Optical Filter Selector

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1.0 Abstract

One of the many challenges with launching projectiles into space is predicting how the environment in space will affect the trajectory. One way to do this is to look at optical emissions, also known as airglow, which can only be seen from earth with sensitive equipment. By taking measurements of the light from the airglow, properties about the upper atmosphere can be inferred. This is important because variability in the atmosphere can cause variability in space that can affect astronauts and satellites. In order to accomplish this task, optical filters must be used to observe different bands of wavelengths of light that target specific airglow emission features. The scope of this project is to design a product that autonomously switches through four filters of differing colors and wavelengths. This document will summarize the background research that has been performed to develop an understanding of the project and the objectives and requirements for the project. Additionally, this document will reiterate the problem, lay out the scope of the project and the engineering specifications, and provide a basic overview of testing the design against the specifications. This document will then describe the process for creating a solution to the problem. Then it will describe the final chosen design, the manufacturing plan, and the design verification plan. It will also summarize the manufacturing performed and the testing plans created. Finally, it will summarize what still needs to be completed and what team recommends moving forward.

1.1 Introduction

Typically, aurora emissions are thought to be restricted to near the North and South poles. However, airglow that the naked eye cannot see is emitted at all latitudes. This airglow can only be seen by very sensitive instruments. By observing multiple wavelengths, it is possible to infer important characteristics about the upper atmosphere. This information could lead to a better understanding of the atmosphere that will support the launch of three satellites [1].

Brian Harding, an engineer at the Space Sciences Laboratory at UC Berkeley, has introduced the problem of designing, prototyping, and building an optical filter selector that will be integrated into a larger instrument. This instrument will allow the lab to gather information from atmospheric light using four different filters that will be rotated throughout the night. There are existing solutions that solve similar problems, but their cost is too high. The size of the required product is also smaller than those currently on the market and handles filters of a larger size. Current products also do not allow for tilting of the filters. Research on these existing solutions can be found in the background section of this document.

The team who has taken on this project includes Callen Schwefler, Camaryn Chambers, Joel Pitzer, and Matthew Allen. All these students are fourth-year mechanical engineering students at California Polytechnic State University, San Luis Obispo.

The goal of this report is to summarize the design process of the project and establish a design to be tested and implemented in the future. It will also be a tool to organize the background research of the project. It will also describe the design process and the design that was chosen. The report will then discuss the manufacturing plans and testing procedures to be implemented. Ultimately, it will formulate a plan for completion and replication of the project.

To summarize the background information, this report will discuss relevant patents, current products, related literature, and any important industry standards. The objective section will establish the requirements and objectives of the project as well as the required deliverables. The concept design section will detail the design process implemented and its results. The final design section will detail the design chosen and analysis to support its selection. The manufacturing plan section will detail how the design will be built. The design verification plan section will describe the planned testing. Finally, the project management section will present how the organization of the project as well as an overview of the project and major milestones.

The background section that follows will show that adequate research and analysis of the problem has been conducted in order to create a successful and complete design.

2.0 Background Research

Optical filter selectors are common instruments used to observe either the atmosphere or space. They are implemented to change filters for these observations so that different wavelengths of light may be observed by the instrument for data collection. There are several approaches that can be taken to switch between filters with the most common method being a filter wheel.

2.1 Sponsor Meeting Summary

Conversations with Dr. Brian Harding of Berkeley Space Sciences Lab (SSL) have been held with the team to fully communicate the parameters and attributes desired for an optical filter selector unique to their project observing the atmosphere. Weekly video conferences have also been held to communicate these desires and ensure that both Berkeley SSL and the team are working towards a design to solve the same set of requirements. The problem statement and requirements that were decided upon are a direct result of these meetings and are included within Section 4.0.

The team first met with Dr. Harding on October 4, 2019. Basic project outlines and specifications were outlined with requirements discussed and drawings shared to visualize the constraints of the design. Dr. Harding is considered the customer of this project as he will be implementing the team's design when it has been completed. A concern brought up to the team during the first meeting had to do with the effects changes in temperature could have on the filters. This was left as a topic for further investigation.

The team met for a second time with Dr. Harding on October 10, 2019. This meeting explored several desired design specifications presented earlier by Dr. Harding. The tilting of the filters was discussed, and Dr. Harding explained that the tilting of the filters could be done gradually or in steps. The tilting of the filters will also be manual. The temperature concern was also further discussed with expected design temperature gradients chosen to be similar to those at McDonald Observatory although the exact location is still to be determined.

2.2 Related Research

Many existing designs of filter selectors use a wheel geometry to select different filters. Weidlich et al. conducted research on the optimal filter selector for the James Webb Space Telescope and developed a filter wheel structure with 8 positions [2]. The filter wheel is driven by a motor and designed to minimize vibrational effects. It is made with a combination of titanium and aluminum alloys to provide structural support to the filter selector. This article is important for the project by demonstrating an effective use of filter selection with motors and the common types of material considered for filter selectors.

