$39.97	$39.97
Motor Housing Stock	1	$300.00	$300.00
Outer Housing Stock	1	$65.43	$65.43
X Bracket Stock	1	$14.23	$14.23
Screws	1	$6.49	$6.49
Balancing per Wheel	3	$100.00	$300.00
1 mm shafts	2	$5.31	$10.62
Epoxy: Scotch Weld Epoxy *in lab	1	$50.80	$50.80
Maxon Adapter (for motor ribbon cable)	1	$19.75	$19.75
Soft Jaw Aluminum	1	$25.00	$25.00
TiAlN-Coated High-Speed Steel Drill Bit	2	$4.36	$8.72
TiN-Coated Carbide Rounded-Edge Square End Mill	3	$18.33	$54.99
Fast-Cutting Carbide Square End Mill	2	$24.52	$49.04
Fast-Cutting Carbide Square End Mill	2	$31.28	$62.56
Fast-Cutting Carbide Square End Mill	2	$25.03	$50.06
TiN-Coated High-Speed Steel Drill Bit	3	$3.06	$9.18
TiN-Coated High-Speed Steel Drill Bit	2	$3.60	$7.20
0.0385 HSS Straight Flute Chucking Reamer	2	$18.62	$37.24
0.04 HSS Straight Flute Chucking Reamer	2	$23.47	$46.93
TiAlN-Coated High-Speed Steel Drill Bit	2	$4.36	$8.72
		Total Cost	**$2,237.43**

6.2 Manufacturing Techniques

For highly complicated machining parts computer-aided design/computer-aided manufacturing (CAD/CAM) and computer-numerical-control (CNC) techniques are some of the only ways in our student shops to obtain tight tolerance parts in a reasonable amount of time. Most of the machining was performed in Mustang 60 utilizing the two CNC Mills (the Haas VF3 and the Haas Mini Mill) as well as the CNC Lathe (Haas TL-1). The only parts machined in the Hangar were the set of milled soft jaws and some drilled holes in the inner housing. Last quarter, Winter 2021, a member of our senior project team was able to get CNC Lathe certified, in addition to her existing CNC Mill certification. This gave flexibility in the method of manufacture for the wheel component.



(a) **(b)**

Figure 32. (a) Image of flywheel CNC mill setup with soft jaws (b) Completed flywheels

The 316 Stainless Steel wheel was made in multiple operations, beginning with the CNC Lathe and then the CNC Mill. First, the outer contour of the part was created using the CNC Lathe. Once in the Mill, it was secured using a set of custom machined soft jaws. In the first mill operation, the top part of the wheel was machined with various tooling operations: one for facing, one for the inner loop, a chamfer tool, and a .973 mm drill bit. To get the necessary tolerances, the hole was then formed with a 0.040” reamer. When this operation was completed, the part was then flipped and re-secured. At that point, the wheel was faced, bored out using an end-mill, and then chamfered (to get the desired epoxy relief and centering for the center hole).

The second parts that needed to be made were both the inner motor housing and its corresponding endcap. The outer contours of these parts were again faced and turned using the CNC Lathe. It was then faced, the outer diameter was turned, and then the piece was supposed to be parted. However, because the HyMu-80 is a superalloy it is very hard to cut through. After breaking a few parting tools, it was suggested by another tech who had worked with similarly strong materials to instead cut the piece off with a bandsaw at the end of machining. This was done slowly using the horizontal bandsaw, and then the part was transferred to its CNC Mill operations. For the motor housing, there was one part of the outer turning operations that required a left-handed tool for its back contour. The same set of soft-jaws was used once these parts were transferred to the CNC Mill for the next set of operations. This was a trial-and-error process for feeds and speeds of the HyMu-80 Alloy, documented in their corresponding CAM files. After these CNC operations, the part was placed in a manual lathe in order to drill the inner bore and the thicker inner bore was drilled on the CNC to assure accuracy. The motor end caps were also placed in a manual lathe in order to drill a hole at the end for the end of the motor to stick out. The final step was to drill two holes on either side of the motor housings d for epoxy relief.

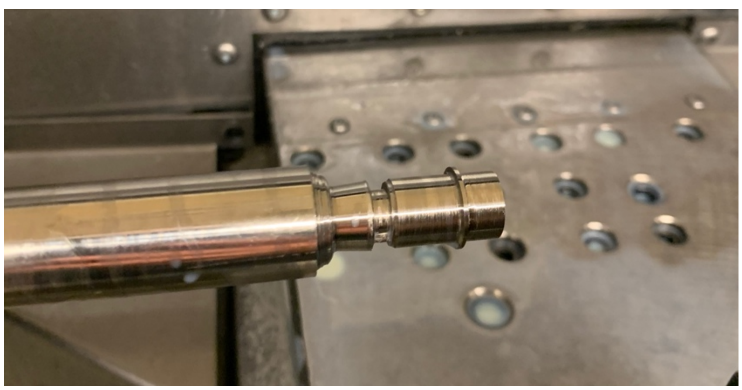
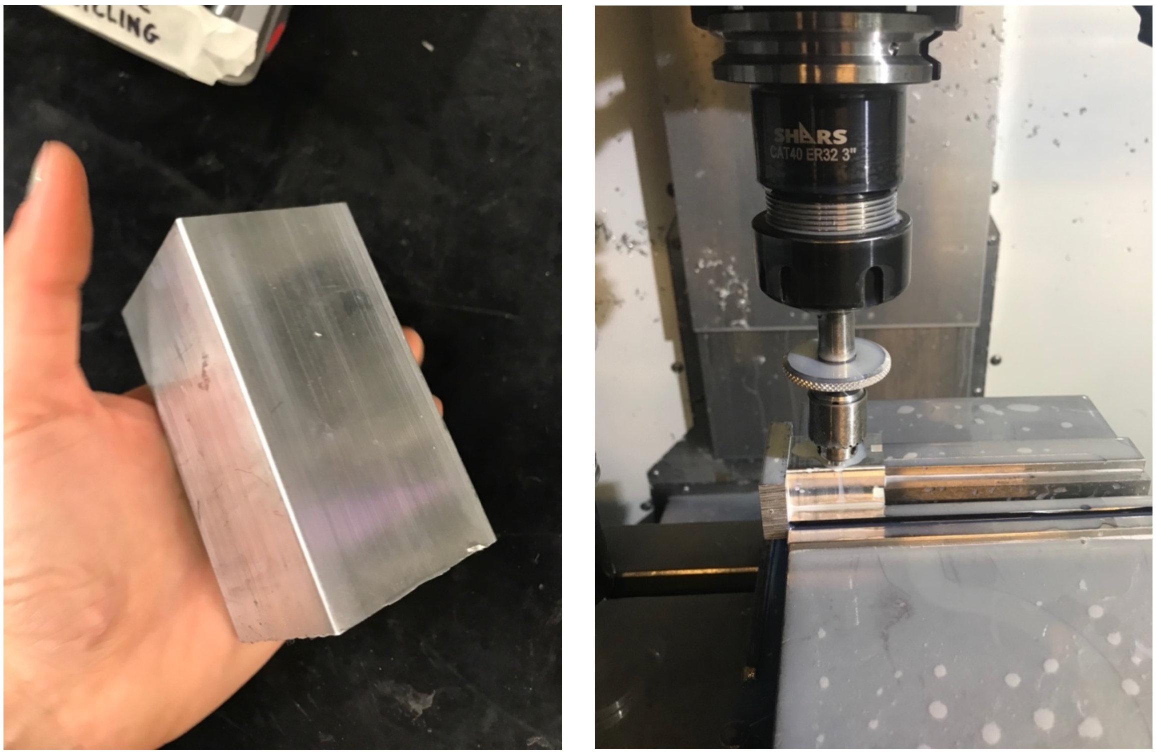


Figure 33. Completed outer operation of inner (motor) housing on CNC

Figure 34. Completed inner bore of motor housing done on manual mill

The outer housing was CNC Mill machined out of 6061 Aluminum. Since this material is a standard for PolySat machining, all the tooling required was already within our repertoire, borrowed from other CPCL projects. The outer housing, due to its square shape, was manufactured using standard vice-jaws and parallels, however extra care was needed to delicately machine its many tapped 2-56 holes. Furthermore, there were three setups required for this, and many unforeseen mistakes made in the machining process that had to be surmounted.



(a) **(b)**

Figure 35. (a) 6061 Aluminum stock cut to length to be used in machining (b) Outer housing in the second operation to drill holes for screws on the side

The final component manufactured was the X-Bracket that was secured to the outer housing. This was easily and quickly cut on the Waterjet, made of Aluminum sheet metal. The only preparation was sending out the simple 2D .dxf file prepared for the FlowJet and FlowCut software on the Water Jet to the machine shop request so that the parts could be made for us. This was the only part that was outsourced to Mustang 60 shop techs to make for us because of the experience required to operate the Waterjet and the time required to make the other components.

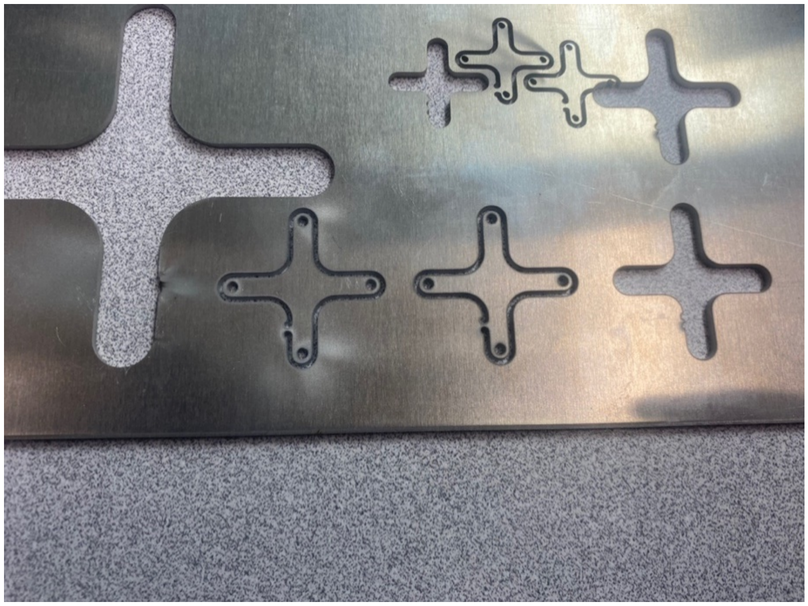


Figure 36. X-bracket cut out of 6061 Aluminum sheet metal with WaterJet in Mustang 60 Machine shop

Figure 37. (From left to right) Completed flywheel, motor housing, Maxon motor, and motor endcap

6.2.1 Manufacturing Challenges and Suggested Solutions

There were quite a few challenges to this assembly, beginning with the constraints placed upon machine time due to the COVID-19 Pandemic The capacity of the machine shops was limited to only 12 people at a time and, more importantly, the hours were limited to only 8am-5pm daily. In a typical year, as a shop tech, our group would be able to access the shop at any time. This would play into effect when doing long

CNC-ing operations, where the most time-consuming part is in the detailed set up and probing operations to verify the code. Furthermore, this time constraint made it very difficult to be able to obtain the necessary CNC lathe certification for the project, adding more stress to our main manufacturing member. This time constraint amplified the problem, and this would be remedied by performing the manufacturing process in a time when the pandemic was not upon us.

The next main manufacturing challenge was in working with a brand-new material which holds a reputation for being difficult to work with -- HyMu-80. The feeds and speeds for this were previously unknown when it comes to both turning (the CNC lathe operations) and milling (the CNC mill operations). Therefore, a trial-and-error process was utilized to optimize the necessary cutting conditions to avoid breaking tools on the material and have the desired tolerances and surface finish. Through this trial-and-error process the required feeds and speeds for the HyMu Material were obtained. Knowing these feeds and speeds for the HyMu80 material the project could be replicated by a different machinist with considerably more ease. Nickel-based super-alloys like this one are suggested to not part on the lathe (even a CNC lathe) but instead cut off using a band-saw, as recommended by a peer who had worked with similar alloys. This added step was another challenge, as the cutting process took approximately 45 minutes for one small part. All these challenges were compounded by the fact that there was only one CNC certified machinist making all these difficult, new parts. In future iterations of this project, the manufacturing technique will be already laid out, and therefore the process will be much more streamlined. Therefore, in summary, the three major difficulties were: working with limited accessible machine time, working with new materials to tight tolerances, and that the brunt of the load was just on one machinist (5 unique components that make each assembly (15 for 3 assemblies)).

To adjust for these difficulties, after approval from our sponsor, we decided to change our functional prototype goal to only create one assembly (only 5 components). This is attainable in the remaining weeks of the quarter, and the rest of the two other reaction wheel assemblies can be made after the end of the quarter and after all the testing has been performed. Therefore, we will know that the design is acceptable, and the remaining two subassemblies will be within flight qualifications, ensuring the success of the missions that will use our reaction wheel assemblies.

6.3 Assembly Procedure

The step-by-step procedure and details/pictures of assembly will be excluded in compliance with the International Trade and Arms Regulation (ITAR) and CPCL Intellectual Property (IP) agreement.

6.3.1 Shaft Hole Clearance Fit

One of the main concerns with assembly is that there are tight tolerances and precision required for the hole and shaft fit of the 1mm diameter motor shaft into the flywheel hole. Precaution must be taken to avoid bending the shaft when fitting it into the hole or else it will be rejected by the balancer. In preliminary testing with the structural prototype, both clearance and interference fits were successful when using an arbor press and by hand (see Section 5.5.1 for more detail). Both fits maintained a secure interaction between the hole and shaft when the wheel was spun up to 2000 rpm (comparatively low rpms) which verified a snug fit and that the shaft was aligned. Additionally, according to the hole fit analysis in Section 5.2.5, both the interference and clearance fits resulted in the same tolerance for the hole of 0.01 mm or about 0.3 thou.

However, after further research and a discussion with David Hinkley, and engineer from Aerospace Corp involved in the development of Bonafede's thesis and very familiar with the reaction wheel process, he suggested the use of shaft-locking adhesive with a large clearance fit. This is beneficial for two reasons. The first of which, there is little to no chance the motor shaft will bend when there is a clearance fit of +0.7 thou to +1 thou and the second being that this method was tested and verified by Aerospace corp. engineers as the best method for the hole fit.

The exact shaft locking adhesive used by Aerospace corp. has been discontinued, however, David Hinkley provided suggestions for other shaft locking adhesives with similar properties, namely the 3M RT-38 and RT-48 adhesives (see Appendix J for specifics). The RT-38 is less viscous than the RT-48 but both have close to the same strength. The RT-38 was difficult to find in a small quantity and with a reasonable lead time so in result we ordered the RT-48 to use for proof testing (see section 7.3 Shaft Load Proof Test for more information).

6.4 Manufacturing Timeline

Table 18. Manufacturing Timeline

Estimated Quarter, Week	Actual Quarter, Week	Part	Manufacturing Operation	Machine Used	Estimated Hours Required	Actual Hours Required
Q2, W4	Q2, W6	Wheel	Turning OD, Facing	CNC Lathe	4	4
Q2, W5	Q2, W7	Wheel	Inner Pockets (Top & Bottom)	CNC Mill	5-6	6
Q2, W6	Q2, W8	Wheel	Repeat process	CNC Lathe, CNC Mill	8-10	10
Q2, W5/6	Q2, W8	Test Disks	Face and part thin disks for shaft proof load test	Manual lathe	4	8
Q2, W5/6	Q3, W1	Test Disks	Drill holes	Drill press	2	2
Q2, W6/7	Q2, W5	Wheel	Machine set of custom soft jaws	CNC Mill	6	5
Q3, W1	Q3, W2	Inner Housing	Attempt feeds/speeds with HyMu80; face, do OD & features, part	CNC Lathe	8+	15
Q3, W2	Q3, W2	Inner Housing	Attempt #2	CNC Lathe	8+	10

Q3, W4/5	Q3, W5	X-Brackets	Test with scrap x2, actual x3	Water Jet	2-4	3
Q3, W2/3	Q3, W3	Inner Housing	Inner Bore, finishing	CNC Mill	4-6	4
Q3, W2/3	Q3, W3	Inner Housing	Drill epoxy relief holes	Drill Press	0.5-1	2
Q3, W4	Q3, W5	Outer Housing	4 Set-Ups	CNC Mill	7-9	14
Q3, W4/5	Q2, W7-8	Make 2 more wheels	3 Set-Ups	CNC Lathe, CNC Mill	4-6	4
Q3, W4/5	Q3, W6	Make second and third outer housing	4-Set Ups	CNC Mill	4-6	N/A

6.5 Electronics Integration

To operate the motor, a Maxon ESCON Module 24/1, 4-Q servo controller with halls sensors will be used. The programming and integration will be outsourced to the Electrical and Software Engineers in CPCL. The CPCL Electrical and Software team have verified that the controller supports all of the input output capability the team needs to command the wheel, have speed control, and receive rpm data.

The controller used in the project will not be utilized on any future flight mission, the controller will only be utilized during testing. The Electrical and Software team are currently looking into integrating the controller into the standard electronic board stack used on most of our spacecraft.

6.6 Balancing

The team scheduled a trip to Wilmington, CA to balance the wheels for the project due to the complex procedure to power and spin the wheel. In the future CPCL will simplify the process of powering and commanding the wheel in order for the RWA to be able to be shipped over to the facility and balanced without a CPCL member present.

The procedure that we followed at the balancing facility was to first set up our power supply and connect our electronics to the RasPi and the power supply. Next the balancer took the RWA and secured it to the balancing fixture. The technician then instructed us to power the wheel and spin it to a rpm no greater than 5500 rpm. We then ran a python script that commanded the wheel to spin to 5000 rpm the technician recorded a residual imbalance and then proceeded to take the wheel out of the fixture and grind small amounts of material from the outer perimeter of the wheel using a vertical belt sander. The technician then placed the RWA back into the fixture and instructed us to spin the wheel again. After recording the residual imbalance after removing material, the technician then removed the RWA from the fixture and removed more material from the flywheel using the belt sander. This process was repeated over 15 times as the technician gradually removed material from balancing planes to meet the balancing specification.

The wheel was successfully balanced, and we were provided with a balancing certification and a data sheet seen in Appendix U. Which stated that .0618 g-in and .048 g-in of residual imbalance were removed. Assuming the mass removed was lumped at the diameter of the wheel which was measured to be .827 in, we can conclude that .133g or 133 mg of material was removed during balancing.

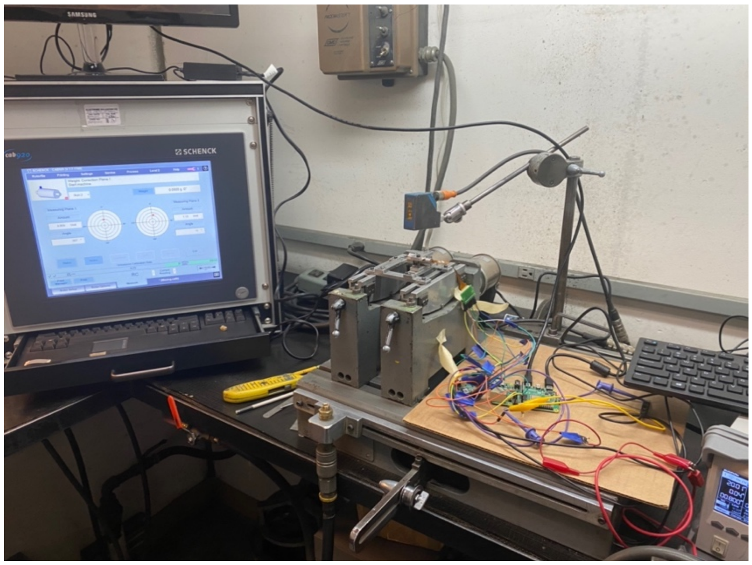


Figure 38. Balancing Configuration

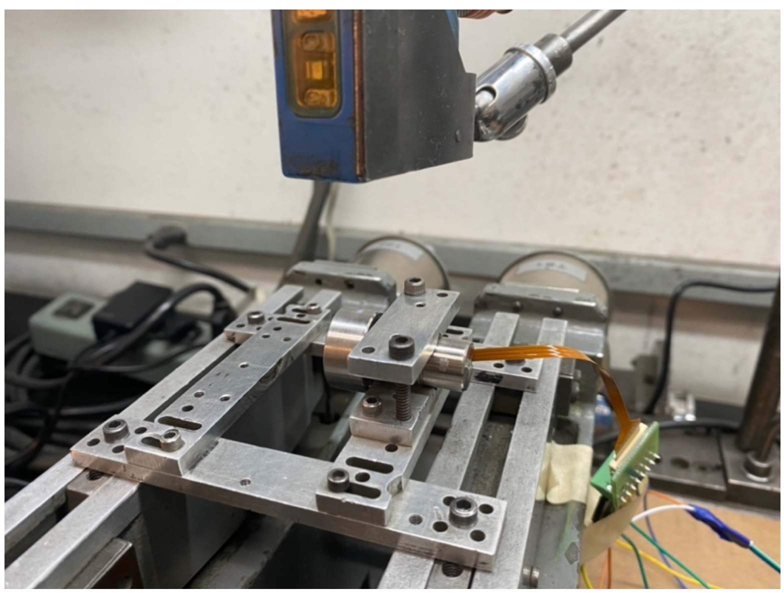


Figure 39. Reaction Wheel Balancing Fixture

Figure 40. Fly Wheel after Balancing

7.0 Design Verification

7.1 Required Testing Methods

Once manufacturing was completed, various metrology devices were used to determine the final mass and dimensions of the flywheels: the optical comparator, a mass scale, micrometers, and various calipers. Then, after assembly and balancing of the reaction wheel, the max rpm and actual performance of the reaction wheel was measured using a laser tachometer to record the rpm of the wheel. Finally, the reaction wheel assembly was verified with the two main testing methods: TVAC (Thermal Vacuum Chamber) and Vibes (Vibrational Testing). Additionally, a shaft load proof test was performed pre-assembly with test shafts and disks in order to verify that the shaft-locking adhesive cured properly. A detailed description of each test and its results are described in the following sections.

Table 19. Design Verification Tests Summary

DVP&R - Design Verification Plan (& Report)

Project: F63- Cubesat Reaction Wheel | Sponsor: Cal Poly Cubesat Lab - John Bellardo | Edit Date: 5/13/21

TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
1	1.Mass	Measure total system mass on a digital scale	mass in grams	A mass below 660 g total	CP Mustang 60/Aero Hanger Digital Scale	FP	Rose	5/21/21	5/29/21	65.45g	mass of 1 Reaction Wheel Assembly
2	4. Size/Volume	Measure Length Width and Height with a pair of Dial Calipers	dimensions in cm	A volume under 500 cm^3	CP Mustang 60/Aero Hanger/CPCL Dial Caliper	FP	Rose	5/21/21	5/29/21	23.81cm^3	Volume of 1 Reaction Wheel Assembly
3	5.Thermal Testing - Bakeout	Complete a 60 C for 6 hours or 70 C for 3 hours Thermal Bake out in the TVAC Chamber	Thermistor data throughout Bakeout	Temperatures with in CPCL Standard acceptable range	CPCL TVAC Chamber in Aero Hangar	FP	Daniel	5/17/21			n/a - due to timeline constraints, this test will not be completed
4	6. Vacuum Testing	Complete a 60 C for 6 hours or 70 C for 3 hours at 1 * 10-4 Torr Thermal Bake out in the TVAC Chamber	Thermistor data throughout Bakeout	Minimal particle outgassing	CPCL TVAC Chamber in Aero Hangar	FP	Daniel	5/17/21			n/a - due to timeline constraints, this test will not be completed
5	7.Torque	Messure RPM with a laser tacheometer	RPM	A calculated torque of 1.0 mNm -10% using measured rpm,mass, and moment of inertia	Laser Tachemeter	FP	Pablo	5/17/21	5/29/21	Torque Perfromance was met with in 10% of target torque	see FDR report for torque vs. RPM plots
6	9. Total Momentum	Masure RPM with a laser tacheometer	RPM	A calculated momentum of 5 mNms using measured rpm,mass, and moment of inertia	Laser tachemoeter	FP	Pablo	5/17/21	5/29/21	Momentum Perfromance was met with in 10% of target value	
7	12. Vibration Testing	Perfrom X,Y and Z axis Vibration testing to NASA GEVS PSD Profile	Accelerometer data throughout test	NASA GEVS (NASA STD 7000 Table 2.4-3) [21	Vibration Tables in bldg 41B	FP	Alex	5/20/21			n/a - due to timeline constraints, this test will not be completed
8	13. Press fit Testing	Practice a press fit with a wheel and test shaft	Hole Diameter and Shaft Diameter	no noticable deflection on the shaft	CP Mustang 60/Aero Hanger Arbor Press	SP	Alex	4/28/21	4/26/21	Tested disk B up to max of 146 N and disk C to max of 235 N and disk D up to 200N.	Disk A did not cure when using the RT48. Disk B and C used the staking and the shaft slipped slightly but still held in place. We concluded that the staking was the best option for the shaft-locking adhesive but shoud NOT be tested to the max on the actual assembly.

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7.2 Shaft Load Proof Test

7.2.1 Description

The shaft load proof test was designed to verify the strength of a shaft-locking adhesive in securing the inner bore of the flywheel to the 1 mm motor shaft. We evaluated the strength and workmanship of the 3M Scotch-Weld RT48 High Temperature Retaining Compound by applying a compressive load *directly* on the shaft after it was cured to the disk using a force gauge positioned in an arbor press and evaluating the bond to see if the shaft slipped.

This test is designed to mitigate multiple failure modes identified in the Failure Mode Effect Analysis (FMEA) in Appendix S in which the flywheel could spin so fast that it comes off the motor shaft. Since the flywheel will be operating at speeds upwards of 40,000 rpm, we need to be sure that it will stay secure to the shaft. This could happen due to improper curing or an adhesive that was not strong enough. Another failure mode is an inaccurate fit between the motor shaft and flywheel (too tight of a fit will cause the shaft to bend or break and too loose will not allow the wheel to be balanced because it is too far off in alignment). All of these failure modes are the basis of this test and can be mitigated by performing the proof test on the test shafts and disks first and then the actual assembly.

Some supplementary goals of this test were to evaluate whether the use of a vacuum chamber to cure the shaft is necessary and affects the strength of effectiveness of the bond, and to compare the strength and effectiveness of different adhesives.

The shaft load proof test took place in two locations: the CPCL cleanroom in the ATL (Building 07 Room 15) and in the Cal Poly Aero Hangar (Building 04) and the equipment used is as follows:

- Four test disks, 0.827 in diameter, 0.079 in thick with 0.039 in hole (note: One disk has two 0.04 in holes for two test shafts)
- Five test shafts A-E
- Thin needle
- 3M Scotch-Weld RT-48 Shaft Locking Adhesive
- 3M Scotch-Weld Epoxy Adhesive 2216, Translucent, Part B/A
- *Glass Vac* chamber and Vacuum Pump
- Aluminum test fixture to hold shaft and disk
- 200N Analog Force Gauge
- Arbor press (Building 04)

The test shafts were ordered off Amazon and cut to a proper length. Then, each shaft diameter was measured with an optical comparator in the Mustang 60 machine shop and recorded in the table below. The test disks were made out of leftover 316 stainless steel from the flywheel and cut to the proper diameter (0.827 in) and thickness (0.079 in) on a manual lathe. Subsequently a hole (0.039 in) was drilled in each test disk that matches the dimensions of the hole in the flywheel. There are four disks total, labeled A-D, and five shafts total labeled A-E and one of the disks has to holes with two shafts in it. Individual measurements of the disks and shafts were taken and recorded in a spreadsheet in order to accurately evaluate the strength of the adhesive in the small range of possible clearances between the motor shafts and flywheel bore. The measurements are listed in a table in the test procedure in Appendix V and also in the table below.

Table 20. Test Shaft and Disk Measurements and Clearances

Disk	Hole Diameter (in)	Shaft	Shaft Diameter (in)	Clearance (in)
A	0.0439	A	0.0394	0.0045
	0.0426	E	0.0391	0.0035
B	0.0441	B	0.0393	0.0048
C	0.0435	C	0.0392	0.0043
D	0.0439	D	0.0391	0.0048

Each test disk and shaft assembly was tested to its calculated max load, which slightly varied depending on the geometry of the individual disks. The measured hole diameter and disk thickness was plugged into the equation of the surface area of the *outside* of a cylinder, $SA = \pi Dh$, (where D is the measured diameter of the hole and h is the thickness of the disk) to calculate the contact area in in^2. Then, the contact area was multiplied by the ultimate shear strength (or compressive shear strength of the adhesive). It is important to note that disks A and D were the only two cured with the 3M Scotch-Weld RT48 shaft locking compound and shafts B and C were cured with 3M Scotch-Weld Epoxy that has been used on previous flight missions (the reason for this will be explained in the results section). The Shear strength of the RT48 is 4970 psi and the shear strength of the epoxy is 3200 psi so those tested with the epoxy were tested to lower max loads.

Table 21. Max Load Calculations for Proof Test

Disk	Hole Diameter (in)	Thickness (in)	Contact Area (in^2)	Adhesive Used	Shear Strength (psi)	Max Load (lbs)	Max Load (N)
A	0.0439	0.087	0.0120	RT48	4970	59.5982	265.1046071
	0.0426	0.087	0.0117	RT48	4970	57.9242	257.6586504
B	0.0441	0.074	0.0103	Epoxy	3200	32.8178	145.9802454
C	0.0435	0.121	0.0165	Epoxy	3200	52.8762	235.2989155
D	0.0439	0.085	0.0117	RT48	4970	58.3012	259.3356381

Before the proof test could be performed, the test shafts must be cured to the disks. This step was done in the CPCL cleanroom (Building 07 Room 15) where each component was labeled and cleaned and then adhesive was carefully applied to the hole and outside of the shaft using a needle or thin, pointed tool. The RT48 has a very low viscosity, which meant it was easy to apply, but dripped out quickly. The process can be seen in the following images. Then, some assemblies were cured in a vacuum chamber and others were left out to cure for at least 24 hours.

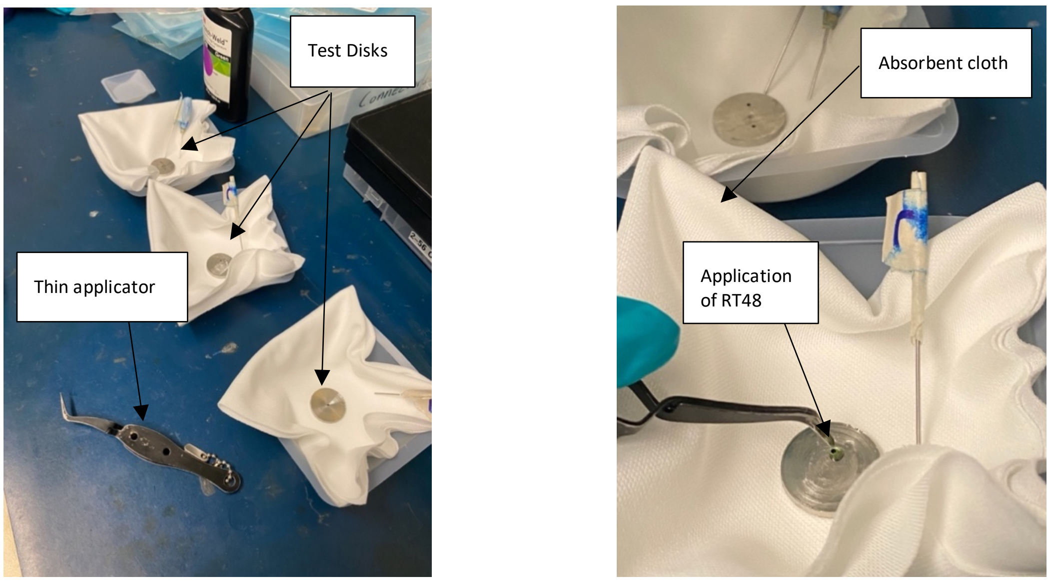


Figure 41. Application of 3M Scotch-Weld RT48 to test shafts and disks in Building 7 Room 15

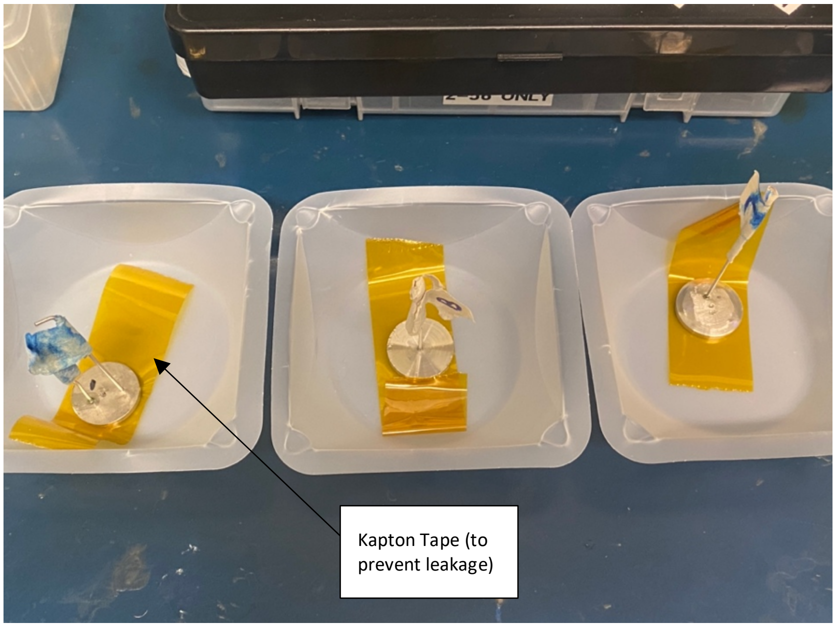


Figure 42. Test disks and shafts after applying adhesive and ready to cure

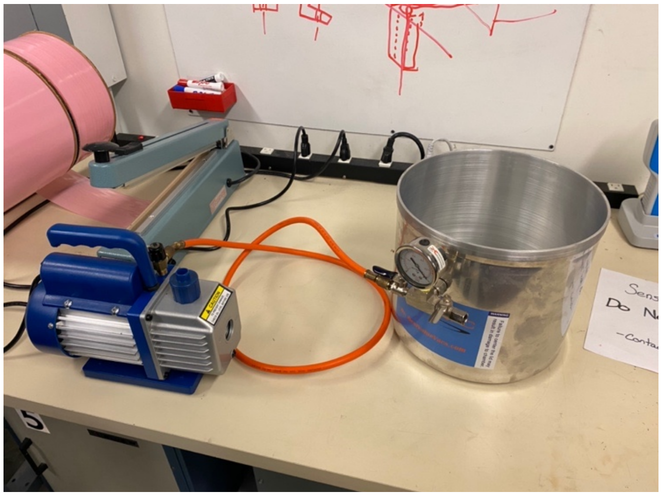


Figure 43. Vacuum chamber and pump used to cure select disks

Following the curing process, the proof test was performed in the Aero Hangar using the setup in the figure below. The force gauge was positioned in between the test fixture and the arbor press and the arbor press was lowered steadily by hand waiting the force gauge until the max load was reached. The test fixture, shown below, was made out of scrap aluminum and a countersink was created to hold the disk (or flywheel) while the shaft (or motor) is unsupported in the smaller hole. The load is only applied to the top surface of the shaft in order to ensure that the shear strength of the adhesive is what is being evaluated.

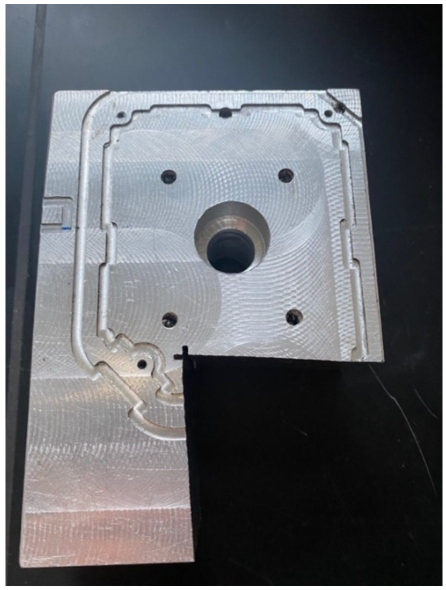
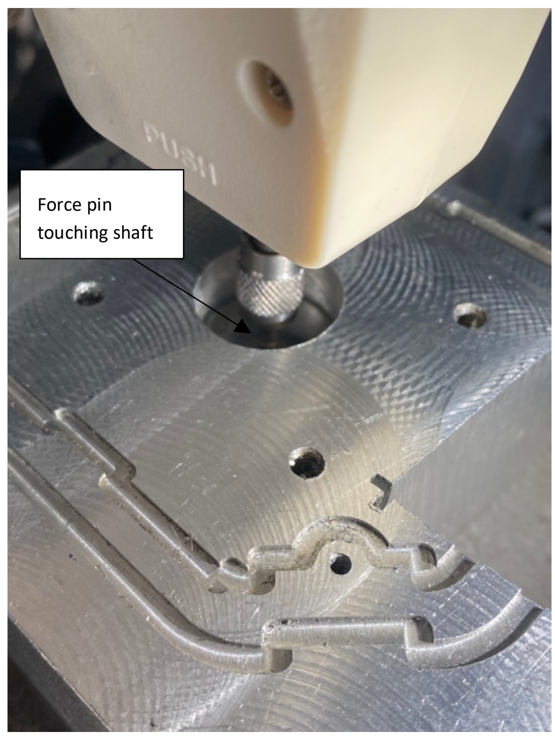


Figure 44. Testing fixture for shaft load proof test with counterbore for disk and shaft

(a)

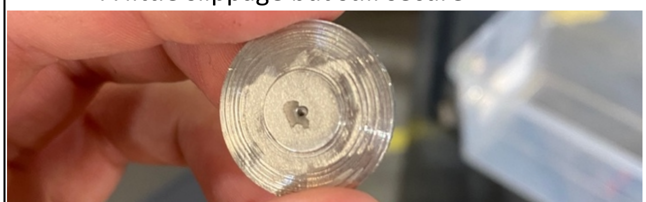
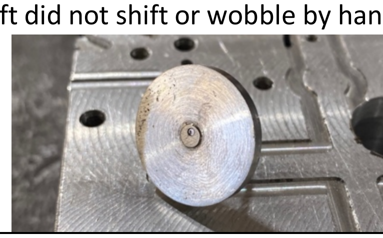


(b)

Figure 42. Testing setup (a) 200N analog force gauge setup in arbor press with test figure underneath (b) bottom of analog force gauge with pin to apply force to only shaft

7.2.2 Results

Table 22. Shaft Load Proof Test Results

Disk	Shaft	Clearance (in)	Max Load (N)	Observations (From during test and post-test visual inspection)
A	A	0.0045	171	• Cured with 3M Rite Lock 48 with tape in vacuum for 26 hours • ***Did not cure and weren't able to test***
A	E	0.0035	166	• Cured with 3M Rite Lock 48 with tape in vacuum for 26 hours • ***Did not cure and weren't able to test***
B	B	0.0048	146	• Cured with epoxy NOT in vacuum for 26 hours • Tested up to 146 N • A little slippage but still secure 
C	C	0.0043	235	• Cured with scotch weld epoxy NOT in vacuum for 26 hours • Tested up to 235 N • Slight slippage of shaft but fixture remained secure after test • (tested 1^{st}) 
D	D	0.0048	167	• NOT cured in vacuum • Cured with RT48 • Only one that cured out of three with other two in vacuum • 200N (44.9 lb) force, no visual change during test • From visual inspection, shaft slipped into the hole slightly • Shaft did not shift or wobble by hand 

7.2.3 Analysis & Recommendations

We learned a lot from our shaft load proof tests, in terms of what adhesive to use and whether or not the use of a vacuum chamber is entirely necessary for curing the adhesive.

Our tests yielded inconsistent results when it came to the RT48 adhesive, with only a single set of disk and shaft properly curing. This is because the adhesive was such a low viscosity that it would leak right out of the bore, in the future the team highly discourages the use of RT48 and encourages the use of 3M Scotch-Weld Epoxy Adhesive 2216, Translucent, Part B/A also known as RT38.

In our initial tests with the RT48 adhesive we found that the only successfully cured test disk and shaft were left outside of the vacuum chamber, and that test article successfully passed the proof test as seen in section 7.2.2. This suggests that the use of a vacuum chamber to cure the RT48 anaerobic adhesive is not necessary.

Due to our unsuccessful attempts to reproduce additional test articles using the RT 48 adhesive, we decided to explore alternatives, we considered 3M Scotch-Weld Epoxy Adhesive 2216, Translucent, Part B/A and using RT 38 (a higher viscosity, higher strength anaerobic adhesive). Due to the lead time and price of the RT38 adhesive the team decided to explore using the Scotch-Weld two-part epoxy first. The RT38 adhesive is not an off the shelf component, an order must be placed for it to be manufactured and a minimum order quantity of 10 bottles of 50ml is typically required from most manufacturing companies making this adhesive difficult to obtain in a fast timeline and in a small quantity.

3M Scotch-Weld two-part Epoxy Adhesive 2216 is an epoxy we typically use to secure fasteners on our spacecraft. This adhesive is a material that is already widely used in CPCL, and the adhesive is readily available in small quantities in a reasonable time frame. Two test articles were cured using the Scotch-Weld adhesive and both articles cured successfully and passed the proof test.

Given the inconsistency of results using the RT48 adhesive, the difficulty to obtain RT38 in a small quantity and in a fast timeframe, we highly recommend moving forward with using the 3M Scotch-Weld two-part Epoxy Adhesive.

7.3 MASS AND SIZE TESTS

7.3.1 Description and Results

Once each part was complete in manufacture and assembly, there were a few critical dimensions that needed to be measured to compare to the intended dimensions. The part with its most critical dimensions is the 318 Stainless Steel Wheel, as its mass and size drives the entire system's desired torque output.

While small discrepancies in its outer diameter and depth could be remediated during the balancing material removal process, the inner hole is the tightest tolerance feature. This is because its ability to secure to the shaft (using adhesive) will determine whether the wheel will stay attached to the motor, and therefore whether the system can function as desired.

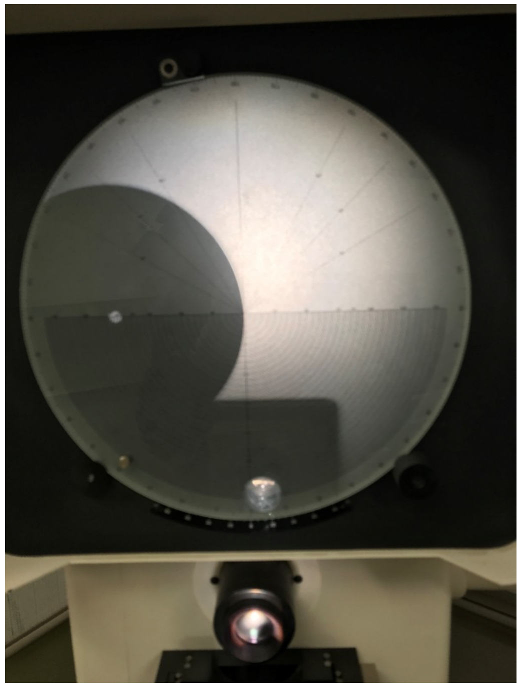


Figure 46. Optical Comparator measurements of completed reaction wheel

Table 23. Wheel dimensions

Component	Inner Diameter (in)	Outer Diameter (in)	Thickness (in)	Bore Depth (in)	Overall Calculated Volume (in^3)	Pass/Fail
Design Dimensions	.040 +/- .004	.827	.394	.315	.087	-
Actual 1	.0401	.826	.3935	.315		P
Actual 2	.0398	.827	.394	.315		P
Actual 3	.0399	.826	.394	.315		P

After assembly, the whole system was kept in the clean room (as it is a flight-ready component). So, the measurement of the entire system's weight was also performed in the clean room. The desired result was for this weight to be within the allotted mass budget for one reaction wheel assembly, verifying that our proposed weight of the three-axis system would be accurate enough to be used for future flight mission system engineering and coordinating between the allotted mass of the subsystems. All CubeSats have overall mass budgets due to the high cost of sending things to space, with 1.33 kg allotted for each 1-U of space.

Table 24. Mass budget theoretical versus Actual

	Mass (g)	**Pass/Fail**
Theoretical Wheel	11.46	-
Actual Wheel	11.43	P
Theoretical Single Reaction Wheel	165	-
Actual Single Reaction Wheel	65.45	P

7.3.2 Analysis & Recommendations

Overall, the parts were made to the specifications due to the use of CNC machines, which are able to use tool wear compensation to dial in a precision fit between pieces or a specific desired dimension. Furthermore, the use of the reamer was successful for the wheels so that the desired clearance was able to fall within the very tight tolerance. One recommendation is to use more precision measurement equipment for weight so that a better estimate of how much mass actually exists will be obtained. Also, the CMM is a more precise measurement device, so potentially using that for all measurements as opposed to only the optical comparator would improve the detail and reliability of these measurements.

7.4 Performance Validation

To validate the performance of the wheel the team performed a test that accelerates the wheel through its operational velocity range (0-50,900 rpm) such that 1.0 mNm of torque is produced this happens to be 0 to 50.9 krpm in 4.3 seconds. In addition, the team recreated the fly wheel CAD post balancing adding the chamfers and removing material in the CAD model where material was removed during the balancing process. From the CAD model a post-balancing wheel inertia was determined, and this new wheel inertia was fed into Nicholas Bonafede's thesis simulation in order to determine the torque performance. Nick's fly wheel designed allotted a 10% margin in torque performance, as the machining tolerance and material removal from balancing would affect the wheel's final inertia. These tests aim to evaluate the degradation of torque performance from balancing.

7.4.1 Description

The RPM test was performed using the internal hall effect sensors inside the Maxon Motor, a software team was able to enable a speed comparator allowed for a target speed to be set and the time required to meet the target speed to be recorded by a Raspberry Pi.

As mentioned above the torque performance was determined by taking measurements of chamfers made to the wheel post balancing and modeling the material removed in CAD. Once the new wheel inertia was determined from SOLIDWORKS mass properties it was updated in Nick's Operational Torque Performance MATLAB simulation. The design wheel inertia and balanced wheel's inertia can be observed in Table 24.

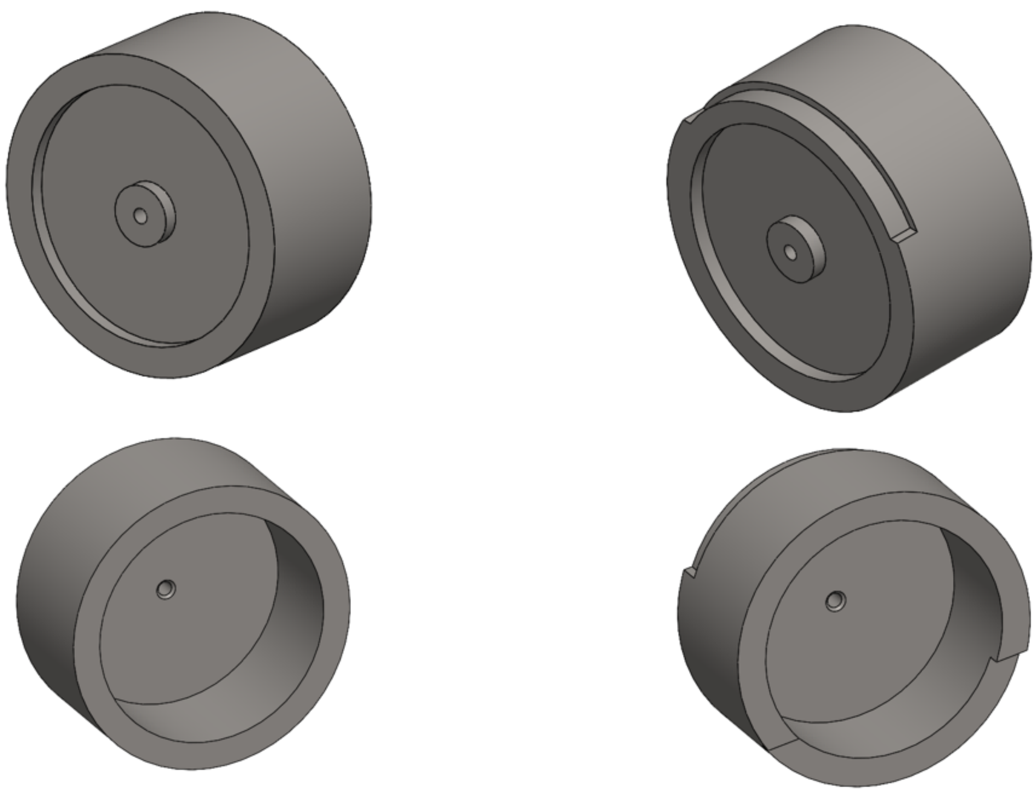


Figure 47. Original Wheel CAD vs. Balanced Wheel CAD

Table 25. Fly Wheel Inertia

Design Fly Wheel Inertia	Balanced Fly Wheel Inertia
9.37 $g * cm^2$	8.91 $g * cm^2$

7.4.2 Results

Table 26. RPM Test Data

Goal Velocity (RPM)	Time to Target Speed (Seconds)
51000	3.124
51000	3.103
51000	3.104
51000	3.008
51000	3.101
30000	1.706
30000	1.706
30000	1.705
30000	1.704
30000	1.704
15000	0.742
15000	0.74
15000	0.742
15000	0.741
15000	0.742
60000	3.755

The RPM test data seen in Table 25 suggest that the Final assembled system is capable of following the velocity profile seen in Figure 45. Which tell us that 1mNm of torque is theoretically possible pending the impact that the material removal from balancing on the wheel's inertia.

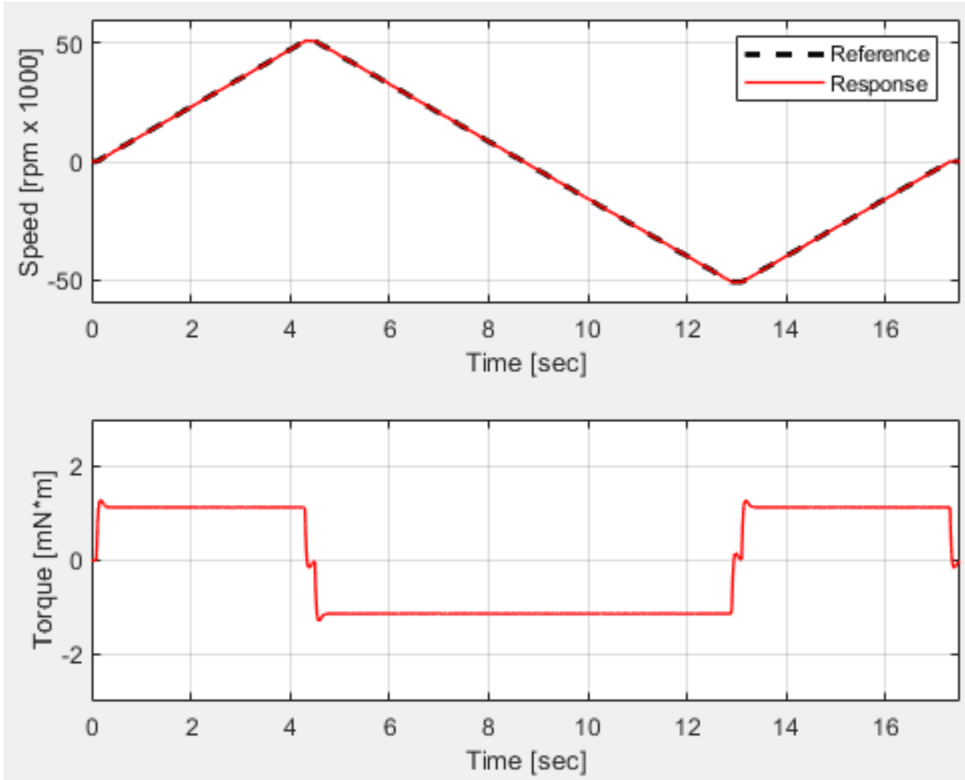


Figure 48. Calculated Torque over time given a set Velocity Profile (with a calculated wheel Moment of Inertia of 8.91 g*cm^2)

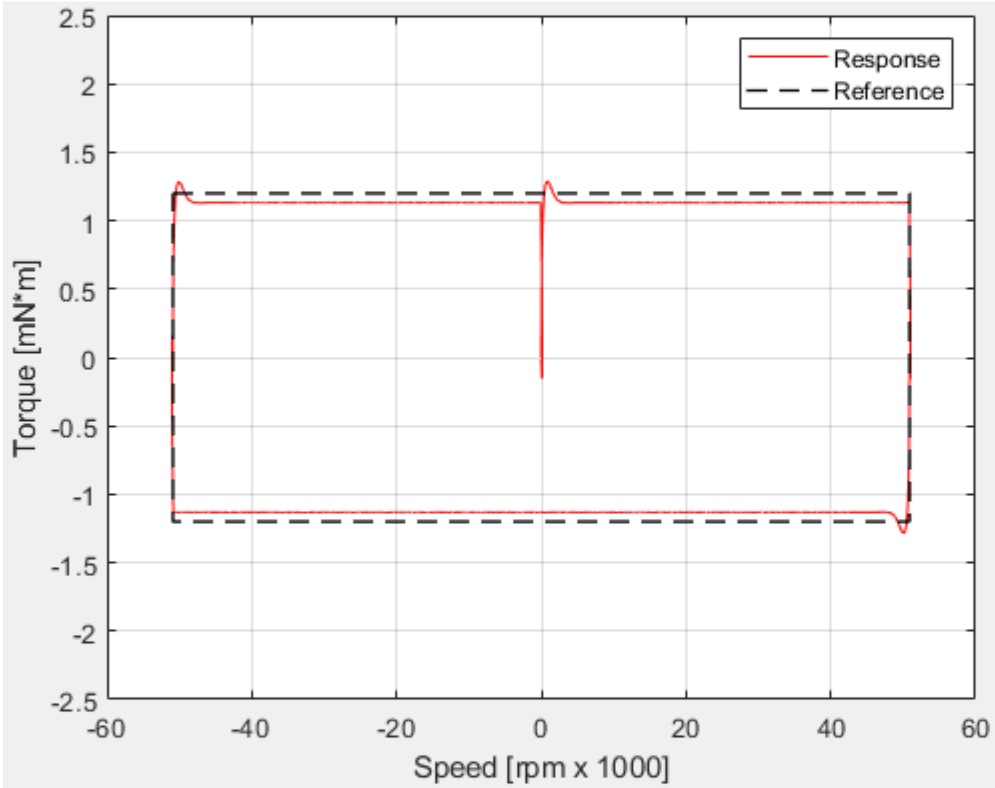


Figure 49. Calculated Torque over a set Velocity Profile (with a calculated wheel Moment of Inertia of 8.91 g*cm^2). Reference curve is based on an unbalanced wheel Moment of Inertia of 9.37 g*cm^2.