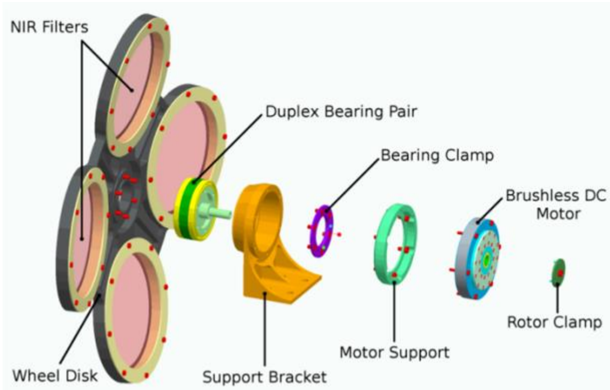


Figure 2.1. Exploded View of a Proposed Filter Selector for the Cosmic Vision Program [2]

Another approach to filter selectors was taken by Holmes et al. who developed a filter wheel for the Euclid mission within the European Space Agency's Cosmic Vision Program [3,4]. For this project, the filters stood out by being brittle and large (127 mm diameter). The filter wheel was designed with step increments instead of continuous control to mitigate sources of error and is a centrally driven titanium filter wheel as seen in Figure 2.1. This article is useful for the project because it involves an approach on designing a filter selector for large filters. Schenkel and Ogorzalek take a similar approach using a filter wheel for their apparatus that is powered by a motor seen in Figure 2.2 [5].

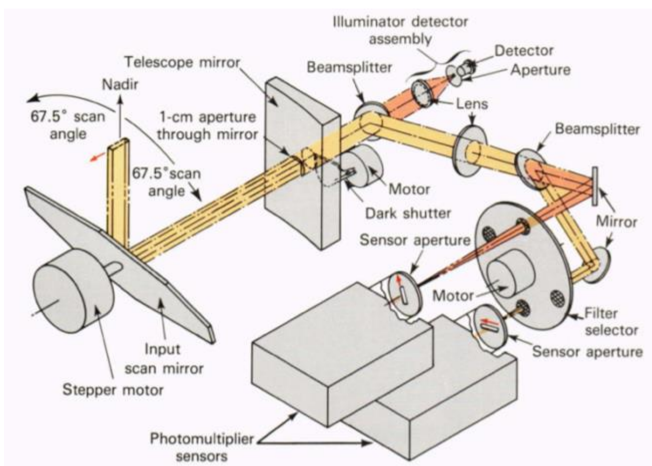


Figure 2.2. The Design of the AIRS Optical Instrument [5]

An approach to filter selection with a similar use to that of the team's project is done by engineers at the Indian Institute of Tropical Meteorology [6]. An experimental setup was created to regularly monitor aerosol parameters in the lower atmosphere where a filter wheel with a stepper motor was used for filter selection as seen in Figure 2.3. This article is useful by reaffirming that a motor-based setup is a viable approach for implementing a filter selector for longer spans of time.

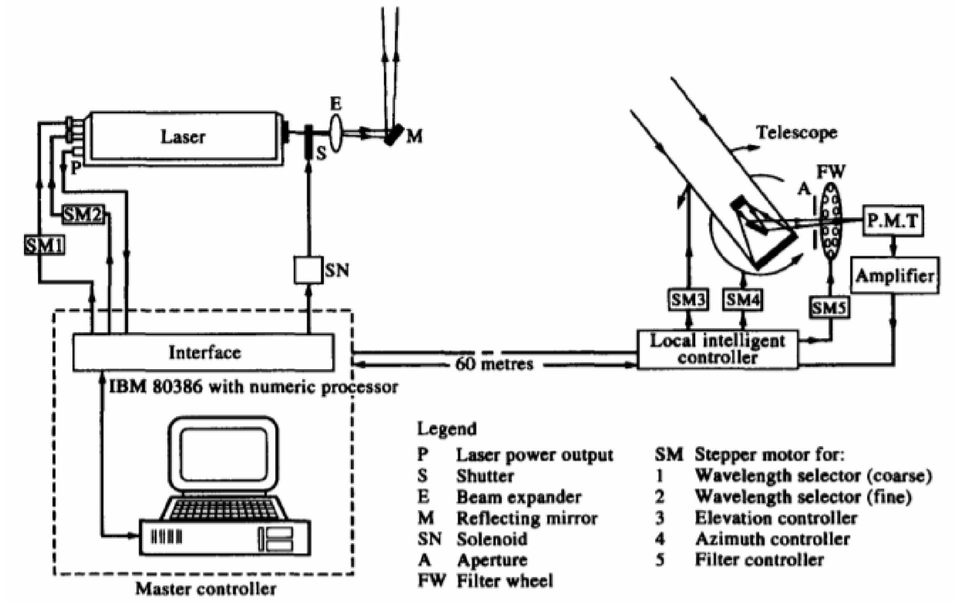


Figure 2.3. Experimental Setup for Monitoring the Atmosphere [6]

The basis of all literature the team has researched is a filter wheel. It is a simple device requiring one motor and can fit as many filters as necessary. However, due to the specifications of this project requiring a lower cost and less space, a different, more complex, design may be necessary.