In Figure 45 and 46 it can be observed that the black dashed line indicates the wheel's design torque performance which was overdesigned to reach a max torque of 1.2 mNm corresponding to wheel inertia of 9.37 g*cm^2. The torque performance decreased to 1.1 mNm corresponding to a wheel inertia of 8.91 g*cm^2 . This data suggests that our Reaction Wheel Assembly can still meet the target 1.0 mNm max torque even after material removal after balancing.

7.4.3 Analysis & Recommendations

The performance testing verified that the reaction wheel can produce the required torque identified in the specifications table (Table 3 Spec #7) of 1.0 mN-m and exceeded it within 10% margin. It also demonstrated that the wheel can be spun up to a max speed of 60,000 rpm, however, this was not verified for long lengths of time and would need to be tested in a TVAC procedure.

7.5 Vibration Test

7.5.1 Description

Vibrational testing is necessary to ensure the spacecraft components will endure the extreme vibrational environment during launch. Often during vibrational testing, an error in workmanship or assembly can be found and remedied. The vibrational environment often causes fasteners to unthread themselves or "back -out", which can lead to a free screw to rattle and damage sensitive components on a spacecraft such as a solar panel cell or a printed circuit board. In order to prevent a screw from "backing out" a two-part epoxy is adhered to the head of each fastener to prevent it from rotating out of the tapped hole. The vibrational test aims to expose any components on the spacecraft that are not properly secured or held in place.

The vibration test takes place at Cal Poly, inside building 41 in the Aerospace Engineering Composites Lab (Bldg. 41 Rm. 137) using a vibration table. The test is typically performed on entire spacecraft sometime before launch however individual components can also be tested. To perform the test on component-level assemblies, they must either be interfaced to a generic, pre-existing spacecraft structure or have an interface plate machined to interface directly to the vibration table. Testing components using a pre-existing spacecraft structure is preferable as it better simulates the vibrations that the component will experience.

The test begins by first attaching all the necessary equipment, such as accelerometers and the interface plate (used between the spacecraft and the vibrations table). After everything is properly assembled, including proper torquing of all screws, the first vibration test performed is a sine-sweep test for the z-axis. After the entire vibration profile has been completed, the spacecraft is visually inspected for any anomalies (such as backed-out screws) and pictures are taken for documentation. Following the visual inspection, a random vibration test is performed in the z-axis. Once again, after the entire vibration profile has been completed, the spacecraft is inspected for any anomalies and pictures are taken. This process of a sin-sweep vibration profile, visual inspection, random vibration profile, and a final visual inspection, is performed for the remaining two axes (X and Y).

7.5.2 Recommendations

This test was not able to be completed due to time constraints and not getting the staff support needed to run the test. Since manufacturing and assembly ran into setbacks due to the tight precision and time required for these tasks, only a week was left for testing and there was another big project going on in CPCL that occupied the staff's time so they could not support reaction wheel testing. However, a testing procedure was created and included in Appendix V so future work should reference and follow this procedure and perform vibrational testing in Bldg. 41 Rm137. This testing is necessary to validate that the reaction wheel is structurally stable and will survive the launch environment and the reaction wheel cannot be considered flight-ready until it is verified with this test.

7.6 TVAC TEST

7.6.1 Description

Thermal vacuum chamber testing is used to simulate the temperature extremes of a Low Earth Orbiting (LEO) spacecraft, cycling between temperatures experienced while in earths umbra and in direct exposure to solar radiation. At the same time, the TVAC chamber simulates the vacuum of space. Furthermore, the electrical components are connected to a controller during these tests in order to collect functional data of the systems performance in this environment.

This test is vital to ensure our mechanism will function in its on-orbit environment. This test also is used to expose any materials which release particulate in a vacuum or more formally called “outgassing”. All the adhesives, and materials procured have low out gassing percentages, however the test is useful to validate that as well. Having minimal particulate release is important when a spacecraft is carrying an optical sensor such as a camera or infrared sensor. A piece of particulate on the camera or on the sensor can interfere with a picture or a sensor reading.

The facility used to conduct the TVAC test is the Thermal vacuum chamber in the Cal Poly Aero Hangar, the equipment used are Type T Thermocouples, placed on opposing corners of satellite, shroud, and test stand, High vacuum pressure gauge, Grainville-Phillips Series 260 Gauge Controller, and NI 9213 Thermocouple Input, LabVIEW, with 60 second sampling time.

The General procedure it to place Type T thermocouples on the Reaction Wheel assembly, and run a thermal profile that exposes the hardware to temperature extremes typically encountered in LEO (Low earth Orbit) . At each temperature extreme we will run the wheel at its operational angular velocities and measure the rpm it actually spins at using hall effect sensors built into the motor. In doing so we can validate the performance of wheel in an “on-orbit” environment.

For detailed testing procedures, see the TVAC Test Procedure in Appendix V.

7.6.2 Recommendations

This test was not able to be completed due to time constraints and not being able to get the staff support needed to run the test. However, a testing procedure was created and included in Appendix V so future work should reference and follow this procedure and perform TVAC testing in the Cal Poly Aero Hangar. This testing is necessary to validate that the reaction wheel will perform as expected in the space environment of LEO including extreme high and low temperatures and performing in a vacuum and the reaction wheel cannot be considered flight-ready until it is verified with this test.

7.7 Summary and Recommendations

Our design has been validated for and passes all tests that qualify the specifications listed in Table 3 of the report and a summary can be seen in the table below.

Table 27. Final Results Summary Table

Test	Specification (from Table 3)	Pass/Fail
Shaft Load Proof Test	13) Compatibility/assembly (hole fit)	Pass
Mass and Size Tests	1) Mass 4) Size/Volume	Pass
Performance Validation Test (RPM and Speed Profile Testing)	7) Torque	Pass
Vibration Test	12) Vibration testing of GEVS standard	n/a
TVAC Test	5) Thermal Testing 6) Vacuum testing	n/a

The tests performed to validate our design covered almost all of our specifications, and the one not tested were either validated through inspection or documentation (such as balancing verified by the balancer and deorbit demise verified by research about the materials used). Recommendations we have for future testing is to plan the vibration and TVAC tests ahead of time and make sure there is ample time and resources available to complete them. Additionally, an attachment plate had to be made for the vibes test which slowed down our process and ability to complete the test sooner. Our process mostly got slowed down during the shaft load proof test when we had to try multiple times to cure the shafts and they were not curing successfully. We strongly recommend that the shaft load proof test is performed for the RT38 compound since it has a higher viscosity and might be a better shaft locking adhesive for this application.

8.0 Project Management

8.1 Design Process and Deadlines

The engineering design process was followed to produce functioning reaction wheels for CPCL by June 2021. The problem definition phase occurred in the fall of 2020 and is summarized in this document. That phase included technical, customer, and competition research as well as interviews to develop a strong background of the problem at hand. The scope of work was designed based on the QFD which defined specifications and target values for the project moving forward. After completing PDR and IDR, the design was iteratively improved, and results are presented in the final design section. Analyses and their results are presented to validate the final design. Additionally, a manufacturing plan and process was laid out along with procurement of materials and a cost summary to indicate that the project is within budget for stock but exceeds budget with tooling (in which permission was granted from the project's sponsor). Finally, a design verification plan was formulated to test each specification.

Table 28. Key Deliverables

Date	Deliverable
10/13/20	Scope of Work (SOW) – Presentation and Submission
10/29/20	Concept CAD
11/10/20	Preliminary Design Report - Presentation
11/12/20	Preliminary Design Report - Submission
11/17/20	FMEA
11/19/20	DFMA
01/14/21	Interim Design Review
02/09/21	Critical Design Review - Presentation
02/12/21	Critical Design Review - Submission
03/11/21	Manufacturing & Test Review
03/18/21	DVPR Signoff
05/28/21	Senior Project Expo
06/04/21	Final Design Review

8.1.1 Gantt Chart

To ensure that the team understands the timeline of the project throughout the entire school year, a Gantt chart was developed and can be seen in Appendix G. Each step of the design process is divided into sub-tasks and categories and team members are assigned to those tasks. This project has some unique requirements because to be able to manufacture the flywheels and housing, at least one team member needs a certification on the CNC lathe in the Cal Poly Machine Shops. Rose has taken on this task and has completed her certification and is now the main team member in charge of manufacturing. All tasks for the first one of the wheel assemblies has been completed. From various setbacks in machining the HyMu-80, three full assemblies were not completed, but many of the parts were begun for the next two assemblies. Therefore, the scope was modified with our sponsor approval to only complete manufacture and test of one axis. This also allows us to learn from the experience before finishing up the other axes in the system. Furthermore, due to constraints in the access to lab and staff members necessary to be able to perform the TVAC and vibes tests, it was not possible for our project to complete these within the time frame of senior project. Going into it, we had expected to have testing be our tightest timeline, but due to an unforeseen extension on a different flight mission, the staff member necessary was not able to support our testing. However, this is laid out within the plan for future work at the end of this document.

8.1.2 Reflection

For this project to be successful and meet stakeholder wants and needs, there were some unique techniques that contribute to the scope of the project. Since the preliminary design work has mostly been completed in Bonafede's Thesis, and the sponsor advised that the project be picked up from there, the design work and ideation was limited to modifying existing designs as well as creating the outer housing system. A housing for the reaction wheels still must be completely designed but the wheels themselves have been designed and approved to match the customer needs. This project focused primarily on the design of the housing and implementation strategy as well as the build and test phase since the reaction wheels must be balanced precisely and tested for the more extreme conditions of launch and space environments.

Our design process was successful because we took time to carefully define the problem statement and stakeholder wants and needs so that we can meet our sponsor's goals. Some difficulties and setbacks with this process was the amount of time dedicated to design work that was mostly already completed prior to our project. This set back manufacturing and assembly that only occurred during spring 2021 and was very intensive. In result, only one assembly could be completed and TVAC and vibes testing did not happen. Ideally, all three assemblies would have been made and TVAC and vibes tested so that they would be flight ready. What we would do differently to prevent this is accelerate the design process in the beginning and spend more time focusing on a manufacturing plan and timeline and even possibly getting another person CNC certified to help. In future design projects, it is important once defining the scope to assess the proper timeline to meet the needs of the project, and for this project that would have meant getting to the manufacturing, assembly, and testing phase sooner.

9.0 Conclusion & Recommendations

This document outlines the final design of the 3-axis reaction wheel system based off the cumulative information from background research, project scope, concept design, and analysis. The final design meets all stakeholder needs, wants, and project specifications.

One of the main aspects to this project is developing a manufacturing plan that can be used by future students, there were a lot of lessons learned in this very first iteration of manufacturing. When work-holding the motor housing for epoxy relief holes, after the large inner hole has been drilled out, it is necessary to use a wood plug to prevent deformation. Alternatively, the order of operations could be changed so that the inside of the motor housing would remain solid until after drilling the epoxy relief holes, next, the inner hole and bore would both be drilled in the CNC milling operations. Another recommendation is for the Fly-Wheel hole diameter to be precisely measured on the optical comparator or CMM before curing to shaft.

There are a few aspects of our final design that we recommend improving. First, we recommend moving the lip on the inner housing such that the lip is well beneath the fly wheel. We encountered a tolerance stack up during manufacturing that resulted in the lip being located inside of the bore of the wheel. This lip is meant to accurately position the inner housing assembly inside of the outer housing.

Another recommendation is to weigh the assembly before and after balancing in order to accurately determined the amount of mass removed from wheel.

Moving forward, there is another senior project planning on incorporating these reaction wheels into a full ADCS unit (including solar trackers, more complex control systems, etc.). They will build off the work that we have performed over the course of this year. The first step is finishing up manufacturing 2 more inner housings and 1 more outer housing. In preparation for the hand-off, we have manufactured already 2 more flywheels, 2 motor endcaps, and 1 outer housing as well as purchased 2 motors and 1 connector. Furthermore, the Software and EE teams should develop more user-friendly interface for spinning up the wheel for testing and balancing so the wheels can be shipped to the balancer, avoiding the expedite fee, the complicated setup, and the travel to the balancing company. The last recommended action would be to perform the two environmental tests of the unit: TVAC and Vibrations. This way the entire process will be more fluid in the next iteration of manufacture, assembly, and test.

10.0 Works Cited

[1] Bonafede, Nicholas J. "Low-Cost Reaction Wheel Design for CubeSat Applications" *California Polytechnic State University of San Luis Obispo*, Cal Poly CubeSat Laboratory, 2020, pp. 1–163. *Digital Commons*. Engineering Technical Work.

[2] "Reaction/Momentum Wheel" NASA Spinoff, 1997. https://spinoff.nasa.gov/spinoff1997/t3.html

[3] S. Starin, and J. Eterno. "Spacecraft Attitude Determination and Control Systems." Space Mission Engineering: The New SMAD, by J Wertz et al., Microcosm Press, 2011, pp. 565-591. Journal.

[4] Daniel T. and Rouzbeh A. "Magnetorquer Based Attitude Control for a Nanosatellite Test platform" American Institute of Aeronautics and Astronautics, 2010. https://core.ac.uk/download/pdf/207102607.pdf

[5] Tinling, Bruce E. The Status of Passive-Gravity-Gradient Stabilization, vol. 2, no. 1, 13 June 1965, pp. 234–247.

[6] P. Hughes. *Spacecraft Attitude Dynamics*. Dover Publ., 2004. Engineering Text.

[7] Wie, Bong. *Space Vehicle Dynamics and Control*. American Institute of Aeronautics and Astronautics, 2008. Pp. 395-427. Engineering Text. <https://www.faa.gov/about/office_org/headquarters_offices/avs/offices/aam/cami/library/online_libraries/aerospace_medicine/tutorial/media/III.4.3.1_Space_Vehicle_Control_Systems.pdf>

[8] Muhlfelder et al. *BACKUP WHEEL FOR A THREE AXIS REACTION WHEEL SPACECRAFT.* 2 Dec. 1986. Patent.

[9] "Why Can't You Patent an Idea? What You Can Actually Patent." Affordable Legal Services, Free Legal Documents, Advice & Ask a Lawyer, www.rocketlawyer.com/article/why-cant-you-patent-an-idea-ps.rl.

[10]Stetson Jr., John B. *Reaction wheel friction compensation using dither.* 4 June 1991. Patent. <https://ntrs.nasa.gov/citations/20080004404>

[11]Doty, John. *Reaction Sphere for Spacecraft Attitude Control*. Patent. <https://patents.google.com/patent/WO2010117819A1/zh

[12]Bialke, William E. *Reconfigurable reaction wheel for spacecraft.* 27 Oct. 2006. Patent. <https://patents.google.com/patent/US20080099626A1/en>

[13]Leve, Frederick A., Fitz-Coy, Normal G., & Nagabhusgan, Vivek. *Attitude control system for small satellites*. 19 June 2010. Patent. <https://patents.google.com/patent/US9199746B2/en?q=3-axis+Reaction+wheel+cubesat&oq=3-axis+Reaction+wheel+cubesat>

[14]S. Lee, et al. "CubeSat Design Specification." *CubeSat*, 2014. <https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf> Technical Work.

[15]NASA, Launch Services Program, and Cal Poly CubeSat Labs. "ELaNa: Educational Launch of Nanosatellite, P-POD." National Aeronautics and Space Administration, 2009. <https://www.nasa.gov/pdf/506741main_ppod508.pdf> Technical Work, Proposal.

[16]*PolySat*, Cal Poly CubeSat Laboratory, 2019, www.polysat.org/.

[17]"Reaction Wheels." Sinclair Interplanetary. <www.sinclairinterplanetary.com/reactionwheels>

[18]CubeSpace. "CubeWheel." *CubeSpace*, www.cubespace.co.za/products/adcs-components/cubewheel/.

[19]Blue Canyon Technologies. "Reaction Wheels Data Sheet."

[20]"Reaction Sphere." *CubeSatShop.com*, www.cubesatshop.com/product/reaction-sphere/.

[21]“NASA General Environmental Verification Standard (GEVS): GSFC-STD-7000A, Volume 2, Revision A. NASA, 22 April 2019, <https://standards.nasa.gov/standard/gsfc/gsfc-std-7000> Engineering Literature.

[22]“Balance Quality Requirements of Rigid Rotors.” *IRD Balancing*, The Practical Application of ISO 1940/1, doi:10.3403/01185988u. <http://www.irdproducts.com/assets/balance_quality_requirements_of_rigid_rotors.pdf>

[23] Cal Poly Mechanical Engineering Department. *Student Success Guide*. June 2020.

[24] “HYMU 80 Shielding Alloys.” *HYMU 80 Shielding Alloy*, www.nealloys.com/hymu_80.php.

[25] Budynas, Richard G., et al. *Shigley's Mechanical Engineering Design*. Tenth Edition ed., McGraw-Hill, 2015.

[26] Oberg, Erik, et al. *Machinery's Handbook*. Edited by Christopher J McCauley, 29th ed., Industrial Press, 2012.

[27] Engineers Edge, L. (n.d.). ANSI internal screw Threads size and Tolerances Table Chart. Retrieved February 11, 2021, from https://www.engineersedge.com/thread_strength/internal_screw_threads_chart.htm

[28] Stainless Steel Fasteners. (n.d.). Retrieved from https://www.fluidsealingproducts.com/pdf/stainless-steel-fasteners.pdf

APPENDIX A: QFD/ HOUSE OF QUALITY

Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Reaction Wheel Design

Revision Date: 10/07/2020

Acronym Key

CPCL = Cal Poly CubeSat Loboratory
1U = Classification of CubeSats where 1U = 10cm x 10cm x 10cm cubes with a maximum massof 1.33 kg per U
LEO = Low Earth Orbit (<2000 km)
GEVS = General Environmental Verification Standard (NASA-STD-7000)

							Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
WHO: Customers							Direction of Improvement	▼	▼	▲	▼	◇	◇	◇	◇	◇	◇	◇	◇	◇	▲	▲		NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	CPCL	Student who Manufacture	Students who Integrate into full Bus	Maximum Relationship	WHAT: Customer Requirements (Needs/Wants) / HOW: Engineering Specifications (Tests)	Mass	Cost	Machinable	Volume	Thermal Specifications	Vacuum Testing Specifiactions	Torque Specs	Momentum Bit	Total Momentum	Balance Quality Grade	Deorbit Demise	Vibration Testing Specifications	Compatibility	Safety	Ease of Assembly		Nick's Thesis	Competitor #1: Rocket Labs (Sinclair)	Competitor #2: CubeWheel	Competitor #3: Blue Canyon Technologies		Row #
1		10%	8	8	8	9	Achieving desired performance metrics	○				○	○	●	●	●	●		○					3	5	5	4		1
2		4%	10	1	1	9	Affordable	○	●	○														5	0	0	0		2
3		11%	8	10	6	9	Manufacturable			●	○													4	2	2	2		3
4		4%	10	1	1	9	Shall survive launch and on-orbit environments					●	●					○	●					3	5	5	5		4
5		4%	10	1	1	9	Shall meet typical launch provider mass budget	●			○									○				5	5	5	5		5
6		11%	9	7	10	9	Shall be able to interface with standard CPCL Bus				●									●				3	5	5	3		6
7		9%	10	5	8	9	Shall be able to fit in 1U volume				●									●				4	5	5	5		7
8		5%	10	2	2	3	Completed protype and build by end of year			○							○							4	-	-	-		8
9		5%	10	2	2	9	Can be implemented in a variety of CubeSat projects			●										●				4	5	5	4		9
10		5%	10	2	2	9	Shall meet requirments outlined by a typical LEO Orbital Debris Assessment Report											●						2	5	5	4		10
11		10%	8	8	8	9	Students shall be able to handle the system safely														●			5	5	5	5		11
12		10%	8	8	8	9	The system should minimize risk of damage to surrounding components														●			4	5	5	5		12
13		11%	8	8	10	9	Efficiently assembled and integrated onto bus structure													●		●		4	5	5	4		13
14		0%																											14
15		0%																											15
16		0%																											16

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target Values	< 660 g (165 g per wheel)	<$2000	Needs to fullfill CPCL Structual Review Checklist	<= 10 cm x 10 cm x 5 cm (approx, 1/2 1-U)	60C for 6 hours or 70C for 3 hours	Max Pressure 1x10^-4 Torr	1.0 mNm	17.5 µNms	5 mNms	G 6.3	Does not survive reentry from LEO	NASA GEVS Random&Sine Sweep	Needs to fullfill CPCL Structual Review Checklist	Needs to check no on all boxes in Senior Design Hazzard Checklist	Needs to fullfill CPCL Structual Review Checklist	
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
Technical Importance Rating	77.294	34.45	164.39	228.7	65.81	65.81	94.08	94.08	94.08	108.6	55.17	65.81	343.85	188.17	103.04	0
Relative Weight	4%	2%	9%	13%	4%	4%	5%	5%	5%	6%	3%	4%	19%	11%	6%	0%
Curr. Products: Nick's Thesis	5	4	2	4	3	3	5	5	5	3	4	4	2	2	2	
Competitor #1: Rocket Labs (Sinclair)	5	1	4	4	5	5	4	4	5	5	5	5	5	5	5	
Competitor #2: CubeWheel	5	1	4	4	5	5	4	4	5	5	5	5	5	5	5	
Competitor #3: Blue Canyon Technologies	5	1	4	4	5	5	4	4	5	5	5	5	2	5	3	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

APPENDIX B: DESIGN HAZARD CHECKLIST

PDR Design Hazard Checklist **F63 Reaction Wheel**

Y	N	
⊖		1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
⊖		2. Can any part of the design undergo high accelerations/decelerations?
	⃠	3. Will the system have any large moving masses or large forces?
	⃠	4. Will the system produce a projectile?
	⃠	5. Would it be possible for the system to fall under gravity creating injury?
	⃠	6. Will a user be exposed to overhanging weights as part of the design?
	⃠	7. Will the system have any sharp edges?
	⃠	8. Will any part of the electrical systems not be grounded?
	⃠	9. Will there be any large batteries or electrical voltage in the system above 40 V?
⊖		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	⃠	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	⃠	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	⃠	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	⃠	14. Can the system generate high levels of noise?
⊖		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
	⃠	16. Is it possible for the system to be used in an unsafe manner?
	⃠	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

PDR Design Hazard Checklist **F63 Reaction Wheel**

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
A part of the design creates hazardous revolving, reciprocating, running, including pinch points and sheer points: the wheel when running during tests will rotate and could pinch.	When the wheel is running, no student will near it without protective measures: i.e. safety glasses and no hanging clothing items that would get caught in the rotating machinery.	April 30	May 4
A part of the design undergoes high accelerations/decelerations: the flywheel undergoes high rpms once CubeSat is in orbit	There will be an outer housing that restrains the flywheel and the motor designed to protect the user, the surrounding CubeSat, and the device itself from the dangers of rotating machinery.	Feb 12	May 7
Stored energy in the system: flywheels can store energy in the system	Similarly to the response to the dangers of high accelerations, the dangers of the stored energy in the system are remediated by the corrective action of an outer housing design.	Feb 12	May 7
Exposed to extreme environmental conditions: launch and space environments (including high temperatures)	The system will be tested in a thermal vacuum chamber (TVAC) following safety protocol outlined by CPCL. Also, the vibrations test will similarly follow safety protocol.	May 18	May 15

Referenced from the Senior Project Student Success Guide [23].