2.3 Current Devices

There are many similar products that resemble the optical filter selector design challenge presented by the Space Sciences Laboratory. Unice is an optical equipment and components provider that produces a stepper-motor-driven motorized filter wheel [7]. Images of this device were presented as background information in the original design proposal provided by the Space Sciences Laboratory, shown in Figure 2.4. The wheel costs less than a thousand dollars, however, its dimensions are insufficient for housing the filters described in the design challenge. Requesting for a company like Unice to develop an optical filter selector for the Space Science Laboratory's, would also be costly. Fortunately, Unice provides detailed documentation and CAD models that will be useful when designing the optical filter selector for this design challenge.

Figure 2.4. A Unice Motorized Filter Wheel [7]

Lumicon, a subsidiary of Optical Structure incorporated, approached the idea of a filter selector differently. Their design, shown in Figure 2.5, involves a linear system in which multiple filters slide back and forth through a stationary lens [8]. The Space Sciences Laboratory presented images of a similar system as background information in the original design proposal. Lumicon does not provide any motorized way of automating the filter selection process, although there are conceivable solutions like using a lead screw. This system would be relatively easy to manufacture, as it would reduce the amount of complete geometry. A possible problem with this design might be its size. By lining up filters edge to edge, the system may be too large.

Figure 2.5. The Lumicon 5-Position Multiple Filter Selector [8]

Figure 2.1 depicts an exploded view of a filter wheel. An engineer on Hackerday.io has designed a filter wheel which, when assembled, is similar to the filter wheel in Figure 2.6 [9]. This particular product is useful because it provides step by step instructions on how to build the device. This guide will be useful when the team is working on designing the inner workings of the device.

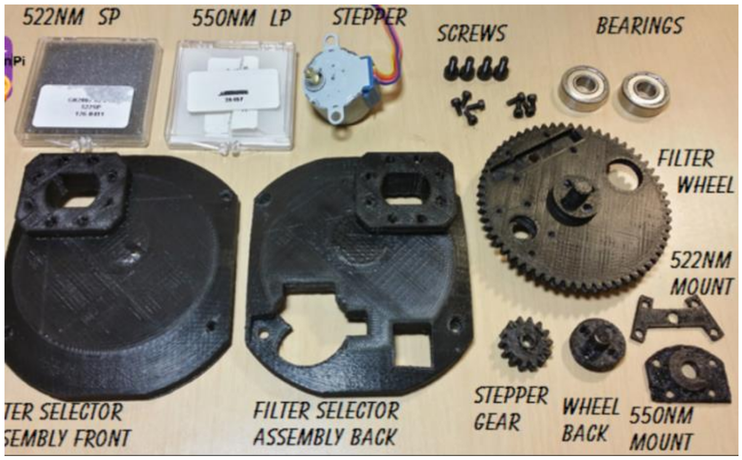


Figure 2.6. An Image from Filter Selector Assembly Build Instructions [9]

The camera and telescope company CCTS, has developed a product that is not only a filter wheel, but also includes a programmable controller, as shown in Figure 2.7 [10]. The filter wheel determines the identification of any particular wheel, and then uses that identification to determine the rate at which the wheel rotates. Although it is not immediately obvious how this technology will benefit the team, it is an interesting technology which may be of use later in the design process.

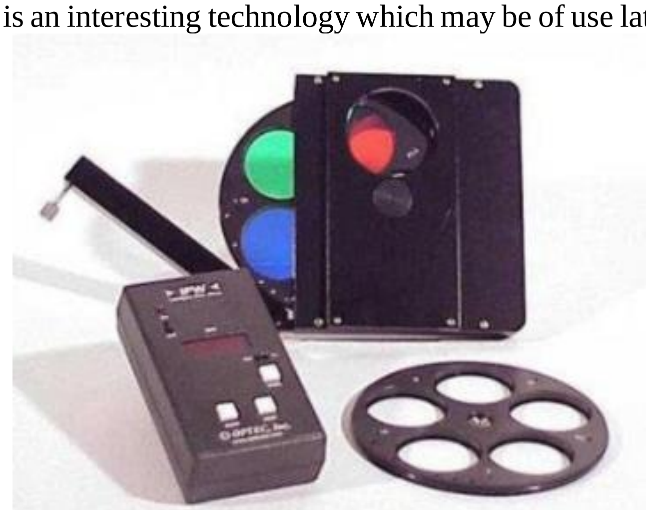


Figure 2.7. A CCTS Filter Wheel Automatic 2 Inch Filter [10]

Thorlabs have also developed a motorized filter wheel, seen in Figure 2.8. It is multifaceted device which a user can control manually and remotely [11]. A user can program the device to allow for any number of different sequences. The filter wheel is well built and has many functions, resulting in a price upwards of a thousand dollars. Thorlab's website has extensive documentation and will serve as an example of a well-made device.

Figure 2.8. A Thorlabs Motorized Filter Wheel [11]

Another important design feature for the device is the ability to accurately tilt the filters. The adjustable platforms in Figure 2.9 are used to precisely tilt optical components [12]. Since the filters for the team's device are circular, they cannot use these platforms directly, but understanding the mechanics of the systems will be useful in the design process.

Figure 2.9. A Set of Multi-Axis Tilt Platforms [12]

2.4 Similar Products

Table 1 summarizes the team's research on current devices including a brief description of the device and lists key characteristics of each design.

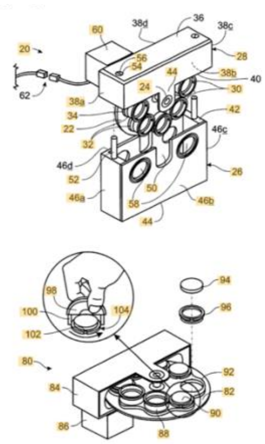
Table 1. Summary of Similar Products

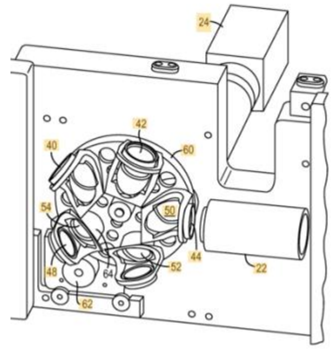
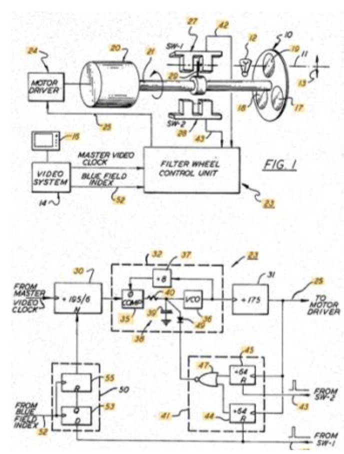
Product Name	Product Description	Important Characteristics
Unice motorized filter wheel	This filter wheel is a robust device which rotates between 6 filters and includes a system management controller.	- 6 filters - Stepper motor driven - Max filter thickness (5mm) - controllers and software included
Lumicon 5-position multiple filter selector	The Lumicon Multiple Filter Selector lets you switch back and forth between filters without having to thread and unthread them.	- Linear system - Not automated - 5 filters -filter stacking
Hackday.io - Build Instructions: Filter Selector Assembly	Detailed and open source build instructions for a filter selector assembly.	- Gear train - Stepper motor - 3D printed - Wheel
CCTS: Filter Wheel Automatic 2 Inch Filter Selector System	The Optec IFW has the ability to determine the identification (ID) of a particular wheel and apply that wheel ID to a preprogrammed set of filters.	- 5 filters - Electronic selector system - Programming changes based on filter wheel
Thorlabs: Motorized Filter Wheels, Stepper Motor Driven	Each unit consists of a motorized housing and a preinstalled filter wheel with either 6 positions for Ø1" (Ø25 mm) optics or 12 positions for Ø1/2" (Ø12.5 mm) optics.	- 6 and 12 position options - remote or manual operation - programmable filter sequences

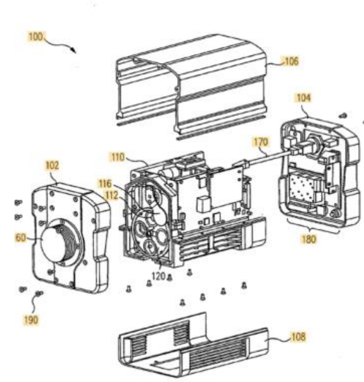
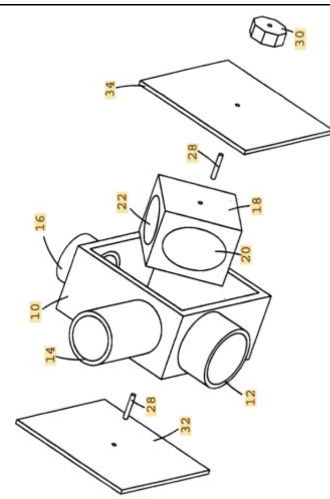
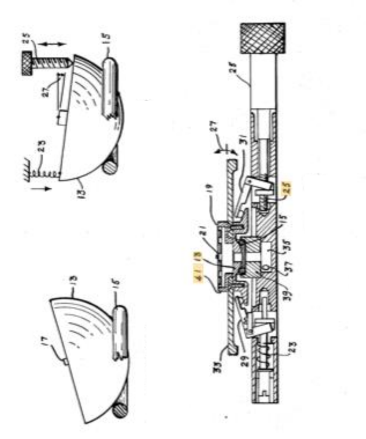
2.5 Relevant Patents

Table 2 outlines a series of patents that are related to designs similar to the optical filter selector requested by the Space Sciences Laboratory. All of these patents describe different filter wheel designs as they are the most standard filter selector geometry. Each one of them utilized different orientations and layouts for filter selection. Breaking down and analyzing these designs will be useful in the brainstorming process for the optical filter selector for the Space Sciences Laboratory.