APPENDIX C: BALANCE QUALITY GRADE FOR REPREHENSIVE RIGID ROTORS

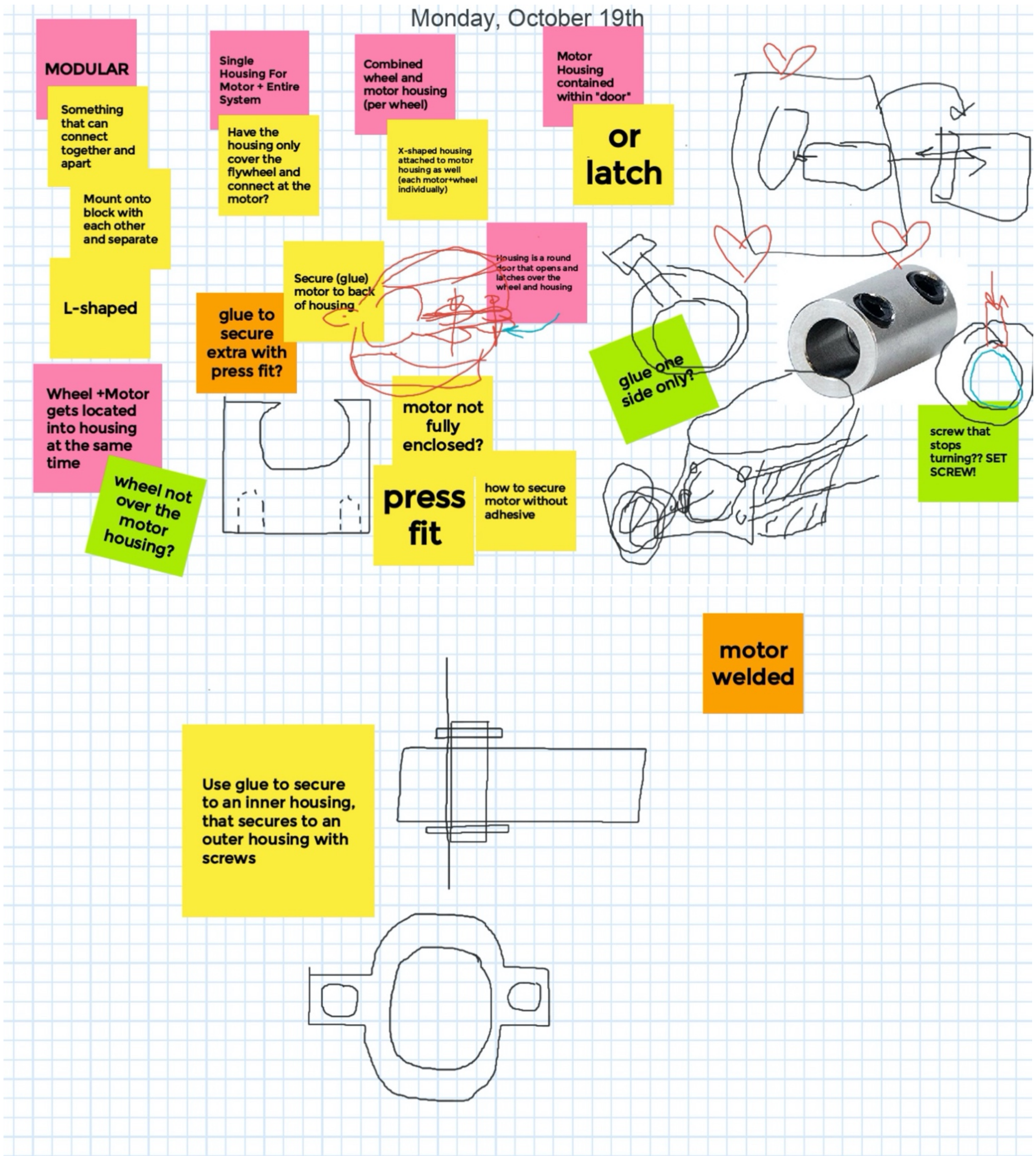
Table 1 Balance quality grades for various groups of representative rigid rotors (From ISO 1940/1)

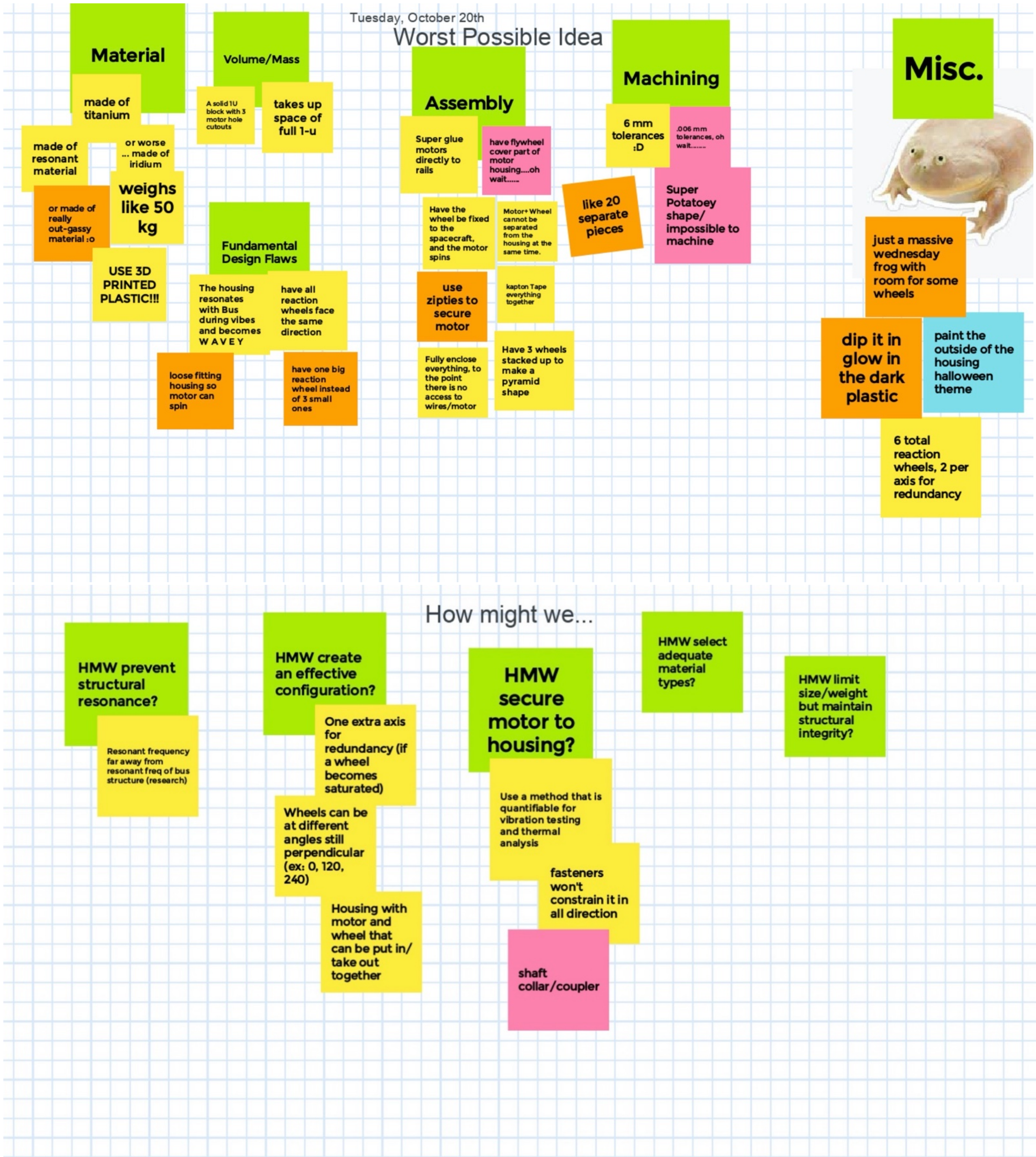
Balance Quality Grade	Product of the Relationship ($e_{per} \times \omega$) (1) (2) mm/s	Rotor Types - General Examples
G 4 000	4 000	Crankshaft/drives(3) of rigidly mounted slow marine diesel engines with uneven number of cylinders(4)
G 1 600	1 600	Crankshaft/drives of rigidly mounted large two-cycle engines
G 630	630	Crankshaft/drives of rigidly mounted large four-cycle engines Crankshaft/drives of elastically mounted marine diesel engines
G 250	250	Crankshaft/drives of rigidly mounted fast four-cylinder diesel engines(4)
G 100	100	Crankshaft/drives of fast diesel engines with six or more cylinders(4) Complete engines (gasoline or diesel) for cars, trucks and locomotives(5)
G 40	40	Car wheels, wheel rims, wheel sets, drive shafts Crankshaft/drives of elastically mounted fast four-cycle engines with six or more cylinders(4) Crankshaft/drives of engines of cars, trucks and locomotives
G 16	16	Drive shafts (propeller shafts, cardan shafts) with special requirements Parts of crushing machines Parts of agricultural machinery Individual components of engines (gasoline or diesel) for cars, trucks and locomotives Crankshaft/drives of engines with six or more cylinders under special requirements
G 6.3	6.3	Parts of process plant machines Marine main turbine gears (merchant service) Centrifuge drums Paper machinery rolls; print rolls Fans Assembled aircraft gas turbine rotors Flywheels Pump impellers Machine-tool and general machinery parts Medium and large electric armatures (of electric motors having at least 80 mm shaft height) without special requirements Small electric armatures, often mass produced, in vibration insensitive applications and/or with vibration-isolating mountings Individual components of engines under special requirements
G 2.5	2.5	Gas and steam turbines, including marine main turbines (merchant service) Rigid turbo-generator rotors Computer memory drums and discs Turbo-compressors Machine-tool drives Medium and large electric armatures with special requirements Small electric armatures not qualifying for one or both of the conditions specified for small electric armatures of balance quality grade G 6.3 Turbine-driven pumps
G 1	1	Tape recorder and phonograph (gramophone) drives Grinding-machine drives Small electric armatures with special requirements
G 0.4	0.4	Spindles, discs and armatures of precision grinders Gyroscopes

1) $\omega = 2\pi n/60 \approx n/10$, if n is measured in revolutions per minute and ω in radians per second.
2) For allocating the permissible residual unbalance to correction planes, refer to "Allocation of U_{per} to correction planes."
3) A crankshaft/drive is an assembly which includes a crankshaft, flywheel, clutch, pulley, vibration damper, rotating portion of connecting rod, etc.
4) For the purposes of this part of ISO 1940/1, slow diesel engines are those with a piston velocity of less than 9 m/s; fast diesel engines are those with a piston velocity of greater than 9 m/s.
5) In complete engines, the rotor mass comprises the sum of all masses belonging to the crankshaft/drive described in note 3 above.

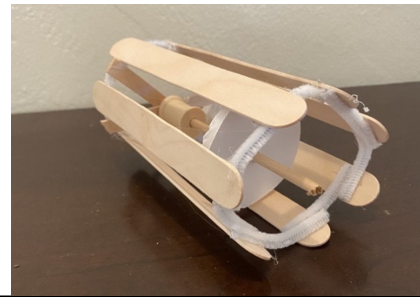
Referenced from IRD Balancing, *Balance Quality Requirements of Rigid Rotors* [22].

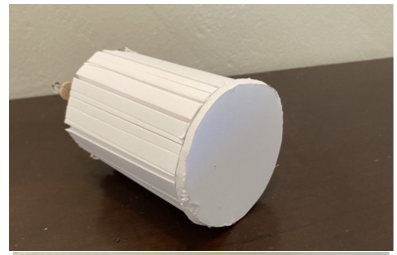
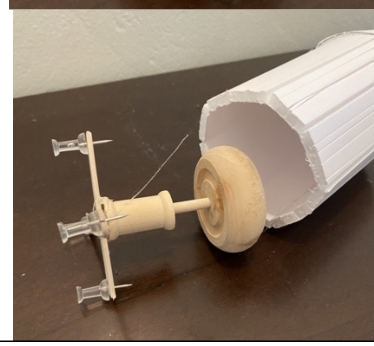
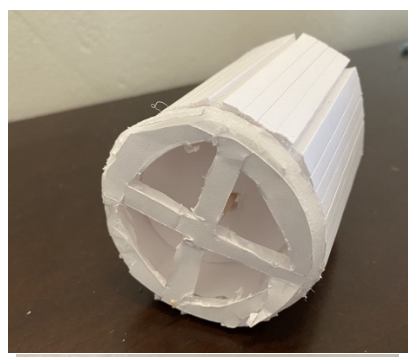
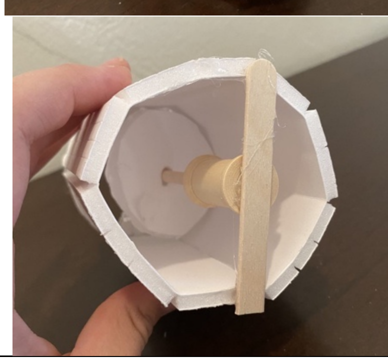
Appendix D: Ideation Jamboard

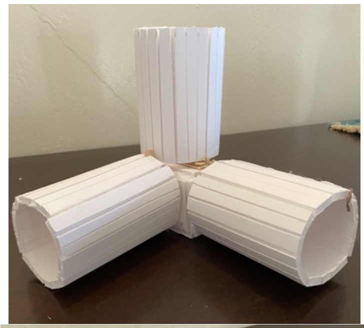
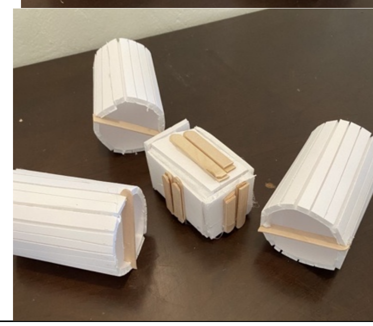
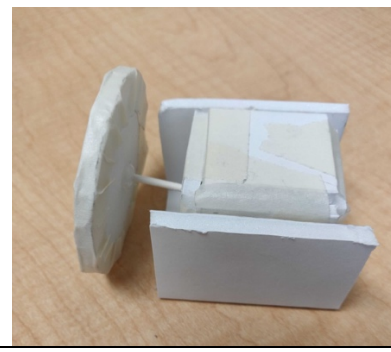
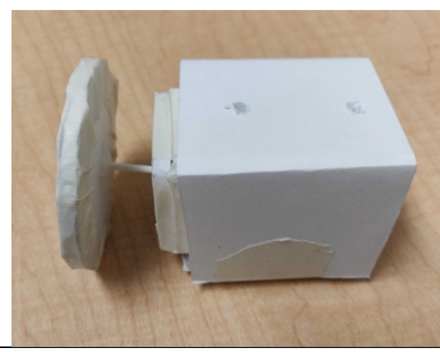


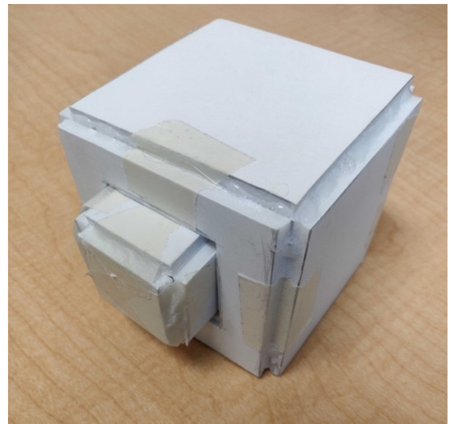
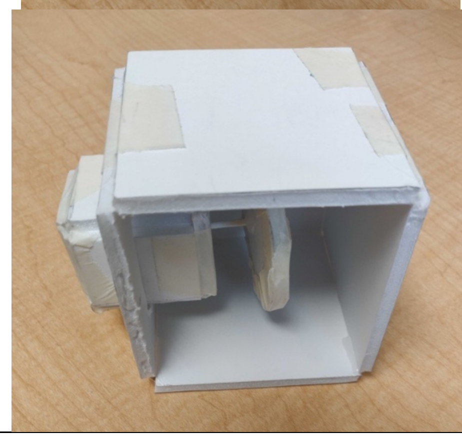
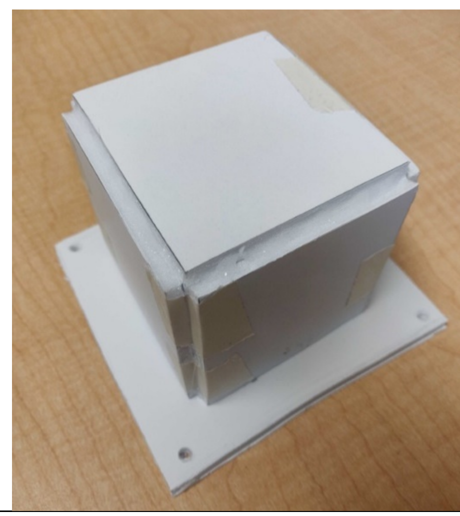

Tuesday, October 20th
Worst Possible Idea
Material
made of titanium
made of resonant material
or worse ... made of iridium
or made of really out-gassy material :o
weighs like 50 kg
USE 3D PRINTED PLASTIC!!!
Volume/Mass
A solid 1U block with 3 motor hole cutouts
takes up space of full 1-u
Fundamental Design Flaws
The housing resonates with Bus during vibes and becomes W A V E Y
have all reaction wheels face the same direction
loose fitting housing so motor can spin
have one big reaction wheel instead of 3 small ones
Assembly
Super glue motors directly to rails
have flywheel cover part of motor housing....oh wait......
Have the wheel be fixed to the spacecraft, and the motor spins
Motor+ Wheel cannot be separated from the housing at the same time.
use zipties to secure motor
kapton Tape everything together
Fully enclose everything, to the point there is no access to wires/motor
Have 3 wheels stacked up to make a pyramid shape
Machining
6 mm tolerances :D
.006 mm tolerances, oh wait......
like 20 separate pieces
Super Potatoey shape/ impossible to machine
Misc.
just a massive wednesday frog with room for some wheels
dip it in glow in the dark plastic
paint the outside of the housing halloween theme
6 total reaction wheels, 2 per axis for redundancy
How might we...
HMW prevent structural resonance?
Resonant frequency far away from resonant freq of bus structure (research)
HMW create an effective configuration?
One extra axis for redundancy (if a wheel becomes saturated)
Wheels can be at different angles still perpendicular (ex: 0, 120, 240)
Housing with motor and wheel that can be put in/ take out together
HMW secure motor to housing?
Use a method that is quantifiable for vibration testing and thermal analysis
fasteners won't constrain it in all direction
shaft collar/coupler
HMW select adequate material types?
HMW limit size/weight but maintain structural integrity?

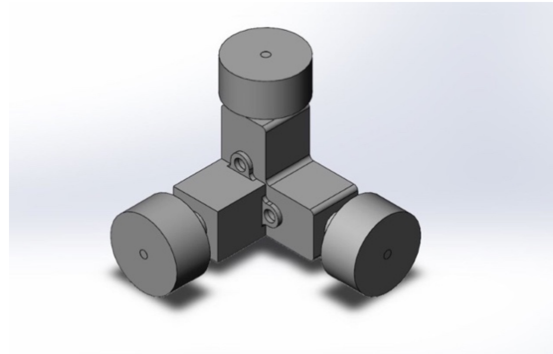
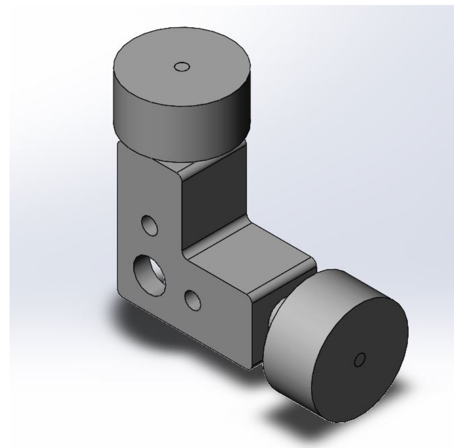
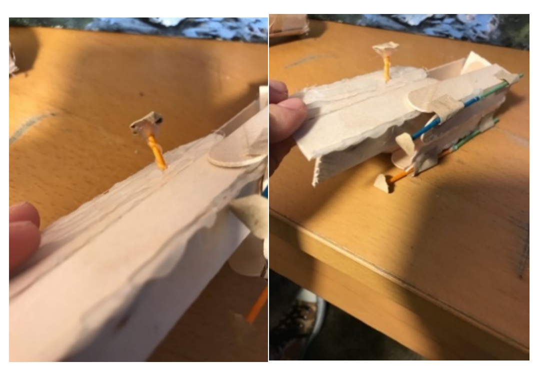
APPENDIX E: FUNCTION CONCEPT PROTOTYPES

Concept	Description	Photo
Mass reduction/open housing concept	This idea has the wheel and motor contained in one housing that has cut-outs on the sides for mass reduction. Each wheel/motor combination would be housed separately.	
Latched/accessibility-driven housing	This is a fully enclosed housing for the motor and wheel that allows the user to unlatch the housing and open it to reach the internal components and adjust (such as during balancing and testing)	 

Fully enclosed with open back/removable components	This concept design encloses the entire wheel and motor system but has an x-bracket on the back with fasteners allowing the motor/wheel configuration to be removed.	  
X-bracket with open back	This concept is like the concept mentioned above where it is a completely enclosed cylindrical housing but has an x-bracket or cutouts on the front for mass reduction.	 

Molar 3-axis	This design has a cylindrical housing for each wheel/motor combination and they each attach to a mounting block at the center through a slot/lock. This way, each wheel and motor can be either mounted to the mounting block or to the bus separately.	 
Snap-In Housing	This design has a motor housing that requires the motor be pressed in. The motor is secured by compression on most of its surface. The housing screws directly to the spacecraft.	
Slide in Housing with Set Screw Coupling	This concept is of a slide-in motor housing with a set screw coupling that secures the motor to its housing. The housing screws directly to the spacecraft.	

Fully enclosed wheel housing with motor press fit	This model is of a wheel housing in which the motor is press-fit into of the sides. The wheel housing is cubic and prevents the wheel from coming in contact with the rest of the spacecraft in the case of any form of failure. The housing interfaces directly to the spacecraft using screws.	 
Fully enclose wheel and motor housing	This design has the motor and wheel completely encased in a rectangular housing for complete isolation from the rest of the internal components of the satellite. The housing interfaces to a baseplate which interfaces to the spacecraft.	

Modular L-Bracket	This model is of a modular 3-axis design. In this design two axes are manufactured as a single piece and a third axes is separately manufactured to interface perpendicular to the first two. The motors are glued into their housings along any of the 3 axes and there is no covering for the wheel. The L-Bracket interfaces directly to the spacecraft.	 
Press fit cylindrical motor housing, tab-mount bracket interface, no wheel housing	This has reduced mass with a cylinder to go around the cylindrical housing. It also had spaced out tabs to attach with extra stability. This design had a completely free wheel (no covering).	
Sliding top, two-piece outer housing, set screw attachment, no wheel housing	This design displays a few different combined concepts of how to attach the inner motor (or the inner motor housing) to its outer housing. The two concepts displayed are a set screw and a sliding lock. The take-away from this design that was implemented was the front fastener design,	

	necessary for the wheel housing decided upon.	
Open-top motor housing, tab-mount bracket interface, no wheel housing	The key feature of this design is a press-fit motor housing into the outer housing, and reduced mass by having it not fully enclosed. Another feature of this design is a half-moon cutout on the housing for the shaft.	
Open-top ridged motor housing, wheel brace framework	This was a bare-bones concept of a wheel brace that is different than the cross, but still restrains the wheel if it were to fly off. Also, in this design are a ridge-style press fit.	
Latch top motor housing, tab-mount bracket interface, no wheel housing	The latch top allowed for the whole motor and wheel assembly to be put in and taken out which is desirable for our designs. And the wheel could be adhered to the back plate. However, I was unsure on how this would be made.	

APPENDIX F: PUGH MATRICES

Pugh Matrix – Modularity
Alex Lee
F63 – 3-Axis Reaction Wheel For Cubesats (Housing Design)

KEY
S = same
+ = better
− = worse

NOTE: Criteria adjusted for ONLY housing not entire system

Criteria \ Concept	① All one housing (No modularity) (Nick's design)	② L-bracket	③ one housing per wheel x3 (for Rectangular)	④ Mounting block	⑤ 4-Axis System	⑥ Removable motor+wheel from housing
1. Affordable	DATUM	−	+	+	−	+
2. Manufacturable		S	+	S	−	+
3. Survive launch + on-orbit environment		−	+	−	S	S
4. Low mass		S	S	−	−	S
5. Compatibility w/ Bus		S	+	+	S	S
6. Volume (<1U)		S	+	−	−	S
7. Versatile w/ diff. Cubesats		+	+	+	+	S
8. Safety		S	S	−	S	+
9. Protects wheel / motor		S	S	S	−	+
10. Assembly		+	+	−	−	+
Total:	0	0	7	−2	−5	5
Rank:	④	③	①	⑥	⑤	②

7. Versatile w/ diff. Cubesats ← Diff sizes, missions, 2-4 axis needs

Pugh Matrix: Wheel Housing

Criteria \ Concept	Datum Nick's Design	No Covering	Slide into Complete Enclosure	Slide into Opened Enclosure	X-Type Covering	Assembled Within Complete Enclosure
Affordable	D	S	S	S	S	−
Manufacturable	D	S	S	−	−	S
Low Mass	D	S	−	S	S	−
Low Volume	D	S	S	S	S	−
Safety	D	S	+	+	+	+
Protects Wheel	D	S	+	+	+	+
Assembly	D	S	+	+	S	−
Total	0	0	+2	+2	+1	−2

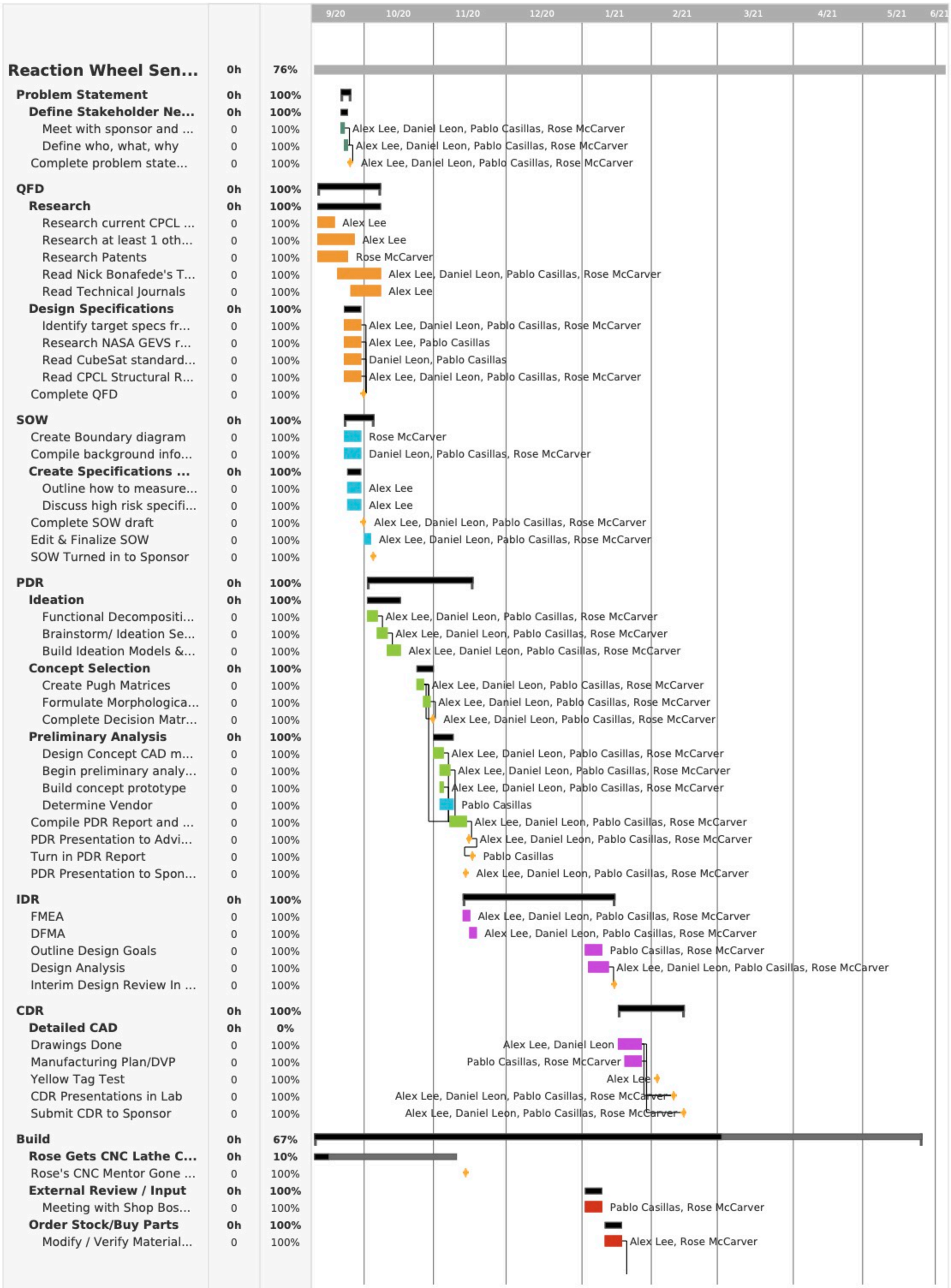
PUGH MATRIX: MOTOR ENCLOSURES

	CYLINDRICAL	SQUARE	LATCH/DOOR	DATUM: NICK'S THESIS
AFFORDABLE	+	+	+	D
MANUFACTURABLE	S	+	S/-?	D
MASS BUDGET	+	+	+	D
LAUNCH ENVIRONMENT	+	+	−	D
FITS IN 1U VOLUME	+	+	+	D
INTEGRATION	+	+	+/S?	D
	+5	+6	+2/+1	X