Table 2. Relevant Patents

Patent Number	Patent Title	Description	Drawing
US6313960B2	Optical filter holder assembly	A patent related to devices for using optical filters in a filter holder that enable filters to be simply, conveniently, and flexibly interchanged [13].	 Figure 2.10. Patent US6313960B2 [13]
CA1091967A	Cam filter wheel for tilting optical filters	A cam filter wheel apparatus disclosed for tilting interference filters in order to achieve variation in the light wavelength transmitted by each filter. The wheel apparatus contains a number of filters each mounted so as to pivot and change its inclination with respect to an incident light beam as the filter wheel rotates each filter through the light path [14].	N/A

Patent Number	Patent Title	Description	Drawing
US8934098B2	Fast-indexing filter wheel and method of use	A patent compromising: a filter wheel having a plurality of filters such that each filter can be placed into optical communication with the excitation source, wherein the plurality of filters includes a plurality of emission filters and a plurality of excitation filters; a motor coupled to the filter wheel, and configured to index between filters in an amount of time within a range of about 40 ms to about 60 ms [15].	 Figure 2.11. Patent US8934098B2 [15]
US4523224A	Color filter wheel synchronizer	Apparatus for synchronizing rotational speed of a color filter wheel to a video field rate using a stepping motor drive. The derivation of the stepping rate is taken directly from the video system's master clock through dividers and a phase locked loop which provide the required fractional rate division [16].	 Figure 2.12. Patent US4523224A [16]

Patent Number	Patent Title	Description	Drawing
EP2350739B1	Infrared camera filter wheel systems and methods	A filter wheel (120) comprising: a plurality of filters (140) adapted to selectively filter infrared radiation prior to the infrared radiation being received by the infrared sensor, and a plurality of filter identifiers (150) associated with the filters, wherein each filter identifier identifies a corresponding one of the filters [17].	 Figure 2.13. Patent EP2350739B1 [17]
US2005027135A1	Combined optical filter wheel, beam splitter, switch, and logic gate	A combined optical filter wheel, beam splitter, switch, and logic gate for a machine that can changeably pass, reflect, filter, or block light along multiple paths [18].	 Figure 2.14. Patent US2005027135A1 [18]
US3826558A	Mechanical rotary tilt stage	A mechanical stage capable of tilting in any direction and rotated 360 degrees at any tilt angle includes a hemispherical support base which rests upon an O-ring bearing allowing tilt and rotary motion [19].	 Figure 2.15. Patent US3826558A [19]

The Space Sciences Laboratory is utilizing a Moog Animatics SmartMotor elsewhere in their instrument and it is desired that the project utilizes the same motor to make interfacing with it simpler. All efforts will be made to use this motor, but its viability for this project cannot be determined until a structural design is complete. The specification sheet for this motor can be found in Appendix A [20].

Now that the relevant background information has been introduced, the needs and wants of the customer and the design specifications will be discussed in section 4.

3.0 Objectives

The research scientists at the Space Sciences Laboratory need a way to remotely change between four optical filters over a telescope. The device must be stable over expected temperature extremes and other disturbances. The temperature is expected to range from 10-35°C (50-95°F) and the filters should be maintained in a range of ±2.5°C. The device must also be cost effective, robust, and easily attach to their current equipment. This section provides a summary of the needs and wants of the Space Sciences Laboratory, as well as specifications for the design. The needs and wants of the customer are summarized in Table 3.

Table 3. Customer Needs and Wants

Needs	Wants
Switches between 4 filters	Temperature stability
Fully automated switching	Maintenance can be performed without removal
Manually tilted	Filters can be changed without touching lens
Low maintenance (every 6 months)	Works with smart motor
Robust – long life	Sealed to dust
Easy installation	
Secure attachments	
Pass a life test of 200,000 cycles	
Protects other equipment from falling debris	

In an effort to further understand the scope of this project, the group created a boundary diagram, shown in Figure 3.1. The boundary diagram depicts where the design will live in respect to other components of the overall device. The optical filter selector will occupy the space between the Sky Scanner and the Fabry Perot. The optical filter selector will play a major role in the overall system. The device must switch between four filters of different colors, which each select for different wavelengths of light, in order to collect the desired data.

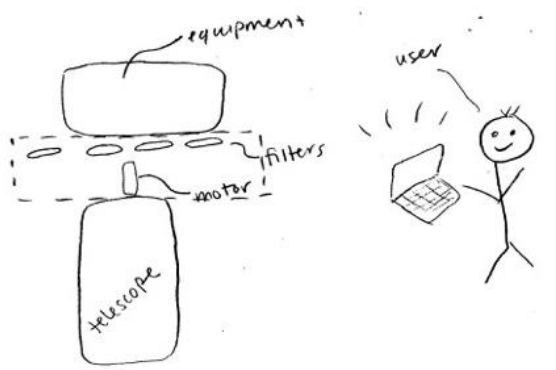


Figure 3.1. Boundary Diagram for Optical Filter Selector

3.1 QFD Description

A quality function deployment, shown in Appendix B, was used to help define the problem that the project will solve. The first step in this process involved determining the customer (in this case the SSL scientists who will use the device, the manufacturers, and the people who will perform maintenance on the device). After this, the customer needs and wants were listed and a weight was assigned to each of these requirements for each customer based on how important that requirement was to that specific customer. The requirements with the highest total relative weights were manufacturability and secure connections to the larger assembly. Next, similar devices that already exist were put into the table and each was assigned a score from zero to five for how well they satisfy each of the customer requirements. This data will be used to determine what attributes from the current devices may be useful to incorporate into the design. It will also inform what areas the new design needs improvement in.