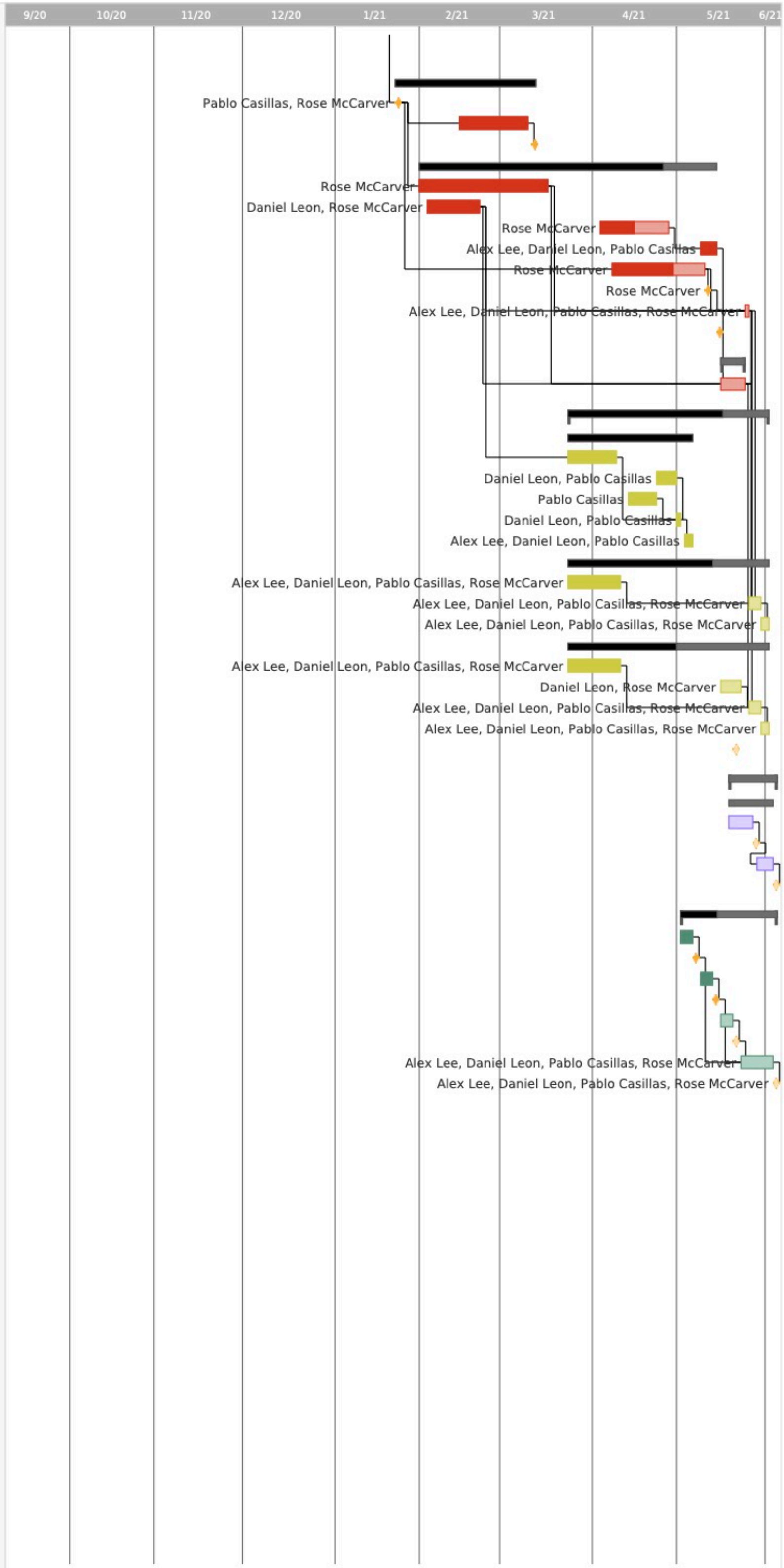
PUGH MATRIX: MOTOR HOUSING INTERFACE

	① JUST STAKING (GLUE) ①a back plate	① JUST STAKING (GLUE) ①b full body	② PRESS FIT CYLINDER	③ PRESS FIT (OPEN TOP)	④ SET SCREW	DATUM: NICK'S DESIGN
AFFORDABLE	+	+	S	S	+	D
MANUFACTURABLE	+	+	S	S	+	D
MASS BUDGET	+	+	+	+	+/S?	D
LAUNCH (SURVIVES)	+	+	S	S	−	D
FITS IN 1U LOW VOLUME	+	+	+	−	S/−?	D
VARIETY OF INTEGRATIONS	+	+	+	−	+	D
TOTAL	+6	+6	+3	−1	+2/+1	X

APPENDIX G: GANTT CHART

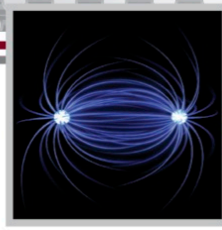


Manufacturing Review	**0h**	**100%**
Meeting with CPCL (Avi...	0	100%
Test planning/design	0	100%
Manufacturing and Test...	0	100%
Machine Reaction Whe...	**0h**	**82%**
Machine Wheels	0	100%
Press Fit Experimenting	0	100%
Machine Inner Housing	0	50%
Subassembly (wheel, m...	0	100%
Machine Outer Housing	0	66%
Complete Machining	0	100%
Final Assembly	0	0%
VP Signoff	0	100%
Balancing Motor	**0h**	**0%**
Send to Balancing Vendor	0	0%
Test	**0h**	**77%**
Adhesive Proof Test	**0h**	**100%**
Develop test plan	0	100%
Cure shaft to disks	0	100%
Machine fixture for test...	0	100%
Run Proof Test	0	100%
Analyze Results	0	100%
TVAC Test	**0h**	**72%**
Develop TVAC testing p...	0	100%
Run the Test	0	0%
Analyze Results	0	0%
Vibes Test	**0h**	**54%**
Develop Vibes Testing P...	0	100%
Design and Make 1U A...	0	0%
Run the Test	0	0%
Analyze results	0	0%
DVPR Sign-Off	0	0%
EXPO	**0h**	**0%**
Design Presentation M...	**0h**	**0%**
Expo Webpage and Proj...	0	0%
Submit Webpage and V...	0	0%
Edit and Finalize Webp...	0	0%
Submit Webpage and Vid...	0	0%
FDR	**0h**	**38%**
FDR Manufacturing Chapt...	0	100%
FDR Manufacturing Chapt...	0	100%
Write User Manual	0	100%
Submit User Manual for P...	0	100%
Design Verification Chapt...	0	0%
Submit DV Chapter for Pe...	0	0%
Compile FDR	0	0%
Submit Final FDR to Spon...	0	0%



Appendix H: HyMu 80 Magnetic Shielding Alloy Properties

SHIELDING ALLOY 80 (HyMu 80)



CHEMICAL COMPOSITION %	
Chemical Element	**HyMu 80**
Nickel	80
Molybdenum	5
Iron	Balance

MECHANICAL PROPERTIES	
Property	**HyMu 80**
Density	.316 lb/in
Specific Gravity	8.7 g/cm
Curie Temperature	830°F (410°C)
Melting Point	2650°F (1454°C)

NOMINAL MECHANICAL PROPERTIES (ANNEALED)

80 max
44,000 psi yield
100,000 psi tensile
40%< elongation in 2"

THERMAL CONDUCTIVITY

134 Btu-inch/ft hour degree F
0.32 W/cm degree C

MEAN COEFFICIENT OF THERMAL EXPANSION

7.2 in/in/degree F x 10-6 between 70° & 400°F
13 cm/cm/degree C x 10-6 between 30° & 204°C

ELECTRICAL RESISTIVITY

349 ohm circ mil/foot
0.55 ohm mm2/m

MAGNETIC PROPERTIES

"Shielding Alloy 80" has a minimum DC permeability of 80,000 at a flux density of 40 gauss when heat treated by the recommended procedure and tested in accordance with ASTM 596.

"Shielding Alloy 80" (ie, Hymu 80, MuMetal2, Ultravac 80) is a magnetic shielding alloy. It's comprised of 80% Nickel, 4-5% Molybdenum and the balance is Iron.

Its main characteristic is high permeability with minimal hysteresis loss, which is useful for shielding against static and low frequency magnetic fields that can interfere with electronic components.

"Shielding Alloy 80" has a minimum DC permeability of 80,000 at a flux density of 40 gauss when properly heat treated. It can be used in its current state of Annealed, however, because forming can reintroduce temper, it is recommended to heat treat parts to achieve optimal shielding capability.

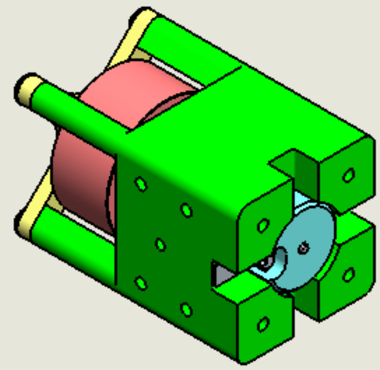
APPENDIX I: DRAWING PACKAGE AND iBOM

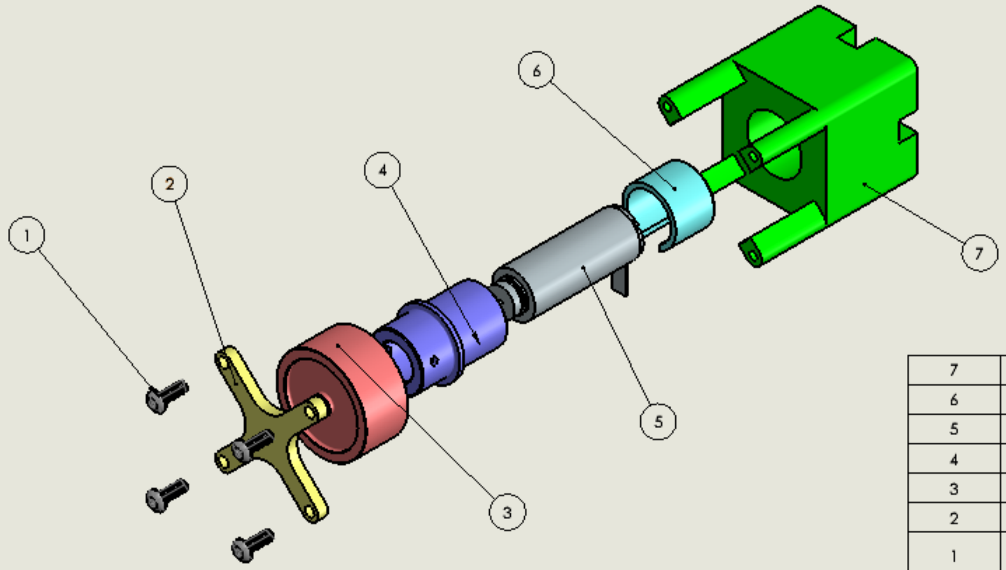
F63- CubeSat Reaction Wheel
Indented Bill of Material (iBOM)

Assembly Level	Part Number	Description (Lvl0 / Lvl1 / Lvl2 / Lvl3 / Lvl4)	Qty	Cost	Ttl Cost	Source	Part No.	More Info	Website
0	100000	Final Assy				------			
1	110000	Top Assembly				------			
2	111000	Outer Wheel and Housing Syst				------			
3	111100	Outer Housing Stock	1	65.43	65.43	McMaster	9246K781	1" Thick, 2" x 48"	https://www.mcmaster.com/9246K781
3	111200	X Bracket Stock	2	13.43	26.86	McMaster	89015K222	0.09" Thick, 4" x 24"	https://www.mcmaster.com/89015K222/
2	112000	Motor System							
3	112100	Motor	3	323.00	969	Maxon	315173	w/ Hall sensors	motor?etcc_cu=onsite&etcc_med_onsite=Product&et
3	112200	HyMu80 Motor Housing Stock	1	300.00	300.00	NEA	n/a	0.76 x 34 in, received quote	https://www.nealloys.com/hymu_80.php
3	112300	Balancing	3	100.00	300.00	EBC	-----	-----	
2	113000	Wheel Stock	1	39.97	39.97	McMaster	89325K194	7/8" x 2ft	https://www.mcmaster.com/89325K19 2 ft ples (~ $40)
1	120000	Tooling and Support Items							
1	121000	Test Shafts	2	5.31	10.62	McMaster	1265K11	316 Stainless Steel 1 mm dia	https://www.mcmaster.com/1265K11/
1	122000	Small Bore Gauge Set	1	62.00	62.00	WestPort	n/a	Black Ox Class zz Gage pin set	Black Ox Class ZZ Gage Pin Set .011" - .060" - 50 gages
1	123000	Boring Bar	1	34.86	34.86	MSC	5252465	0.08" min bore dia, 0.3" max deptl	Accupro - 0.08" Min Bore Diam, 0.3" Max Bore Depth,
1	124000	Tool Blank	2	6.83	13.66	MSC	2603249	3/8 " wide x 3/8" high x 3" OAL	Interstate - M2 High Speed Steel Square Tool Bit Blank
1	125000	Reamer	2	41.80	83.60	MSC	72003858	.0385" dia 1/2 " flute length	Made in USA - 0.0385" High Speed Steel 3 Flute
1	130000	Controller	1	83.22	83.22	Maxon	466023	escon 24/2 module	https://www.maxongroup.us/maxon/view/product/co
1	140000	Epoxy: Scotch Weld	1	50.80	50.80	Amazon	n/a	have some in Polysat lab as well	Epoxy-Adhesive/dp/B00GNLY3PS?th=1
1	150000	Screws	1	3.54	3.54	McMaster	92196A077	#2-56 x 1/4" Socket Head	https://www.mcmaster.com/92196A077/
	Total Parts		25						

NOTES:

UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
   X.XX ±.01
   X.XXX ±.005
   ANGLES ±.5°
5. SURFACE FINISH: 63/√ FAO





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
7	MESP-2002	OUTER HOUSING	1
6	MESP-2003	MOTOR END CAP	1
5	315170	MOTOR, MAXON EC10	1
4	NJB-8812	MOTOR HOUSING	1
3	NJB-8811	FLYWHEEL	1
2	MESP-2001	X-BRACKET	1
1	98164A425	2-56 UNC - 3A X 0.25L SCREW	4

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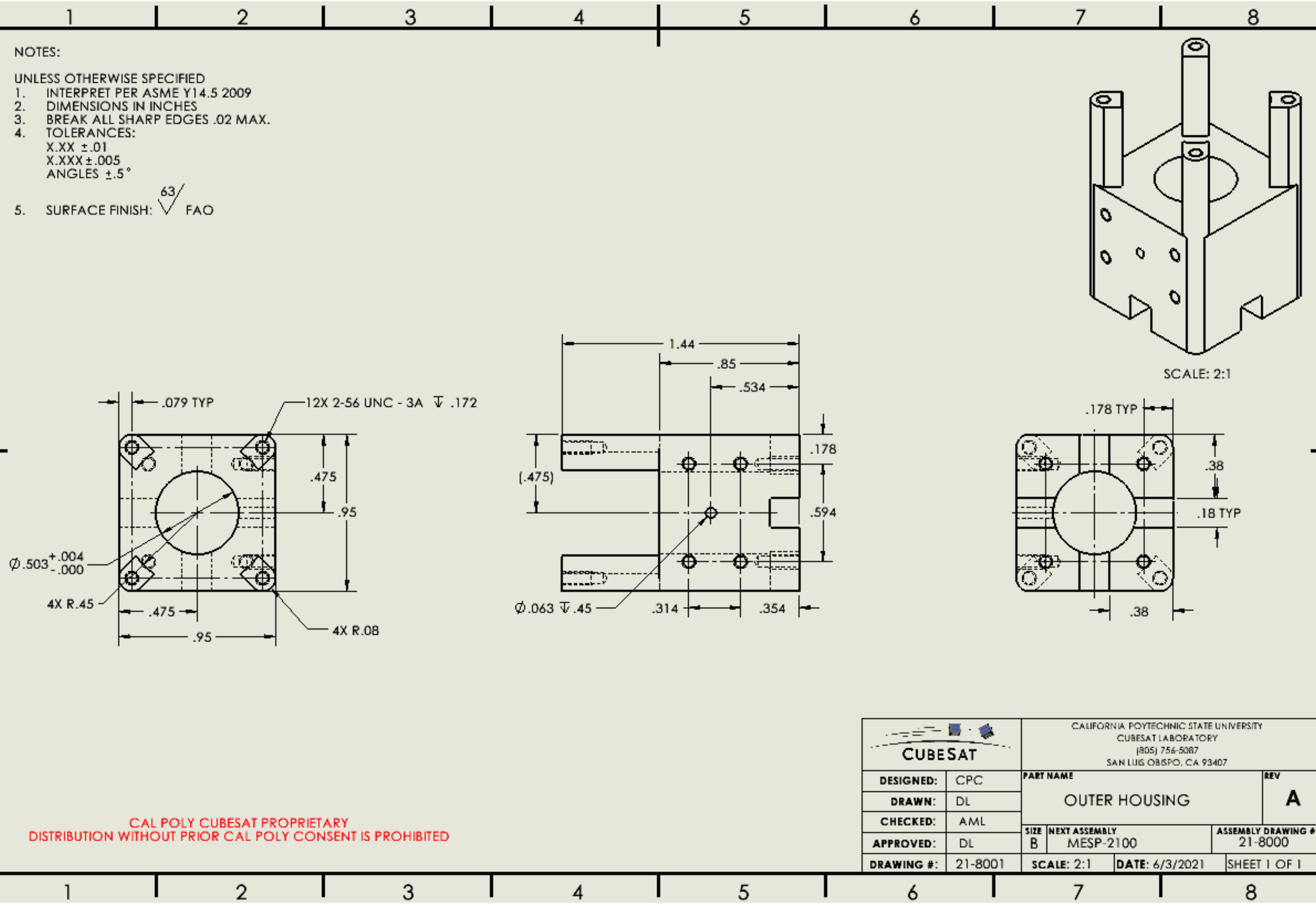
CUBESAT LABORATORY
(805) 756-5087
SAN LUIS OBISPO, CA 93407

DESIGNED:	CPC	PART NAME: REACTION WHEEL ASSEM.	REV: A
DRAWN:	DL		
CHECKED:	RMC	SIZE: B / NEXT ASSEMBLY: MESP-2100	ASSEMBLY DRAWING #: 21-8000
APPROVED:	DL		
DRAWING #:	21-8000	SCALE: 1:1 / DATE: 6/3/2021	SHEET 1 OF 1

A


NOTES:
UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
X.XX ±.01
X.XXX ±.005
ANGLES ±.5°
5. SURFACE FINISH: 63 FAO
SCALE: 2:1
.079 TYP
12X 2-56 UNC - 3A ↧ .172
.475
.95
Ø.503 +.004 -.000
4X R.45
.475
.95
4X R.08
1.44
.85
.534
.178
(.475)
.594
Ø.063 ↧ .45
.314
.354
.178 TYP
.38
.18 TYP
.38
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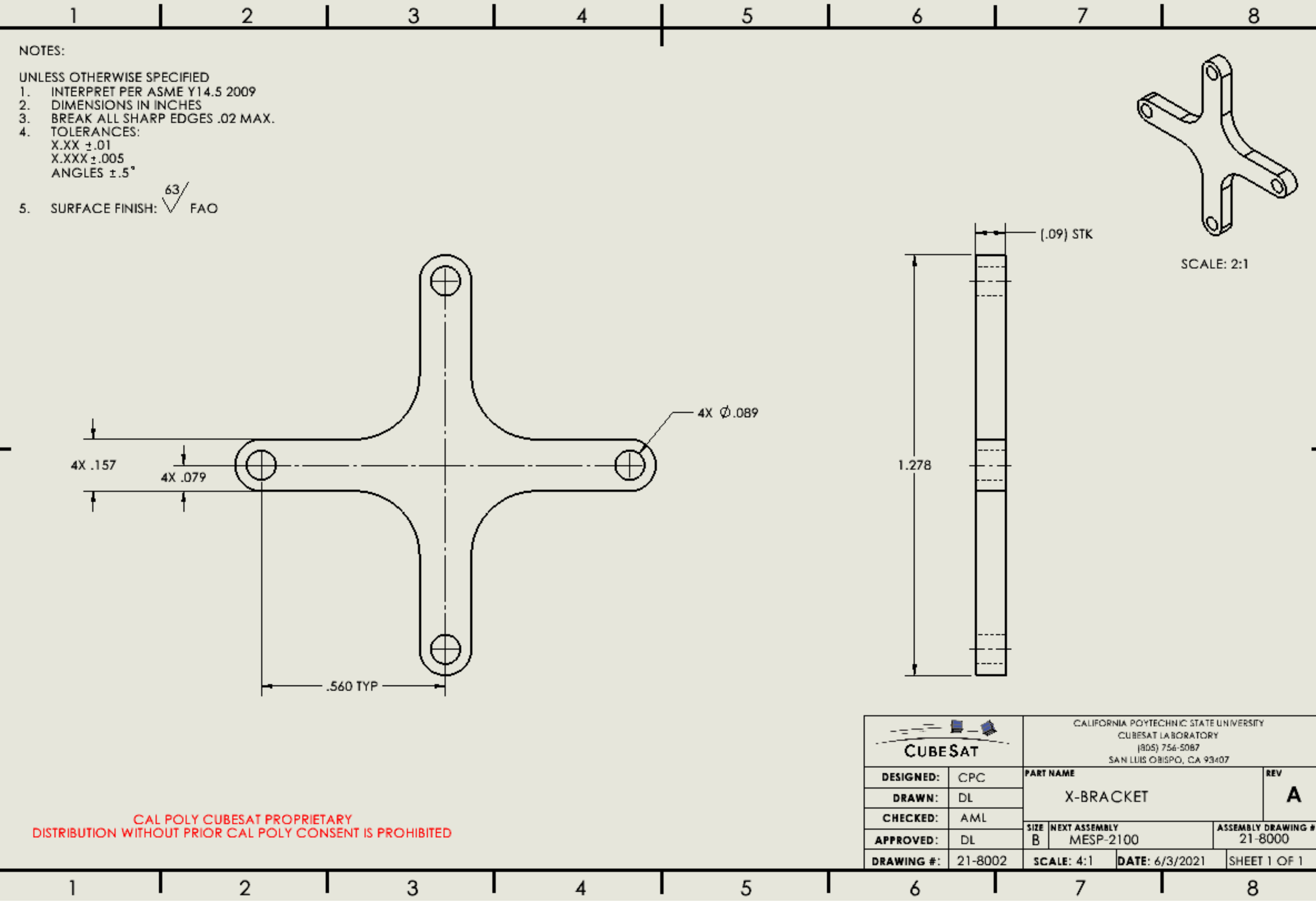
SAN LUIS OBISPO, CA 93407
DESIGNED: CPC
DRAWN: DL
CHECKED: AML
APPROVED: DL
DRAWING #: 21-8001
PART NAME: OUTER HOUSING
REV: A
SIZE: B
NEXT ASSEMBLY: MESP-2100
ASSEMBLY DRAWING #: 21-8000
SCALE: 2:1
DATE: 6/3/2021
SHEET 1 OF 1


1 2 3 4 5 6 7 8
NOTES:
UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
X.XX ±.01
X.XXX ±.005
ANGLES ±.5°
5. SURFACE FINISH: 63 FAO
SCALE: 2:1
(.09) STK
4X ∅.089
4X .157
4X .079
1.278
.560 TYP
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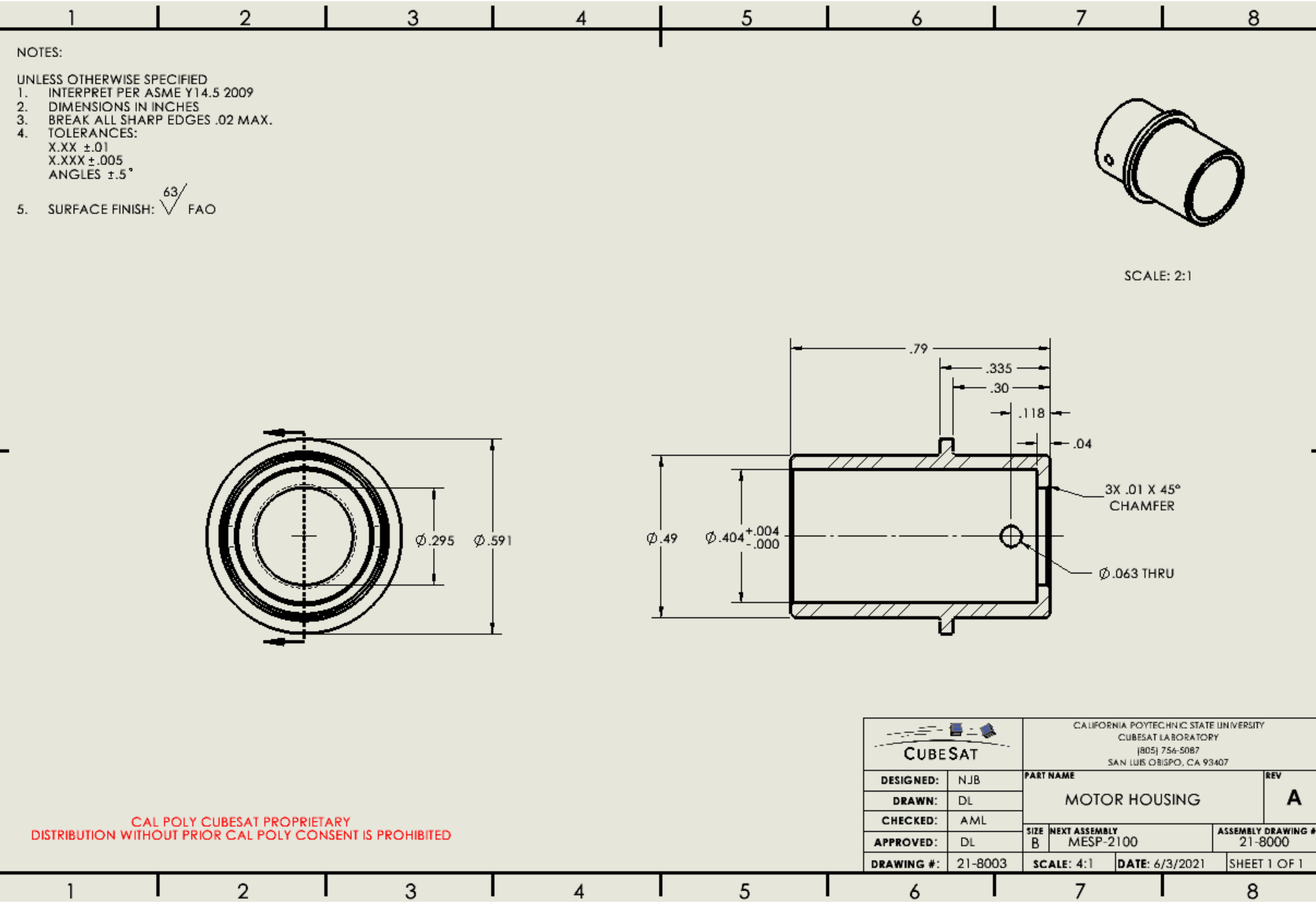
DESIGNED: CPC
DRAWN: DL
CHECKED: AML
APPROVED: DL
DRAWING #: 21-8002
PART NAME
X-BRACKET
REV
A
SIZE B
NEXT ASSEMBLY MESP-2100
ASSEMBLY DRAWING # 21-8000
SCALE: 4:1
DATE: 6/3/2021
SHEET 1 OF 1


NOTES:
UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
X.XX ±.01
X.XXX ±.005
ANGLES ±.5°
5. SURFACE FINISH: 63 FAO
SCALE: 2:1
Ø.295
Ø.591
.79
.335
.30
.118
.04
Ø.49
Ø.404 +.004 -.000
3X .01 X 45° CHAMFER
Ø.063 THRU
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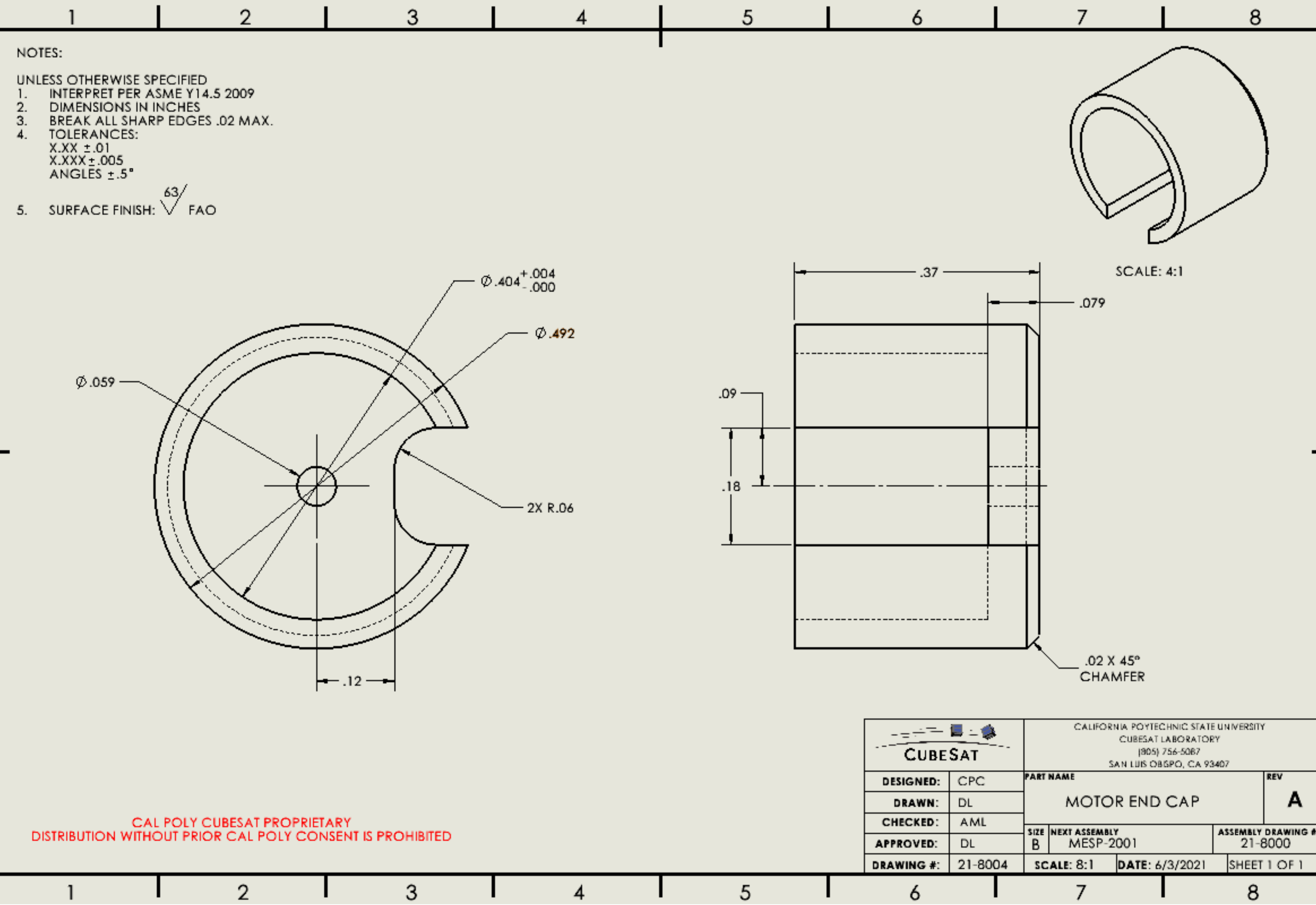
SAN LUIS OBISPO, CA 93407
DESIGNED: NJB
DRAWN: DL
CHECKED: AML
APPROVED: DL
DRAWING #: 21-8003
PART NAME
MOTOR HOUSING
REV
A
SIZE B
NEXT ASSEMBLY MESP-2100
ASSEMBLY DRAWING # 21-8000
SCALE: 4:1
DATE: 6/3/2021
SHEET 1 OF 1

A


NOTES:
UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
X.XX ±.01
X.XXX±.005
ANGLES ±.5°
5. SURFACE FINISH: 63 FAO
Ø.404 +.004 -.000
Ø.492
Ø.059
2X R.06
.12
.37
.079
.09
.18
.02 X 45° CHAMFER
SCALE: 4:1
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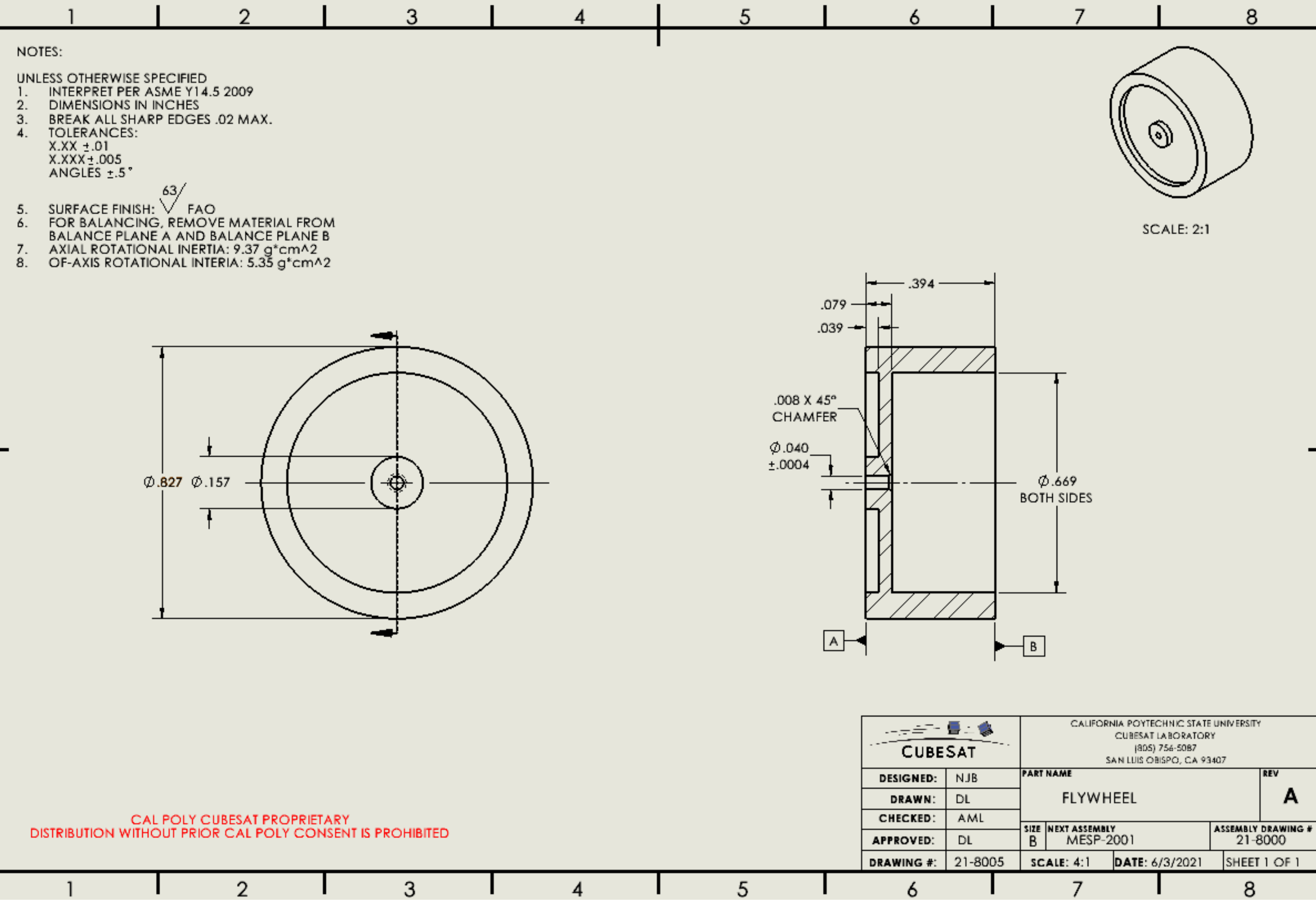
SAN LUIS OBISPO, CA 93407
DESIGNED: CPC
DRAWN: DL
CHECKED: AML
APPROVED: DL
DRAWING #: 21-8004
PART NAME
MOTOR END CAP
REV A
SIZE B
NEXT ASSEMBLY MESP-2001
ASSEMBLY DRAWING # 21-8000
SCALE: 8:1
DATE: 6/3/2021
SHEET 1 OF 1


NOTES:
UNLESS OTHERWISE SPECIFIED
1. INTERPRET PER ASME Y14.5 2009
2. DIMENSIONS IN INCHES
3. BREAK ALL SHARP EDGES .02 MAX.
4. TOLERANCES:
X.XX ±.01
X.XXX±.005
ANGLES ±.5°
5. SURFACE FINISH: 63 FAO
6. FOR BALANCING, REMOVE MATERIAL FROM BALANCE PLANE A AND BALANCE PLANE B
7. AXIAL ROTATIONAL INERTIA: 9.37 g*cm^2
8. OF-AXIS ROTATIONAL INTERIA: 5.35 g*cm^2
SCALE: 2:1
Ø.827
Ø.157
.394
.079
.039
.008 X 45° CHAMFER
Ø.040 ±.0004
Ø.669 BOTH SIDES
A
B
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SAN LUIS OBISPO, CA 93407
DESIGNED: NJB
DRAWN: DL
CHECKED: AML
APPROVED: DL
DRAWING #: 21-8005
PART NAME FLYWHEEL
REV A
SIZE B
NEXT ASSEMBLY MESP-2001
ASSEMBLY DRAWING # 21-8000
SCALE: 4:1
DATE: 6/3/2021
SHEET 1 OF 1

APPENDIX J: FINAL BUDGET STATUS

Item	Qty	Cost	Subtotal	Length/ Info	Part Number	Vendor	Links
		for one	for 3	[customary]			
Controller	1	$101.50	$101.50	ESCON Module 24/2, 4-Q servo controller, 2/6 A, 10-24 VDC	466023	Maxon	https://www.maxongroup.us/maxon/view/product/control/4-Q-Servokontroller/466023?etcc_cu=onsite&etcc_med=Header%20Suche&etcc_cmp=mit%20Ergebnis&etcc_ctv=Layer&query=ESCON%20Module%2024%2F2
Motor	3	$323.00	$969.00	EC 10 - 10 mm dia, brushless, 8W, w/ hall sensors	315173	Maxon	https://www.maxongroup.com/maxon/view/category/motor?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=EC+Program&etcc_plc=product_overview_brushlessdcmotors_ecflat&etcc_var=%5bcom%5d%23en%23_d_&target=filter&filterCategory=ec
Wheel Stock	1	$39.97	$39.97	2 ft rod bar stock, 7/8" dia	89325K19	McMaster	https://www.mcmaster.com/89325K19 2 ft ples (~ $40)
Motor Housing Stock	1	$300.00	$300.00	HyMu 80 bar stock Circular 0.75" dia x 24" length		National Electronic Alloys	https://www.nealloys.com/hymu_80.php
Outer Housing Stock	1	$65.43	$65.43	1" Thick, 2" x 48"	9246K781	McMaster	https://www.mcmaster.com/9246K781
X Bracket Stock	1	$14.23	$14.23	0.09" Thick, 4" x 24"	89015K222	McMaster	https://www.mcmaster.com/89015K222/
Screws	1	$6.49	$6.49	#2-56 x 1/4" Socket Head (pack of 100)	92196A077	McMaster	https://www.mcmaster.com/92196A077/
Balancing per Wheel	3	$100.00	$300.00	Extra cost added for expidited service		Electronic Balancing Co.	
1 mm shafts	2	$5.31	$10.62	316 Stainless Steel 7.31" long	1265K11	McMaster	Rotary Shaft, 316 Stainless Steel, 1 mm Diameter, 200 mm Long | McMaster-Carr
Epoxy: Scotch Weld Epoxy *already in lab	1	$50.80	$50.80	3M Scotch Weld Epoxy Adhesive 2216, Translucent, Part B/A, 2 fl oz kit		Amazon	https://www.amazon.com/3M-Scotch-Weld-20356-Epoxy-Adhesive/dp/B00GNLY3PS?th=1
Adapter for Maxon Motor Ribbon Cable	1	$19.75	$19.75	Adapter 11-pole flexprint connector to 8-pole screw terminal	220300	Maxon	https://www.maxongroup.us/maxon/view/category/accessory?etcc_cu=onsite&etcc_med_onsite=Product&etcc_cmp_onsite=Brakes%2c+Cables%2c+Adapters+and+Other+Accessories.&etcc_plc=Overview-Page-Accessories&etcc_var=%5bus%5d%23en%23_d_&target=filter
Soft Jaw Aluminum	1	$25.00	$25.00	Scavenged		All Industrial	
TiAlN-Coated High-Speed Steel Drill Bit	2	$4.36	$8.72	1/16" Size	3202A244	McMaster	Current Order | McMaster-Carr
TiN-Coated Carbide Rounded-Edge Square End Mill	3	$18.33	$54.99	4 Flute, 1/8" Mill Diameter, 0.015" Corner Cut Radius	2851A211	McMaster	Current Order | McMaster-Carr
Fast-Cutting Carbide Square End Mill	2	$24.52	$49.04	AlTiN Coated, 4 Flutes, 1/8" Mill Diameter, 1/2" Length of Cut	8207A27	McMaster	Current Order | McMaster-Carr
Fast-Cutting Carbide Square End Mill	2	$31.28	$62.56	TiAlN Coated, 5 Flutes, 1/4" Mill Diameter, 3/4" Length of Cut	8207A49	McMaster	Current Order | McMaster-Carr
Fast-Cutting Carbide Square End Mill	2	$25.03	$50.06	TiAlN Coated, 5 Flutes, 3/16" Mill Diameter, 5/8" Length of Cut	8207A489	McMaster	Current Order | McMaster-Carr
TiN-Coated High-Speed Steel Drill Bit	3	$3.06	$9.18	Wire Gauge 63, 1-1/2" Overall Length	29045A821	McMaster	Current Order | McMaster-Carr
TiN-Coated High-Speed Steel Drill Bit	2	$3.60	$7.20	Wire Gauge 62, 1-1/2" Overall Length	29045A822	McMaster	Current Order | McMaster-Carr
0.0385 HSS Straight Flute Chucking Reamer	2	$18.62	$37.24	0.0385 HSS	416-0652	Shars	0.0385 HSS Straight Flute Chucking Reamer (shars.com)
0.04 HSS Straight Flute Chucking Reamer	2	$23.47	$46.93	#60 (0.0400)	416-0222	Shars	0.0385 HSS Straight Flute Chucking Reamer (shars.com)
TiAlN-Coated High-Speed Steel Drill Bit	2	$4.36	$8.72	1/16" Size	2851A212	McMaster	Current Order | McMaster-Carr
		Total Cost	$2,237.43				

APPENDIX K: SHAFT CRITICAL SPEED ANALYSIS

Critical Speed Shaft Analysis

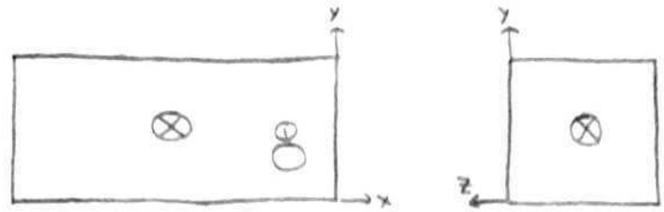
```
clear all
clc
close all

%Shaft Properties - Steel (Table A-5 in Shigley's)
E = 207E9; %Young's Modulus, Pa
sw = 76.5; %Specific weight, KN/m^3

%Shaft dimensions
d = 1e-3; %shaft diameter, m
L = 2.6e-3; %shaft length, m
w_op = 57100; %operational speed, rpm

m_f = 11.5e-3;  %mass of flywheel, kg
g = 9.81;   %m/s
F = (m_f*g)/1000;  %Weight of flywheel (kN)
W_fw = F*1000; %Weight of flywheel (N)
W = sw*(pi/4*d*L); %Weight of shaft, kN
I = pi/64 * d^4; %m^4
A = pi/4 * d^2; %m^2

F_t = F+W;
% Cantilever beam assumption
y = (F_t*L^3)/(3*E*I) %max shaft displacment, m
w_critical = sqrt(g/y) * 60/(2*pi); %Critical speed, rpm
w = w_critical/w_op

% n = safety factor
% Reccommended to have n = 2 where shaft speed is twice the critical
 speed
```

```
y =

   1.5512e-10


w =

   42.0571
```

Published with MATLAB® R2019a

APPENDIX L: BOLT ANALYSIS

Bolt Analysis

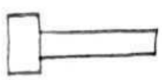


⊗ = Center of Gravity

O = Critical Bolts

a = 10g (direction based on orientation)

m = 63.24g (0.06324 kg)



$I\ \phi = 2.18mm$

$F = ma = (0.06324\,kg)(10 \cdot 9.81\,m/s^2)$

$= \underline{6.2038\,N}$

$A = \frac{\pi}{4}(\phi)^2 = \frac{\pi}{4}(2.18/1000\,m)^2$

$= \underline{3.7476 \times 10^{-6}\,m^2}$

$\tau = \frac{F}{A} = \frac{6.2038\,N}{3.7476 \times 10^{-6}\,m^2}$

$= \underline{1.66\,MPa}$ ← Stress due to force (axial or shear depending on orientation)

Critical Bolt ①

Component Distances from C.G. to Bolt ①

$D_1 = (8.8052632, 7.54380258, 12.13153722)\,mm$

$S_u = 70\,ksi\ (482.6\,MPa)$ ← Bolt Ultimate strength

Acceleration in x-direction

$M_y = (6.2038 N)(7.54380258/1000 \ m)$
$= 0.0468 \ Nm$

$M_z = (6.2038 N)(12.13153722/1000 \ m)$
$= 0.0753 \ Nm$

$\tau_x = 1.66 \ MPa$

$$\sigma_y = \frac{Mc}{I} = \frac{(0.0468 \ Nm)\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}\left(2.18/1000 \ m\right)^4\right)}$$
$= 46.01 \ MPa$

$$\sigma_z = \frac{Mc}{I} = \frac{(0.0753 \ Nm)\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}(2.18/1000 \ m)\right)}$$
$= 74.03 \ MPa$

$$S_{vm} = \sqrt{\sigma^2 + 3\tau^2} = \sqrt{(46.01 + 74.03)^2 + 3(1.66)^2} \ MPa$$
$= 120.07 \ MPa$

$$FOS = \frac{S_u}{S_{vm}} = \frac{482.6}{120.07} = \boxed{4.02}$$

Acceleration in Y

$M_x = (6.2038N)(8.8052632/1000 \ m)$
$= 0.0546 \ Nm$

$M_z = (6.2038N)(12.13153722/1000 \ m)$
$= 0.0753 \ Nm$

$$\sigma_x = \frac{(0.0546 \ Nm)\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}(2.18/1000m)\right)}$$
$= 53.68 \ MPa$

$\tau_y = 1.66 \ MPa$

$$\sigma_z = \frac{(0.0753 \ Nm)\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}(2.18/1000 \ m)\right)}$$
$= 74.03 \ MPa$

$$S_{vN} = \sqrt{(53.69 + 74.03)^2 + 3(1.66)^2} \text{ MPa}$$

$$= 127.74 \text{ MPa}$$

$$FOS = \frac{S_U}{S_{vm}} = \frac{482.6}{127.74} = \boxed{3.78}$$

Acceleration in Z

$$M_x = (6.2038 N)(8.8052632/1000 \text{ m})$$
$$= 0.0546 \text{ Nm}$$

$$M_y = (6.2038 N)(7.54380258/1000 \text{ m})$$
$$= 0.0468 \text{ Nm}$$

$$\sigma_x = \frac{(0.0546 \text{ Nm})\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}(2.18/1000 \text{ m})\right)}$$
$$= 53.68 \text{ MPa}$$

$$\sigma_y = \frac{(0.0468 \text{ Nm})\left(\frac{2.18mm}{2} \cdot \frac{1m}{1000mm}\right)}{\left(\frac{\pi}{64}(2.18/1000 \text{ mm})\right)}$$

$$= 46.01 \text{ MPa}$$

$$\sigma_z = 1.66 \text{ MPa}$$

$$S_{vm} = \sqrt{(53.68 + 46.01 + 1.66)^2} \text{ MPa}$$

$$= 101.35 \text{ MPa}$$

$$FOS = \frac{482.6}{101.35} = \boxed{4.76}$$

Appendix M: Hole fit Analysis

Hole Fit Analysis

Variables:

D = basic size of hole

d = basic size of shaft

δ_u = upper deviation (hole)

δ_l = lower deviation (shaft)

δ_F = fundamental deviation

ΔD = tolerance grade for hole

Δd = tolerance grade for shaft

Part 1: Clearance

Type of fit: *Locational clearance fit (H7/h6)* from Table 7-9 in *Shigley's*

From Tables A-11 in *Shigley's*:

ΔD = IT7 = 0.010 mm

Δd = IT6 = 0.006 mm

From Table A-12 in *Shigley's*:

δ_u = H = 0 mm

δ_l = h = 0 mm

Shaft Specifications and Tolerance Grade:

$$d = 1\ mm$$

$$d_{max} = 0.997\ mm$$

$$d_{min} = 0.991\ mm$$

$$\Delta d = d_{max} - d_{min}$$

$$\Delta d = 0.997 - 0.991$$

Tolerance grade of shaft: $\Delta d = 0.006\ (IT6)$

Shaft Dimensions: $\mathbf{\emptyset 1.000 - 0.003/{-0.009}}$ **mm**

Hole Calculations:

$$D = d_{max} + \delta_u$$

$$D = 0.997 + 0$$

$$D = 0.997$$

$$D_{max} = D + \Delta D$$

$$D_{max} = 0.997 + 0.010\ (IT7)$$

$$D_{max} = 1.007$$

$$D_{min} = D$$

$$D_{min} = 0.997$$

Clearance Hole Dimensions: $\boldsymbol{\emptyset 1.000 + 0.007 / -0.003}$ **mm**

Hole Tolerance: $0.01\ mm = 0.3\ thou$

Part 2: Interference

Type of fit: *Medium drive fit (H7/s6)* from Table 7-9 in *Shigley's*

Note: Shaft dimensions cannot change so change to S7/h6

From Tables A-11 in *Shigley's*:

ΔD = IT7 = 0.010 mm

Δd = IT6 = 0.006 mm

From Table A-12 in *Shigley's*:

δ_u = S = + 0.014 mm

δ_l = h = 0 mm

Shaft Specifications and Tolerance Grade:

$$d = 1\ mm$$

$$d_{max} = 0.997\ mm$$

$$d_{min} = 0.991\ mm$$

$$\Delta d = d_{max} - d_{min}$$

$$\Delta d = 0.997 - 0.991$$

Tolerance grade of shaft: $\Delta d = 0.006\ (IT6)$

Shaft Dimensions: $\boldsymbol{\emptyset 1.000 - 0.003/{-0.009}}$ **mm**

Hole Calculations:

$$D = d_{max} + \delta_l$$

$$D = 0.997 + 0$$

$$D = 0.997$$

$$D_{max} = D - \delta_u$$

$$D_{max} = 0.997 - 0.014$$

$$D_{max} = 0.983$$

$$D_{min} = D_{max} - \Delta D$$

$$D_{min} = 0.983 - 0.010$$

$$D_{min} = 0.973$$

Interference Hole Dimensions: $\boldsymbol{\emptyset 1.000\ - 0.027/\,{-0.017}}$ **mm**

Hole Tolerance: $0.01\ mm = 0.3\ thou$

APPENDIX N: SHIGLEY'S TABLES

Tables from *Shigley's Mechanical Engineering Design*, 10th ed. 2015 [25] used for hole fit analysis.