After this was performed, a list of engineering specifications (or tests) to be used to determine if the new device meets the customer requirements were included. The strengths of the relationships between each test and each requirement were shown. There is a test with a strong relationship for every requirement, which means that the list of tests is complete, and there is a requirement with a strong relationship for every test, which means that there are no superfluous tests on the list. Finally, the target values for each test were decided upon and put into the table. These form the basis for the final specification list.

3.2 Specifications

The design specifications, shown in Table 4, will allow the design to be tested to see if it meets the design requirements. The table also shows how the team intends to test the design and the risk of the specification. The risk, which shows the expected difficulty of meeting the requirement can be high, medium, or low. The testing methods include test, analysis, or inspection. The target temperature of the device is yet to be determined but will be somewhere in the operating range of the device, which is believed to be 10-35°C, but will vary depending on the locations chosen to deploy the instrument. This will be chosen by figuring out what temperature will be easiest to stabilize. Then the device will maintain the temperature within a tolerance of ±2.5°C.

Table 4. Design Specifications

Spec. #	Specification Description	Requirement or Target	Tolerance	Risk	Test
1	Size Constraint	254 x 254 x 203.2 mm	±100 mm	H	I
2	Filter Tilt	0-10 deg (0.2 deg steps)	Min	M	T, I
3	Active Filter Centered	127 mm from x and y edges	±3 mm	L	I
4	Maintenance Life Cycles	200,000	Min	M	A, T
5	Cost Per Device	$4000	Max	M	A
6	Temperature Stability	Target Temperature TBD	±2.5°C	H	T
7	Filter Size	86 mm	±0.25 mm	L	I, T, A

The following section will describe the process used to create design concepts and to select an idea. Then it will describe the chosen design and present preliminary analyses.

4.0 Concept Design

In order to select one final concept, many initial designs were considered. For the ideation phase, the goal was to create a high quantity of solutions. In order to do this, multiple brainstorming methods were utilized. First, functional decomposition was used to break the whole process into smaller functions. For this project, the functions were switching the filters, rotating the filters, attaching to the poles, and stabilizing the temperature. Normal brainstorming was one method initially utilized. This involved writing ideas for the function of rotating the filters onto post-it notes. Then, SCAMPER (substitute, combine, adapt, modify, put to another use, eliminate, and reduce) was utilized for this function as well. This involved applying each adjective to an idea already created. Finally, brainwriting was used to analyze the function of tilting the filters. This process is similar to brainstorming except the concepts are drawn instead of written out. A full list of concepts is shown in Appendix C.

Once many ideas were created, the impossible or too difficult ones were removed. Then, the most simple, interesting, and feasible ideas were selected. For each function, a Pugh matrix was used to evaluate the ideas which allows the ideas for each function to be evaluated on multiple criteria compared to a datum or base idea. The Pugh matrix for each function is shown in Appendix D. The Pugh matrix allowed each function to be narrowed down to the top three ideas which are shown in Table 5, the morphological matrix.

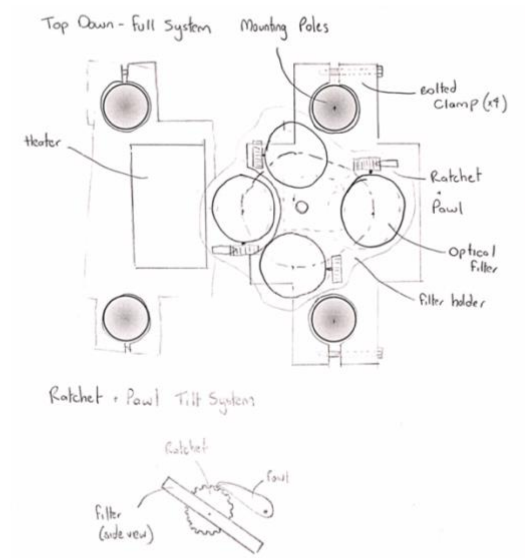
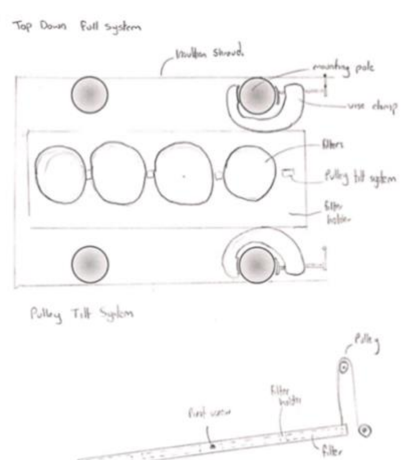
Table 5. Morphological Matrix