Table 7–9

Descriptions of Preferred Fits Using the Basic Hole System

Source: Preferred Metric Limits and Fits, ANSI B4.2-1978. See also BS 4500.

Type of Fit	Description	Symbol
Clearance	*Loose running fit:* for wide commercial tolerances or allowances on external members	H11/c11
	Free running fit: not for use where accuracy is essential, but good for large temperature variations, high running speeds, or heavy journal pressures	H9/d9
	Close running fit: for running on accurate machines and for accurate location at moderate speeds and journal pressures	H8/f7
	Sliding fit: where parts are not intended to run freely, but must move and turn freely and locate accurately	H7/g6
	Locational clearance fit: provides snug fit for location of stationary parts, but can be freely assembled and disassembled	H7/h6
Transition	*Locational transition fit:* for accurate location, a compromise between clearance and interference	H7/k6
	Locational transition fit: for more accurate location where greater interference is permissible	H7/n6
Interference	*Locational interference fit:* for parts requiring rigidity and alignment with prime accuracy of location but without special bore pressure requirements	H7/p6
	Medium drive fit: for ordinary steel parts or shrink fits on light sections, the tightest fit usable with cast iron	H7/s6
	Force fit: suitable for parts that can be highly stressed or for shrink fits where the heavy pressing forces required are impractical	H7/u6

Table A–11

A Selection of International Tolerance Grades—Metric Series (Size Ranges Are for *Over* the Lower Limit and *Including* the Upper Limit. All Values Are in Millimeters)

Source: Preferred Metric Limits and Fits, ANSI B4.2-1978. See also BSI 4500.

Basic Sizes	Tolerance Grades					
	IT6	IT7	IT8	IT9	IT10	IT11
0–3	0.006	0.010	0.014	0.025	0.040	0.060
3–6	0.008	0.012	0.018	0.030	0.048	0.075
6–10	0.009	0.015	0.022	0.036	0.058	0.090
10–18	0.011	0.018	0.027	0.043	0.070	0.110
18–30	0.013	0.021	0.033	0.052	0.084	0.130
30–50	0.016	0.025	0.039	0.062	0.100	0.160
50–80	0.019	0.030	0.046	0.074	0.120	0.190
80–120	0.022	0.035	0.054	0.087	0.140	0.220
120–180	0.025	0.040	0.063	0.100	0.160	0.250
180–250	0.029	0.046	0.072	0.115	0.185	0.290
250–315	0.032	0.052	0.081	0.130	0.210	0.320
315–400	0.036	0.057	0.089	0.140	0.230	0.360

Table A–12

Fundamental Deviations for Shafts—Metric Series
(Size Ranges Are for *Over* the Lower Limit and *Including* the Upper Limit. All Values Are in Millimeters)
Source: Preferred Metric Limits and Fits, ANSI B4.2-1978. See also BSI 4500.

Basic Sizes	Upper-Deviation Letter					Lower-Deviation Letter				
	c	d	f	g	h	k	n	p	s	u
0–3	−0.060	−0.020	−0.006	−0.002	0	0	+0.004	+0.006	+0.014	+0.018
3–6	−0.070	−0.030	−0.010	−0.004	0	+0.001	+0.008	+0.012	+0.019	+0.023
6–10	−0.080	−0.040	−0.013	−0.005	0	+0.001	+0.010	+0.015	+0.023	+0.028
10–14	−0.095	−0.050	−0.016	−0.006	0	+0.001	+0.012	+0.018	+0.028	+0.033
14–18	−0.095	−0.050	−0.016	−0.006	0	+0.001	+0.012	+0.018	+0.028	+0.033
18–24	−0.110	−0.065	−0.020	−0.007	0	+0.002	+0.015	+0.022	+0.035	+0.041
24–30	−0.110	−0.065	−0.020	−0.007	0	+0.002	+0.015	+0.022	+0.035	+0.048
30–40	−0.120	−0.080	−0.025	−0.009	0	+0.002	+0.017	+0.026	+0.043	+0.060
40–50	−0.130	−0.080	−0.025	−0.009	0	+0.002	+0.017	+0.026	+0.043	+0.070
50–65	−0.140	−0.100	−0.030	−0.010	0	+0.002	+0.020	+0.032	+0.053	+0.087
65–80	−0.150	−0.100	−0.030	−0.010	0	+0.002	+0.020	+0.032	+0.059	+0.102
80–100	−0.170	−0.120	−0.036	−0.012	0	+0.003	+0.023	+0.037	+0.071	+0.124
100–120	−0.180	−0.120	−0.036	−0.012	0	+0.003	+0.023	+0.037	+0.079	+0.144
120–140	−0.200	−0.145	−0.043	−0.014	0	+0.003	+0.027	+0.043	+0.092	+0.170
140–160	−0.210	−0.145	−0.043	−0.014	0	+0.003	+0.027	+0.043	+0.100	+0.190
160–180	−0.230	−0.145	−0.043	−0.014	0	+0.003	+0.027	+0.043	+0.108	+0.210
180–200	−0.240	−0.170	−0.050	−0.015	0	+0.004	+0.031	+0.050	+0.122	+0.236
200–225	−0.260	−0.170	−0.050	−0.015	0	+0.004	+0.031	+0.050	+0.130	+0.258
225–250	−0.280	−0.170	−0.050	−0.015	0	+0.004	+0.031	+0.050	+0.140	+0.284
250–280	−0.300	−0.190	−0.056	−0.017	0	+0.004	+0.034	+0.056	+0.158	+0.315
280–315	−0.330	−0.190	−0.056	−0.017	0	+0.004	+0.034	+0.056	+0.170	+0.350
315–355	−0.360	−0.210	−0.062	−0.018	0	+0.004	+0.037	+0.062	+0.190	+0.390
355–400	−0.400	−0.210	−0.062	−0.018	0	+0.004	+0.037	+0.062	+0.208	+0.435

APPENDIX O: DESIGN VERIFICATION PLAN

DVP&R - Design Verification Plan (& Report)

Project: F63- Cubesat Reaction Wheel | Sponsor: Cal Poly Cubesat Lab - John Bellardo | Edit Date: 5/13/21

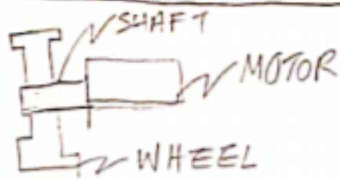
TEST PLAN										TEST RESULTS	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING Start date	Finish date	Numerical Results	Notes on Testing
1	1.Mass	Measure total system mass on a digital scale	mass in grams	A mass below 660 g total	CP Mustang 60/Aero Hanger Digital Scale	FP	Rose	5/21/21	5/29/21	65.45g	mass of 1 Reaction Wheel Assembly
2	4. Size/Volume	Measure Length Width and Height with a pair of Dial Calipers	dimensions in cm	A volume under 500 cm^3	CP Mustang 60/Aero Hanger/CPCL Dial Caliper	FP	Rose	5/21/21	5/29/21	23.81cm^3	Volume of 1 Reaction Wheel Assembly
3	5.Thermal Testing - Bakeout	Complete a 60 C for 6 hours or 70 C for 3 hours Thermal Bake out in the TVAC Chamber	Thermistor data throughout Bakeout	Temperatures with in CPCL Standard acceptable range	CPCL TVAC Chamber in Aero Hangar	FP	Daniel	5/17/21			n/a - due to timeline constraints, this test will not be completed
4	6. Vacuum Testing	Complete a 60 C for 6 hours or 70 C for 3 hours at 1 * 10-4 Torr Thermal Bake out in the TVAC Chamber	Thermistor data throughout Bakeout	Minimal particle outgassing	CPCL TVAC Chamber in Aero Hangar	FP	Daniel	5/17/21			n/a - due to timeline constraints, this test will not be completed
5	7.Torque	Messure RPM with a laser tacheometer	RPM	A calculated torque of 1.0 mNm -10% using measured rpm,mass, and moment of inertia	Laser Tachemeter	FP	Pablo	5/17/21	5/29/21	Torque Perfromance was met with in 10% of target torque	see FDR report for torque vs. RPM plots
6	9. Total Momentum	Masure RPM with a laser tacheometer	RPM	A calculated momentum of 5 mNms using measured rpm,mass, and moment of inertia	Laser tachemoeter	FP	Pablo	5/17/21	5/29/21	Momentum Perfromance was met with in 10% of target value	
7	12. Vibration Testing	Perfrom X,Y and Z axis Vibration testing to NASA GEVS PSD Profile	Accelerometer data throughout test	NASA GEVS (NASA STD 7000 Table 2.4-3) [21	Vibration Tables in bldg 41B	FP	Alex	5/20/21			n/a - due to timeline constraints, this test will not be completed
8	13. Press fit Testing	Practice a press fit with a wheel and test shaft	Hole Diameter and Shaft Diameter	no noticable deflection on the shaft	CP Mustang 60/Aero Hanger Arbor Press	SP	Alex	4/28/21	4/26/21	Tested disk B up to max of 146 N and disk C to max of 235 N and disk D up to 200N.	Disk A did not cure when using the RT48. Disk B and C used the staking and the shaft slipped slightly but still held in place. We concluded that the staking was the best option for the shaft-locking adhesive but shoud NOT be tested to the max on the actual assembly.

Page 1 of 1 Print Date: 5/31/21

Appendix P: Quasi Static Acceleration Load Shaft Analysis

QUASI-STATIC ACCELERATION LOADS	SHAFT ANALYSIS	CHRISTOPHER PABLO CASILLAS	1/2

MOTOR-FLYWHEEL ASSEMBLY

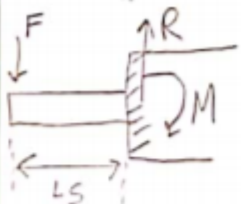


$m_{FW} = 12.5\,g$ (MASS OF FLYWHEEL)

$L_S = 2.6\,mm$ (LENGTH OF SHAFT)

$a_{axial} = 10g$

$d_S = 1\,mm$ (DIAMETER OF SHAFT)



$F = 10mg$

$F = 10 \cdot \left(\frac{12.5}{1000}\right) kg \cdot (9.81\,m/s^2)$

$\rightarrow F = 1.23\,N$

$\sigma_{bend} = \frac{MC}{I}$, $I = \frac{\pi d^4}{64}$, $C = d/2$

$I = \frac{\pi \left(\frac{1}{1000}\right)^4}{64}$

$\rightarrow I = 4.91 \times 10^{-14}\,m^4$

$M = FLS$

$M = 1.23\,N \cdot \left(\frac{2.6}{1000}\right) m$

$\rightarrow M = 0.003198\,N \cdot m$

$\sigma_{bend} = \frac{0.003198\,N \cdot m \left(\frac{0.5}{1000}\right) m}{4.91 \times 10^{-14}\,m^4}$

$\rightarrow \sigma_{bend} = 32.57\,MPa$

QUASI-STATIC ACCELERATION LOADS	SHAFT ANALYSIS	CHRISTOPHER PABLO CASILLAS	2/2

$$n = \frac{S_{ut}}{\sigma_{bend}}$$

$S_{ut} = 635\ MPa$ (carbon steel)

$$n = \frac{635\,MPa}{32.57\,MPa}$$

$$\boxed{n = 19.49}$$

TARGET $n = 2.0$ (FROM NASA GEVS TABLE 2.2-3 FLIGHT HARDWARE DESIGN FACTORS)

Appendix Q: Bolt Tear Out Analysis

Bolt Tear Out Analysis (stripping)

Assume internal threads are stronger than external

$$L_e = \frac{2A_t}{\pi d_{mt}\left[0.5 + n(d_{bmp} - d_{mt})\tan(30°)\right]}$$

↑ min pitch ϕ ↑ max minor ϕ

$d_b = 0.086''$

$d_{bmt} = 0.0813''$

$p = d_{mt} = 0.0737''$

and using the machinist's Handbook for steels up to 100ksi

$A_t = \frac{\pi}{4}(d_b - 0.9382p)^2$ where $n = \#\text{tpi} = 56$

$= \frac{\pi}{4}(0.0860 - 0.9382(0.0737))^2$

$A_t = 0.002552$

$$L_e = \frac{2A_t}{\pi(0.0737)\left[0.5 + 56(0.0813 - 0.0737)\tan(30°)\right]}$$

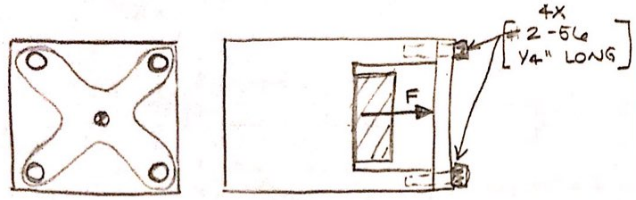
$= 0.0286''$ minimum length of engagement

min. of ≈1.75 threads

Since min length eng. << threaded portion (1/4") thread engagement is adequate and the bolt will break before it strips out of housing (which is preferable) ✓

APPENDIX R: X-BRACKET VALIDATION ANALYSIS

BOLT ANALYSIS: TO PROTECT AGAINST FLYWHEEL FLYING OFF
(FRONT BOLTS)



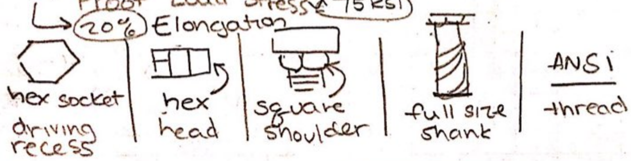
AMT IT CAN HOLD = PROOF LOAD

NOTE: Strength to weight Ratio: 2.8

Rock well B70 and 18-8 SS

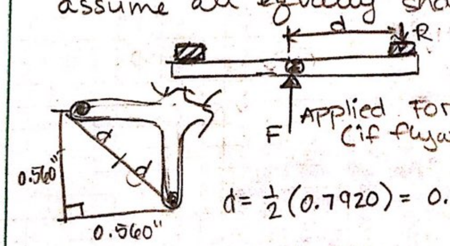
- Yield strength (min) ≈ 30 ksi
- Tensile strength (min) ≈ 70 ksi
- Proof Load Stress ≈ 75 ksi
- 20% Elongation

(Mechanical requirements)



Bolt shear Analysis

assume all equally share loading



$d = \frac{1}{2}(0.7920) = 0.3960"$

$\sigma = \frac{F}{A}$ ← $\frac{\pi}{4}\varnothing^2 = \frac{\pi}{4}(0.086)^2 = 0.00581\ in^2$

where $\sigma_{yield} = \frac{F}{0.005809\ in^2} = 30\times10^3\ \frac{lb}{in^2}$

$\Sigma F = 0$ $\quad F = 174\ lbf$

$R = \frac{F}{N} \Rightarrow \frac{F}{4}$ $\quad \therefore \boxed{R = 43.5\ lbf}$ allowable each screw can hold this amt.

ALTERNATIVELY IF UNDER 10 g loading (launch)

$F = (10)(32.171\ ft/s^2)(11g/(454\ g/lb))$
$= 242.59\ lbf$

$\sigma = \frac{F}{4\varnothing} = 10{,}440.3\ psi \ll 30{,}000\ psi\ (\sigma_{yield})$ ✓

APPENDIX S: FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Product: Reaction Wheel System for CubeSats

Design Failure Mode and Effects Analysis

Prepared by: Alex Lee, Rose McCarver, Pablo Casillas, Daniel Leon

Team: F63

Date: November 19th, 2020 (orig)

												Action Results			
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Outer Wheel System / Contain outer housing	Bolts on X-bracket break	Reaction wheel system detatches from itself	4	1) Flywheel comes off 2) Fastener hole shears 3) Material too weak (bends or breaks)	1) Bolt Analysis 2) Vibration/Modal Analysis	3	vibrational testing &TVAC	3	36						
	Interface bolts break	Reaction wheel system detatches from itself	7	1) too thin (breaks) 2) too thin (bends) 3) fastener hole shears	1) Bolt Analysis 2) Vibration/Modal Analysis	2	vibrational testing &TVAC	3	42						
	Threads on outer housing break	Reaction wheel system detatches from bus	7	1) not enough thread engagement	1) Bolt Analysis 2) Size up threads from 0-80	1	vibrational testing &TVAC	3	21						
	Detatches from spacecraft bus	Reaction wheel system detatches from bus	9	1) fasteners too small 2) vibration in fasteners causes backout 3) fasteners break	1) Bolt Analysis 2) Vibration/Modal Analysis	2	vibrational testing &TVAC	2	36						
Motor system / provide torque & rpm to wheels	Electrical short in motor wires	a) Spacecraft cannot properly adjust its attitude b) Reaction wheels become saturated	4	1) imporpoer connection (frays)	1) Design proper wire harnessing 2) Break sharp edges 3) Anodize metal surfaces	2	vibrational testing &TVAC	2	16						
	Improper motor selection	Spacecraft cannot properly adjust its attitude	4	1) motor doesn't spin at desired speed	1) Verify motor selecion process from thesis	5	test performance metrics using controller after getting wheel back from vendor	1	20						
	Excess friction	a) Spacecraft cannot properly adjust its attitude b) Reaction wheels become saturated	4	1) internal friction in motor bearings	1) Eleminate all unnecessary contacts between moving parts 2) accomodate for internal friction in calculations of rpm	2	test performance metrics using controller after getting wheel back from vendor	0	0						
	Inaccurate press fit between motor and shaft	Reaction wheel system detaches from itself	8	1) shaft bends 2) shaft breaks 3)improper size shaft and hole (in flywheel) for pressfit	1) Perform practice press fits 2) Make extra dummy motor shafts to practice press fit	8	Send wheel to be professionally balances	2	128	Create press fit fixture	Alex 4-15-20	Created press fit fixture out of aluminum stock	7	3	3
	Ribbon cable damaged	Spacecraft cannot properly adjust its attitude	4	1) ribbon cable frays (inproperly connected or high voltage applied)	1) Design proper wire harnessing 2) Break sharp edges 3) Anodize metal surfaces	4	wire conductivity testing	3	48						
Motor System/ constrain motor	Motor housing detaches from outer housing	Reaction wheel system detaches from itself	3	1) not enough epoxy 2) epoxy doesn't dry properly	1) Use proper adhesive 2) Use sufficient adhesive 3) Allow sufficient curing time	3	vibrational testing &TVAC	1	9						
Inner housing system / contrain inner housing	Motor Housing spins freely inside of the Outer Housing	Reaction wheel system detaches from itself	3	1) motor detatches by shaft spinning too much 2) epoxy doesn't dry properly	1) Use proper adhesive 2) Use sufficient adhesive 3) Allow sufficient curing time	3	test wheel system running once fully assembled to ensure security+	1	9						
Flywheel system / provides desired rotational inertia	Improper balancing	Spacecraft cannot properly adjust its attitude	4	1) gets damaged in shipping when sent to balancer 2) material is difficult to remove 3) incorrect press fit	1) ensure the system has proper cushining in shipping 2) ensure steel used for flywheel can be easily machined 3) Achieve proper press fit	7	test performance metrics using controller after getting wheel back from vendor+ Vibrational testing and TVAC testing	1	28						
	Reaches max possible acceleration and cannot produce more momentum	a) Spacecraft cannot properly adjust its attitude b) Reaction wheels become saturated	8	1) motor doesn't output desired rpm 2) maximum acceleration doesn't acheive proper momentum impulse	1) Verify motor selecion process from thesis 2) test maximum acceleration of wheel and ensure this will produce the desired momentum bit	5	test performance metrics using controller after getting wheel back from vendor	0	0						
Flywheel system / cosntrains flywheel	Flywheel flies off	Reaction wheel system detaches from itself	8	1) incorrect pressfit 2) X-bracket detatches (too thin) 3) x-bracket breaks (too thing)	1) Achieve proper press fit 2) Structural analysis on X-Bracket 3) Sufficient amount staking 4) Allow sufficient amount of time for curing	6	vibrational testing (and TVAC) shaft adhesive proof test	2	96	Conduct shaft adhesive proof test using test shaft and disks to verify adhesive holds	Daniel 4-25-21	Planned and implemented shaft load proof test	7	2	2
	Components separate	Reaction wheel system detaches from itself	9	1)Expoxy doesn't dry correctly 2) epoxy doesn't have sufficient properties	1) Ensure proper tolerances 2) Ensure proper assembly	5	vibrational testing (and TVAC)	3	135	Verify epoxy selection with CPCL Staff	Pablo 3-14-21	Verified epoxy selection with CPCL staff and Aerospace Corp.	7	1	2

Design FMEA.xlsx | Page 1 of 3 | Revision Date: 4/27/21

Design Failure Mode and Effects Analysis

Product: ______________________________ Prepared by: ______________________________

Team: ______________________________ Date: __________________ (orig)

												Action Results			
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
General/ hold parts together	Excess vibration induced in the system from launch	Reaction wheel system detaches from itself	6	1) fasteners not screwed in correctly 2) not enough thread engagement	1) bolt/fastener analysis 2) Ensure proper tolerances for press fit 3) Further secure press fit with adhesive	7	vibrational testing (and TVAC)	1	42						
	Epoxy shears off/ can't withstand loading	Reaction wheel system detaches from itself	6	1) low bonding strength epoxy was used	1) Verify epoxy selection with CPCL Staff 2) Work with information from Aerospace Corp.	4	a) test wheel system running once fully assembled to ensure security b) research previous mission epoxies used and compare to these when selecting	1	24						

Design FMEA.xlsx Page 2 of 3 Revision Date: 4/27/21

APPENDIX T: RISK ANALYSIS

F63 Reaction Wheels

4/25/2021

designsafe Report

Application:	F63 Reaction Wheels	Analyst Name(s):	Rose McCarver, Pablo Casillas, Alex Lee, Daniel Leon
Description:	This analysis is a risk assessment for the senior project group	Company:	CPCL
Product Identifier:		Facility Location:	Cal Poly SLO
Assessment Type:	Detailed		
Limits:	this encompasses the full reaction wheel system and all who will interact with it where risks can be remediated		
Sources:	personnel experiences, assembly drawings		
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	Machinist tool change	mechanical : cutting / severing tool sharp	Moderate Likely	Medium	Hold tool with rag	Minor		Rose
1-1-2	Machinist tool change	mechanical : pinch point auto tool change	Minor Likely	Low	Hold tool with rag	Minor		Rose
1-2-1	Machinist set-up or changeover	mechanical : cutting / severing tool sharp	Minor Unlikely	Negligible		Minor		Rose
1-2-2	Machinist set-up or changeover	ergonomics / human factors : lifting / bending / twisting heavy vice jaws	Moderate Unlikely	Low	get others to help lift	Minor		Rose
1-2-3	Machinist set-up or changeover	heat / temperature : burns / scalds part hot after operations / not enoughg coolant	Minor Unlikely	Negligible	use coolant	Minor		Rose
1-2-4	Machinist set-up or changeover	material handling : excessive weight heavy vice jaws	Minor Unlikely	Negligible	get others to help lift	Minor		Rose
1-3-1	Machinist parts replacement	mechanical : cutting / severing sharp tool	Minor Likely	Low	change tool to blunt stop for machining, or move to high z	Minor		Rose

Page 1

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-4-1	Machinist adjust controls / settings / alignment	ergonomics / human factors : posture long hours	Moderate Likely	Medium	use a machinists foot rug thing	Minor		Rose
1-4-2	Machinist adjust controls / settings / alignment	ergonomics / human factors : repetition long hours	Moderate Likely	Medium	have a good method, take breaks	Moderate		Rose
1-4-3	Machinist adjust controls / settings / alignment	ergonomics / human factors : duration long hours	Moderate Likely	Medium	take breaks	Moderate		Rose
1-4-4	Machinist adjust controls / settings / alignment	heat / temperature : burns / scalds hot metal	Moderate Likely	Medium	dont touch hot parts	Moderate		Rose
1-4-5	Machinist adjust controls / settings / alignment	fluid / pressure : high pressure air compressed air if sprayed into skin can kill you	Catastrophic Remote	Low	dont spray it into your skin	Minor		Rose
1-5-1	Machinist periodic maintenance	electrical / electronic : water / wet locations coolant gets everywhere	Minor Likely	Low	use compressed air to dry	Minor		Rose
1-6-1	Machinist trouble-shooting / problem solving	electrical / electronic : energized equipment / live parts error in software?	Moderate Likely	Medium	use e-stop	Minor		Rose
1-6-2	Machinist trouble-shooting / problem solving	ergonomics / human factors : lifting / bending / twisting heavy vice jaws	Moderate Likely	Medium	2 person lift, look into hoist system	Minor		Rose
1-6-3	Machinist trouble-shooting / problem solving	heat / temperature : burns / scalds hot parts after machining	Moderate Likely	Medium	gloves	Moderate		Rose

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-6-4	Machinist trouble-shooting / problem solving	noise / vibration : noise / sound levels > 80 dBA loud machines	Minor Very Likely	Medium	wear earplugs	Minor		Rose
1-7-1	Machinist start machine	electrical / electronic : unexpected start up / motion machine error	Minor Unlikely	Negligible	reset at beginning of day	Minor		Rose
1-7-2	Machinist start machine	noise / vibration : noise / sound levels > 80 dBA loud machines	Minor Very Likely	Medium	wear earplugs	Minor		Rose
1-7-3	Machinist start machine	wastes (Lean) : waiting / delay cant get access to machine, not coming in with a plan, needing to CAM when i get there	Moderate Likely	Medium	reserve machine time	Moderate		Rose
2-1-1	Assembly Operator(s) normal operation	mechanical : impact dropped parts	Minor Unlikely	Negligible	gloves, standard procedures, footwear	Minor		Pablo
2-2-1	Assembly Operator(s) clean up	slips / trips / falls : slip parts on floor	Minor Unlikely	Negligible	dont walk by machine before cleanup, dont step on fallen parts	Minor		Pablo
2-2-2	Assembly Operator(s) clean up	slips / trips / falls : trip parts on floor	Minor Unlikely	Negligible	dont walk by machine before cleanup, dont step on fallen parts	Minor		Pablo
2-2-3	Assembly Operator(s) clean up	ingress / egress : material storage interference stuff in front of doors	Minor Unlikely	Negligible	dont store stuff in front of doors	Minor		Pablo

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-3-1	Assembly Operator(s) basic trouble shooting / problem solving	mechanical : drawing-in / trapping / entanglement wires all twisted or stuck in epoxy	Minor Very Likely	Medium	wear gloves in assembly, be careful w epoxy	Minor		Pablo
2-3-2	Assembly Operator(s) basic trouble shooting / problem solving	mechanical : pinch point pieces put together	Minor Likely	Low	be careful with assembly (slow)	Minor		Pablo
2-4-1	Assembly Operator(s) load / unload materials	mechanical : cutting / severing sharp edges	Moderate Likely	Medium	gloves, deburr parts	Minor		Pablo
2-4-2	Assembly Operator(s) load / unload materials	slips / trips / falls : impact to / with dropped parts	Minor Likely	Low	install lift table, standard procedures	Minor		Pablo
2-5	Assembly Operator(s) gaging part	<None>						
2-6-1	Assembly Operator(s) quality sampling	mechanical : pinch point from drive system	Minor Likely	Low	interlocked switches, access panel	Minor		Pablo
2-6-2	Assembly Operator(s) quality sampling	noise / vibration : noise / sound levels > 80 dBA when system running wheel spins fast and may make a sound?	Minor Unlikely	Negligible		Minor		Pablo
2-7-1	Assembly Operator(s) clean system	mechanical : drawing-in / trapping / entanglement extra epoxy dries on outside	Minor Likely	Low	wipe off extra before it dries	Minor		Pablo
2-7-2	Assembly Operator(s) clean system	chemical : reaction to / with irritant chemicals fingers epoxied together	Moderate Likely	Medium	gloves, standard cleaning procedures	Moderate		Pablo

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
3-1-1	Test Operator(s) Common Tasks	mechanical : drawing-in / trapping / entanglement hook up wires wrong	Moderate Likely	Medium	follow harnessing layout prepared ahead of time	Minor		Daniel
3-1-2	Test Operator(s) Common Tasks	mechanical : pinch point secure to vibes/tvac table	Moderate Likely	Medium	have adequate fixturing	Minor		Daniel
3-1-3	Test Operator(s) Common Tasks	mechanical : impact when system running wheel spins fast and may spin off	Serious Unlikely	Medium	do a good analysis for hole fit	Serious		
3-2-1	Test Operator(s) repair / replace wiring / systems	mechanical : drawing-in / trapping / entanglement when running could get caught in it	Moderate Likely	Medium	tuck in loose objects and make sure clothing is adequate	Minor		Daniel
3-2-2	Test Operator(s) repair / replace wiring / systems	electrical / electronic : improper wiring problem with purchased motor	Moderate Unlikely	Low	get good motor	Moderate		Daniel
3-3	Test Operator(s) grounding panels / controls / machinery	<None>						
3-4-1	Test Operator(s) install / test / repair circuit	electrical / electronic : energized equipment / live parts bad controller	Moderate Unlikely	Low	get good controller	Minor		Daniel
3-5-1	Test Operator(s) adjust controls	electrical / electronic : improper wiring problem with purchased motor	Moderate Unlikely	Low	get good motor	Minor		Daniel
3-5-2	Test Operator(s) adjust controls	electrical / electronic : unexpected start up / motion bad controller	Moderate Unlikely	Low	get good controller	Minor		Daniel

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
4-1-1	Non-user work next to / near machinery	slips / trips / falls : debris chips or parts on floor	Minor Unlikely	Negligible	dont walk by machine before cleanup, dont step on fallen parts	Minor		Alex
4-2-1	Non-user walk near machinery	noise / vibration : noise / sound levels > 80 dBA lound machines/ test equip.	Minor Unlikely	Negligible	wear earplugs if observing machining	Minor		Alex

APPENDIX U: BALANCING CERTIFICATION

Electronic Balancing Company, Inc.

660 East "D" Street
Wilmington, CA 90744

Phone #	Fax #
(310) 830-4995	(310) 830-2447

Bill To
CAL POLY SAN LUIS OBISPO

Invoice

Date	Invoice #
5/19/2021	EB172095

Via	P.O. Number	Terms
	COD	COD

Quantity	Description	Price Each	Amount
1	REACTION WHEEL, BALANCED	0.00	0.00
1	CERTIFICATION	0.00	0.00
1	DATA SHEET	0.00	0.00
1	LOT CHARGE	180.00	180.00

5-19-21
Pd ~~CK~~ by CC
Susan

Effective January 10, 2019:
All expedited jobs will incur a $75.00 expedite charge and the unit cost will be billed at a multiplier rate of 1.5.

Total $180.00

Balance Due $180.00

A 1 1/2% service charge will be added to this invoice if not paid within the above terms. Any invoice that extends beyond the above or prior agreed to terms will forfeit any applied discounts.

Web Site	E-mail
www.electronicbalancingco.com	susan@electronicbalancingco.com

FAA Repair Station
QP3R797L

Electronic Balancing Company Inc.

660 East "D" Street Wilmington, CA 90744 Phone: 310-830-4995 Fax: 310-830-2447 FAA Repair Station #QP3R797L

Your Order No.________ DATE 13 MAY 2021

Shipper No.________

TO: CAL POLY SAN LUIS OBISPO
1 GRAND AVENUE
SAN LUIS OBISPO, CA 93407

QUANTITY	DESCRIPTION
1	REACTION WHEEL, DYNAMICALLY BALANCED TO .001 GR-IN IN PLANE 1&2
	BALANCED PER CUSTOMER INSTRUCTIONS
	OUR REF #172095

We certify that the above parts were balanced to specified tolerance on the above date.

Material
Stamped
Tagged

ELECTRONIC BALANCING CO.
LANCE KOUCHI QC MGR
By EB FORM 7503 REV. A 6/07

CERTIFICATE

DATA SHEET

Date	5/19/2021
Work Order #	172095
Customer	Cal Poly San Luis Opisbo
PO#	
Part Number	
Part Description	REACTION WHEEL

Electronic Balancing Company

660 east D street
Wilmington CA 90744
310-830-4995
www.electronicbalancingco.com

SETUP DATA

Radius Plane 1	0.415	INCHES	Dimension A		Operator: A REYES
Radius Plane 2	0.415	INCHES	Dimension B		
Weight		POUNDS	Dimension C		
Balancing Speed	5000	RPM	Machine	SCHENCK CAB 820R R10 SQATS0306	

BALANCE TOLERANCE PER:

☐ API ☐ ISO 1940 ☐ ISO 21-94011 ☑ Customer Spec or other

CUSTOMER INSTRUCTIONS

Plane 1	0.0010000	GR/IN
Plane 2	0.0010000	GR/IN

BALANCE DATA

SERIAL NUMBER	AS FOUND				FINAL			
	PLANE 1		PLANE 2		PLANE 1		PLANE 2	
	GR/IN	ANGLE	GR/IN	ANGLE	GR/IN	ANGLE	GR/IN	ANGLE
	0.0618		0.048		0.0004		0.0005	

RESIDUAL UNBALANCE READINGS

DEGREES	PLANE 1			PLANE 2		
	GR/IN	GM/MM	ANGLE	GR/IN	GM/MM	ANGLE
0		0.00000			0.00000	
60		0.00000			0.00000	
120		0.00000			0.00000	
180		0.00000			0.00000	
240		0.00000			0.00000	
300		0.00000			0.00000	
360		0.00000			0.00000	

Residual Weight Used in grams — Plane 1: — Plane 2:

APPENDIX V: TEST PROCEDURES

X	Cal Poly Proprietary

Reaction Wheel Shaft Load Proof Test Procedure

Satellite Team Change Log

Revision	Date	Author	Change Log
0	4/7/21	A. Lee	Creation
1	4/26	A. Lee	Edit

Satellite Team Responsible Engineer

Author	Contact
Alex Lee	alee315@calpoly.edu
Christopher Pablo Casillas	chris.pablo.casillas@gmail.com
Daniel Leon	dleon04@calpoly.edu
Rose McCarver	rmccarve@calpoly.edu

Purpose: The purpose of this procedure is to test and evaluate the strength and workmanship of a shaft-locking adhesive, Rite-lock 48 (RT48), when used to bond a 1mm shaft of a motor to a 1mm clearance-fit hole of the reaction wheel. For this procedure, test shafts and disks will be used to evaluate the adhesive strength and effectiveness, as not to damage the motor and reaction wheel themselves. The goal is to verify that this shaft-locking adhesive will hold under a 50 lb load.

1. **Requirements Verified:**
    - **Compatibility/Assembly (Req. #13)**

      The reaction wheel system shall fulfill CPCL Structural Review Checklist guidelines and shall be structurally sound and verified with tests.

2. **Load Calculation**

   Compressive shear strength of RT-48

   $$S_{48} = 4970\,psi$$

   Surface area between wheel and shaft circumference (from CAD model)

   $$A = 0.0088in^2$$

   To calculate maximum shear force that can be applied to shaft before adhesive yields:

   $$F = S * A$$
   $$F_{48} = 4970\frac{lbf}{in^2} * 0.0088\,in^2$$
   $$F_{48} = 43.7\,lbf$$

3. **Test Location, Equipment, and Safety:**

   Facilities: Advanced Technologies Laboratory, CPCL Cleanroom (Building 7 Rm 15)

   Aero Hangar Senior Project Laboratory (Building 04)

   Equipment:

    - Four test disks, 0.827 in diameter, 0.079 in thick with 0.04 in hole (note: One disk has two 0.04 in holes for two test shafts)
    - Five test shafts A-E with sizes in Table 1
    - Thin needle
    - 3M Scotch-Weld RT-48 Shaft Locking Adhesive

- 3M Scotch-Weld Epoxy
- Glass Vac chamber and Vacuum Pump
- Aluminum test fixture to hold shaft and disk
- 200N Analog Force Gauge
- Arbor press (Building 04)

Table 1. Shaft Measurements

Shaft	Diameter (in)	Clearance (in)
A	0.0394	0.0045
B	0.0391	0.0035
C	0.0393	0.0048
D	0.0392	0.0043
E	0.0391	0.0048

Table 2. Disk Measurements

Disk	Thickness (in)	Hole diameter (in)	Contact Area (in^2)
A	0.087	0.0439	0.0120
	0.087	0.0426	0.0117
B	0.074	0.0441	0.0103
C	0.121	0.0435	0.0165
D	0.0117	0.0439	0.0117

Safety and PPE:

- All participants must wear safety glasses at all times
- Tie long hair back and tuck away dangling clothing items
- Keep hands away from shaft, disk, and load pin while testing
- Use caution when observing shaft loading, as parts may break and fly off

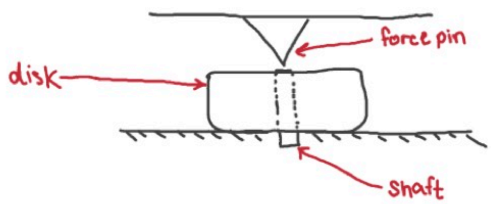
Table 3. Potential Safety Issues and Responses

Safety Issue	Response
1. Force pin breaks shaft bond with hole	Immediately turn off machine if this occurs (signaled by a snapping sound or a standstill in the gradual increase of load)
2. Someone's hand/finger gets caught under the load pin	Immediately turn off the machine and remove hand. Inspect for injuries and if needed seek medical help. This can be prevented by keeping hands away from testing fixture when test is running.

4. **Pre-Test Procedures** (to be done at least 24 hours in advance)

PRE-TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	Take measurements of all four test disks and input into Table 2 above.			
2.	In cleanroom, clean disks and shafts with isopropyl alcohol (IPA) and place each disk into individual trays. Label each try to correspond with the disk identification. Place thin cloths underneath disks in trays to prevent leakage.			
	Carefully insert RT-48 adhesive into the hole of one of the disks, taking care to cover all of the inner surface. Do this by dipping a thin needle into the adhesive and letting it drip off the needle into the hole. Then, slip a shaft into the hole and hold for 10 seconds. Place the shaft/disk assembly in a vacuum chamber (Space Environments Lab 41B-13) and let cure for ***24 hours***.			
3.	Repeat step 2 for the rest of the disks.			

5. **Test Procedures**

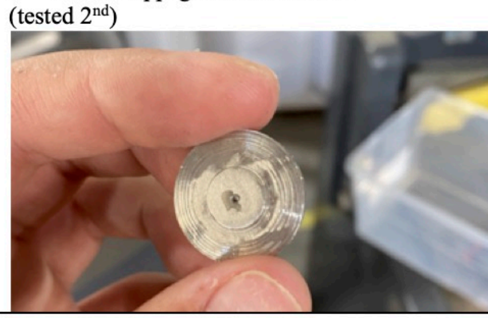
TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	Set up disk/shaft assembly in fixture so that the side where top of the disk that is flush with the top of the shaft is facing up (toward the force pin) and that only the disk is supported on the other side. The shaft will stick through the hole in the test fixture.  			
2.	Take out the force gauge from the casing. Screw on the attachment that is a small point to the side labeled "Push". Place the force gauge in the arbor press with the "pull" side facing up and resting with the wooden block in between it and the arbor press and the force pin aligned with the shaft in the test fixture. Note: It is important to make sure the force gauge is aligned vertically before applying the force. Also it is imperative that the tip of the force pin is ONLY touching the top of the shaft.			
3.	Slowly lower the arbor press at a gradual pace, watching the force dial until reaching the maximum specified load for the specific shaft.			
4.	Once the force gauge has reached the max load, release the pressure on the arbor press and take out the force gauge.			
5.	Visually inspect the assembly to see that the shaft has not slipped out of the hole. Record observations in Table 4.			
6.	Repeat for the remaining disk/shaft assemblies.			

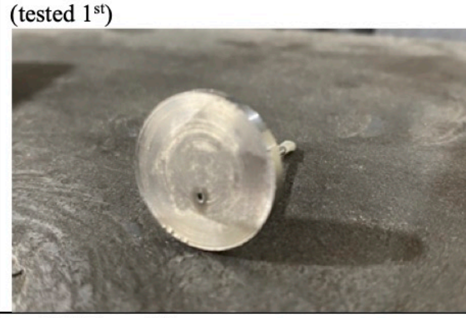
6. **Post-Test Procedures**

POST-TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	Record observations of shaft to note any visual slippage (also note if the force gauge did not increase steadily) in Table 4 of the Results section. Include before and after pictures.			
2.	Clean up and put away all equipment.			

7. **Results**

Table 4. Results

Disk	**Shaft**	**Clearance (in)**	**Max Load (N)**	**Observations** (From during test and post-test visual inspection)
A	A	0.0045	171	• Cured with 3M Rite Lock 48 with tape in vacuum for 26 hours • Did not cure and weren't able to test
A	E	0.0035	166	• Cured with 3M Rite Lock 48 with tape in vacuum for 26 hours • Did not cure and weren't able to test
B	B	0.0048	146	• Cured with epoxy in NOT in vacuum for 26 hours • Tested up to 146 N • A little slippage but still secure (tested 2nd) 

C	C	0.0043	235	• Cured with scotch weld epoxy NOT in vacuum for 26 hours • Tested up to 235 N • Slight slippage of shaft but fixture remained secure after test (tested 1st) 
D	D	0.0048	167	• NOT cured in vacuum • Cured with RT48 • Only one that cured out of three with other two in vacuum • 200N (44.9 lb) force, no visual change during test • From visual inspection, shaft slipped into the hole slightly • Shaft did not shift or wobble by hand 

8. **Summary**

How did each shaft-locking adhesive perform? How did the clearances of the holes affect performance, if at all?

The RT-48 only cured for shaft D which was NOT in the vacuum and did not cure multiple times for the other shafts when we tried in and outside the vacuum. Therefore, we determined this adhesive is either expired, the vacuum was not at a low enough pressure, or the adhesive leaked out and did not cure. For trials with the cloth underneath the disk, the adhesive appeared to have leaked out. For one trial using Kapton tape, it appeared no adhesive has leaked out, but the shaft wasn't cured, and the adhesive was nowhere to be seen. Due to the extensive issues with the Rite Lock 48, we transitioned to using the 3M Scotch Weld Epoxy that has already been used in PolySat flight missions so has been verified for outgassing and space environment. Since it is an aerobic adhesive, we cured the shafts outside the vacuum and they cured successfully.

The proof test was then then performed for shafts B and C and was successful, although there was a little bit of slippage as seen in the images in the results section. Therefore, we concluded the 3M Scotch Weld Epoxy used as staking in PolySat lab should be used to cure the motor shaft to the flywheel but should only be tested to about 80-90% of its max load for the actual assembly proof test to prevent any slippage.

For future use, we recommend using the 3M Scotch Weld Epoxy, but if it is desired to use a shaft-locking adhesive then we recommend ordering the Rite-Lock 38 adhesive since it has a higher viscosity and has less of a chance of leaking (if that was the issue with the RT48) and performing this validation test before using on the reaction wheel assembly.

Cal Poly CubeSat Lab
California Polytechnic State University – San Luis Obispo, CA 93407

X	Cal Poly Proprietary

Reaction Wheel Vibration Testing Procedure

Satellite Team Change Log

Revision	Date	Author	Change Log
0	4/8/21	CP. Casillas	Creation

Satellite Team Responsible Engineer

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Daniel Leon	dleon04@calpoly.edu
Rose McCarver	rmccarve@calpoly.edu

1. INTRODUCTION

In order to ensure the survivability of payloads on a launch vehicle, all hardware must undergo random vibration testing. The following test will expose the Reaction Wheel Assembly (RWA) Flight Unit, built by Cal Poly San Luis, to acceptance random vibration levels as defined by the NASA GEVS vibration profile. The results will determine whether the current design is robust enough to survive the vibrations environments experienced during launch.

1.1 Objectives

This test procedure outlines the steps to perform the NASA GEVS acceptance random vibration test for the RWA. The objective of this test is to:

- Determine survivability of solar cells on side panels.
- Determine whether the epoxy methods and fasteners will withstand the vibration levels.
- Test overall strength of the RWA mechanical and electrical components.

Abbreviations and Acronyms:

Cal Poly	California Polytechnic State University
CAC	CubeSat Acceptance Checklist
SLO	San Luis Obispo
QA	Quality Assurance
Vibes	Vibrations
RWA	Reaction Wheel Assembly
UCP	U-Class Payload

1.2 Requirements Verified

- **Vibration Testing (Req. #12)**

  Reaction wheel shall withstand component level vibration loads specified by NASA GEVS Acceptance PSD profile. (NASA STD 7000 Table 2.4-3)

1. INTRODUCTION

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UCP	U-Class Payload

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SLO	San Luis Obispo
QA	Quality Assurance
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X	Cal Poly Proprietary

Reaction Wheel TVAC Functional Testing Procedure

Satellite Team Change Log

Revision	Date	Author	Change Log
0	4/7/2021	C.P.Casillas	Creation

Satellite Team Responsible Engineer

Author	Contact
Christopher Pablo Casillas	chris.pablo.casillas@gmail.com
Alex Lee	Alee315@calpoly.edu
Daniel Leon	Dleon04@calpoly.edu
Rose McCarver	rmccarve@calpoly.edu

Purpose: The purpose of this document is to outline the procedure and results for thermal vacuum (TVAC) functional testing for 3-Axis Reaction Wheel Assembly (RWA). TVAC Functional Testing is performed to validate the performance of the RWA in an on-orbit environment, in addition to remove any potentially outgassing materials from the CubeSat according to CubeSat to P-POD ICD. These tests were performed in the T-Vac chamber at Cal Poly Hangar by several CubeSat members.

1. **Requirements Verified:**
   - **Thermal Testing (Bakeout) (Req. #5)**

     Reaction wheel assembly shall withstand bakeout of 60 C for 6 hours or 70 C for 3 hours in order to be qualified for on-orbit environment.

   - **Vacuum Testing (Req. #6)**

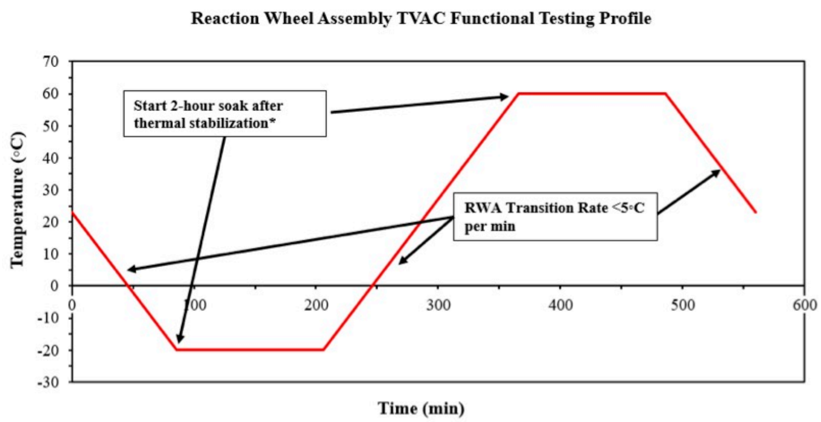
     Reaction wheel assembly shall withstand 1*10^-4 Torr of pressure in order to qualify for on-orbit environment.

Table 3: Thermal Vacuum Temperature Profiles

Profile	Minimum Vacuum Level	Minimum Temperature	Duration	Transition Rate
1	1x10^{-4} Torr	-20°C	2 Hours	< 5°/min
2	1x10^{-4} Torr	60°C	2 Hours	< 5°/min

2. **Test Levels:**

In order to validate the functionality at a Low Earth Orbit "on-orbit" environment, the temperature extremes selected in this profile are typical of a CubeSat's temperature telemetry This profile is shown in Figure 1.



*Each profile is one continuous soak at the temperature and duration specified

Figure 1: Thermal Vacuum Functional Testing Profile

3. **Location and Equipment**

Facility: Cal Poly Aero Hangar Building 4B

Table 2: Hardware

Test Chamber	Cal Poly CubeSat TVAC Chamber
Temperature Sensors	Type T Thermocouples, placed on opposing corners of satellite, shroud, and test stand
Gauge(s)	High vacuum pressure gauge, Grainville-Phillips Series 260 Gauge Controller
Data Acquisition	NI 9213 Thermocouple Input, LabVIEW, 60 second sampling time

4. **Safety and PPE:**
   - All participants must wear safety glasses at all times
   - Tie long hair back and tuck away dangling clothing items
   - Keep hands away from TVAC chamber when testing
   - Do not reach into chamber when the reaction wheel is still hot

Table 3. Potential Safety Issues and Responses

Safety Issue	Response
1. Student touches chamber at 60C	Students shall wait until thermal stabilization at room temperature to approach the chamber

5. **Pre-Test Procedures**

PRE-TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	With the RWA in the chamber, attach thermocouple to –X-Y-Z corner of RWA.			
2.	Take picture of thermocouple location.			
3.	Attach thermocouple to +X+Y+Z corner of RWA.			
4.	Take picture of thermocouple location.			
5.	Place two thermocouples on the shroud.			
6.	Take picture of thermocouple location.			
7.	Place two thermocouples on the test stand.			
8.	Take picture of thermocouple location.			

9.	Record the locations of each thermocouple in the table below. **Channel** / **Location**: -X; -Y; -Z; +X; +Y; +Z; Shroud 1; Shroud 2; Stand 1; Stand 2			

Channel	Location
	-X
	-Y
	-Z
	+X
	+Y
	+Z
	Shroud 1
	Shroud 2
	Stand 1
	Stand 2

6. **Test Procedures**

TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	Seal the door.			
2.	Begin recording data in LabVIEW. Note: Sample rate of 5 mins for temp, 10 mins for pressure or better is recommended. Be sure to record the start and end times.			
3.	Pull vacuum in the chamber to *at least* 1E-4 Torr. The chamber *must* stay below this vacuum level for the entirety of the test.			
4.	Once the vacuum level is achieved, begin to heat the chamber to 60ºC while ensuring that the heating rate is less than 5ºC/minutes.			

5.	Begin the soak once the thermocouples on the RWA read greater than 60ºC.			
6.	Soak the RWA for 2 hours, ensuring that the thermocouples on the RWA read at least 60ºC for the entirety of the soak. There will need to be at least two people watching the chamber at all times.			
7.	Verify that the RWA has soaked for a minimum of 2 hours at a minimum temperature of 60ºC.			
8.	Bring down the temperature in the chamber to 30ºC at a rate less than 5ºC/minute.			
9.	Stop recording data in LabVIEW. Save the data file.			

7. **Post-Test Procedures**

POST-TEST PROCEDURES				
Step #	**Description**	**Time**	**Date**	**Sig.**
1.	Restore the chamber to atmospheric pressure.			
2.	Open the chamber door.			
3.	Remove thermocouples from chamber and RWA.			
4.	Remove RWA from chamber and place in appropriate clean container/carrying case. Note: Volatiles have now been baked off the RWA so be sure to keep as clean as possible.			

8. **Results**

8.1. RWA –X-Y-Z Corner Temperature Data

[insert graph of temp data]
[insert pic of thermocouples taped to RWA]

Figure 2: Location of –X-Y-Z thermocouple on RWA

[insert thermocouple data]

Figure 3: Thermocouple reading from –X-Y-Z corner of RWA

8.2. RWA +X+Y+Z Corner Temperature Data

Figure 4: Location of +X+Y+Z thermocouple on RWA

[insert thermocouple data]

Figure 5: Thermocouple reading form +X+Y+Z corner of RWA

8.3. Compiled Temperature Data

Figure 6: Thermocouple readings from both corners of RWA

8.4. Most Extreme Temperatures

	RWA -X-Y-Z	RWA +X+Y+Z
Highest Temperature Reached During Testing		
Lowest Temperature Reached During Testing		

.

8.5. Pressure

[insert pressure data]

Figure 7: Vacuum pressure in chamber

Time Since Start of Data Recording (hr:min)	Time Stamp Description
0:00	Pressure drop and ramp up begins
	Both thermocouples read above 60˚C, pressure reads < 1E04 Torr, 2-hour soak begins
	Possible anomaly
	Possible anomaly fixed
	Possible anomaly
	2-hour soak is completed, ramp down begins
	RWA returns to normal temps, pressure is raised, tests ends

7.5 Thermocouple Location after TVAC Test

[insert pic of location of thermocouples after test]

Figure 8: Location of thermocouple on RWA after test

9. **Summary**

Appendix W: User Manual

ITAR controlled