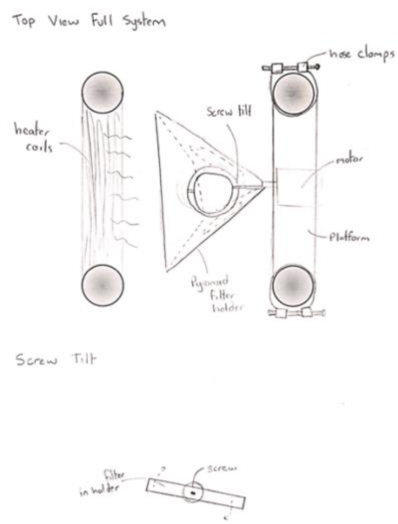
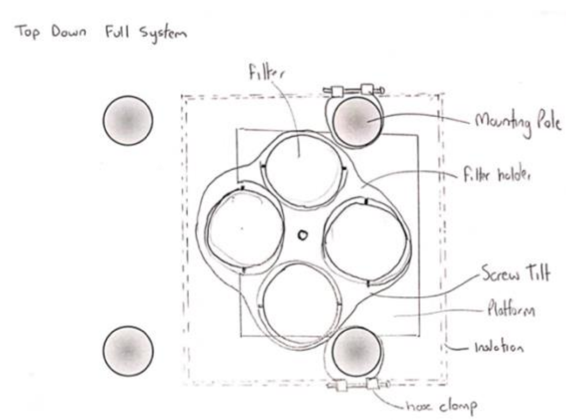
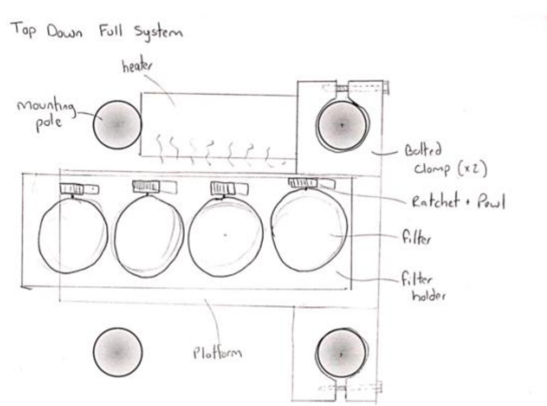
No	Sub-Function	Concept		
		I	II	III
1	Filter Selection	Wheel	Linear	Pyramid
2	Filter Tilt	Ratchet	Screw	Pulley
3	Attachments	Bolted Clamp	Hose Clamp	Vise
4	Temperature Stability	Heated Coils	Insulation	Heater

4.1 Initial Concepts

Using the morphological matrix in Table 5, five possible options were selected, as shown in Table 6. A concept for each sub-function was combined into five solutions that were logical and feasible.

Table 6. Description of Design Options

Option	Description	Sketch
1: Wheel, Ratchet, Bolted Clamp, Heater	This option utilized a filter wheel that is driven directly by the motor shaft. The filter tilt is handled by a ratchet and pawl system embedded into the filter wheel. The system is clamped onto the poles using a bolted clamp. Lastly, a heater is clamped on to the two remaining poles.	 Figure 4.1. Design Option 1
2: Linear, Pulley, Vise, Insulation	This option utilized a linear filter holder which is driven by a gear system and the motor. The filter tilt is handled by a pulley system which pulls up on one end of the filter holder. The system is clamped onto the mounting poles using a vise clamp. Lastly, insulation surrounded the system to take care of temperature stability.	 Figure 4.2. Design Option 2

Option	Description	Sketch
3: Pyramid, Screw, Hose Clamp, Insulation	This option arranged the filters in a pyramid formation, with the motor rotating the pyramid at its point. The filter tilt is handled by a screw that allows the filters to spin freely and be locked in place. The system is connected to the mounting poles using hose clamps. Lastly, heating coils took care of temperature stability.	 Figure 4.3. Design Option 3
4: Wheel, Screw, Hose Clamp, Insulation	This option utilized a filter wheel that is driven directly by the motor shaft. The filter tilt is handled by a screw that allows the filters to spin freely and be locked in place. The system is clamped onto the poles using hose clamps. Lastly, insulation surrounds the system to take care of temperature stability.	 Figure 4.4. Design Option 4
5: Linear, Ratchet, Bolted Clamp, Heater	This option utilized a linear filter holder which is driven by a gear system and the motor. The filter tilt is handled by a ratchet and pawl system embedded into the filter wheel. Lastly, a heater is clamped on to one of the two remaining poles.	 Figure 4.5. Design Option 5

Once the top five ideas were selected, they were inserted into a weighted decision matrix, shown in Table 7. The five ideas were evaluated against the design specifications in the QFD. Each criterion was given a weight of importance from 1 to 5. Then, each design was evaluated against the criteria on a scale from 1 to 10 which gave a total score. The idea with the top score was the basic filter wheel (concept 1) which matched the intuitions of the group.

Table 7. Decision Matrix

Criteria	Weight	Design Concepts				
		1	2	3	4	5
Space	1	8	8	9	8	8
Tilting	5	8	4	6	6	8
Robustness	4	8	7	5	8	7
Cost	4	7	9	6	8	7
Maintenance	3	7	7	7	7	7
Filter Changes	3	8	8	6	8	8
Connections	5	8	7	6	6	8
Installation	2	7	7	6	6	7
Manufacturability	3	6	8	4	8	6
Usability	4	9	4	5	5	8
Autonomous	5	8	8	8	8	8
Filter Positioning	5	9	8	7	9	8
	Total	346	306	271	318	333

4.2 Selected Design Direction

The selected design concept is shown in Figure 4.6. The design will utilize a basic filter wheel. The design will now be discussed in more detail.

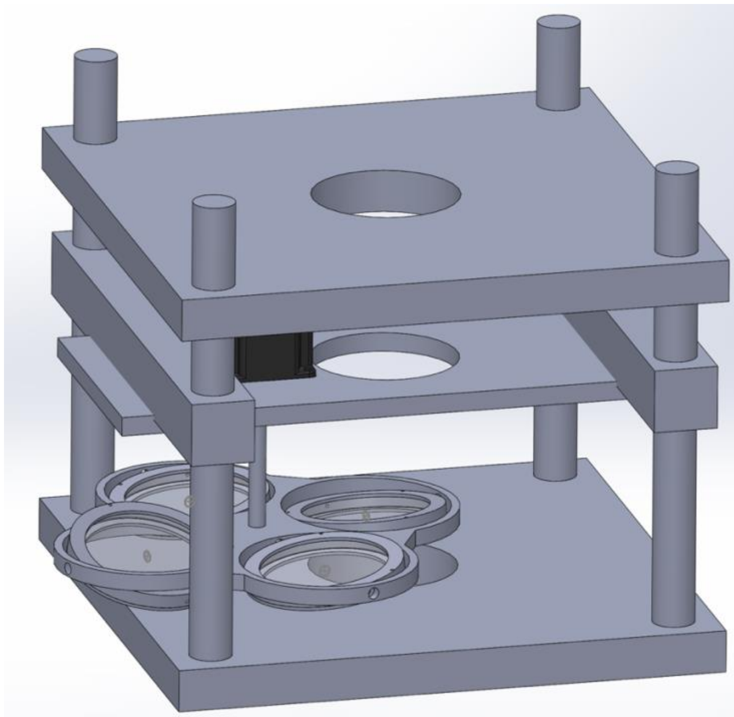


Figure 4.6. Concept CAD Isometric View

The selected concept will be one that puts the filters in a holder as shown in Figure 4.7. These holders will include two pieces: a bottom piece that will hold the filter and a top piece that will keep the filter secure. Four screws will be used to connect the two pieces with the filter held in between them. These filters will likely be machined of aluminum 6061 using a CNC mill.

Figure 4.7. Filter Holder

There will be four of the filter holders placed in the filter wheel as shown in Figure 4.8. This filter wheel will have a shaft that will be coupled to the motor shaft. In each of the four locations where the filter holders are inserted into the filter wheel there will be a hole cut into the side of the filter wheel. This will allow the shaft from the filter tilt mechanism to be connected to the filter holder through the filter wheel. The wheel will also likely be made from aluminum 6061.

Figure 4.8. Filter Wheel

The filter wheel will be on a shaft connected to a motor that will be used to turn the wheel and switch between filters. As seen in Figure 4.9, the filter wheel can be turned such that the filters will be centered in the enclosure when they are selected by the user. The motor will be held up by a platform that will be supported by clamps attached to the enclosure poles. Another platform may be attached to the poles and used to support the base of the filter wheel. These platforms will also probably be created from aluminum 6061.

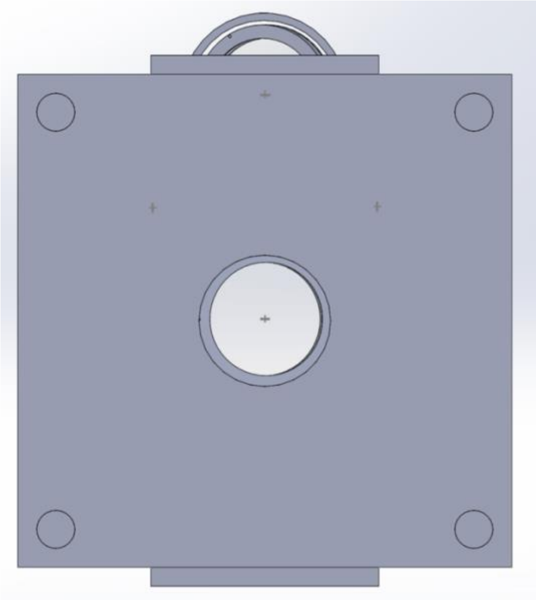


Figure 4.9. Concept CAD Top View

All of the important components involved in the design are shown and labeled in Figure 4.10. These include the poles, the motor, the platform, the filter holders, and the filter wheel.

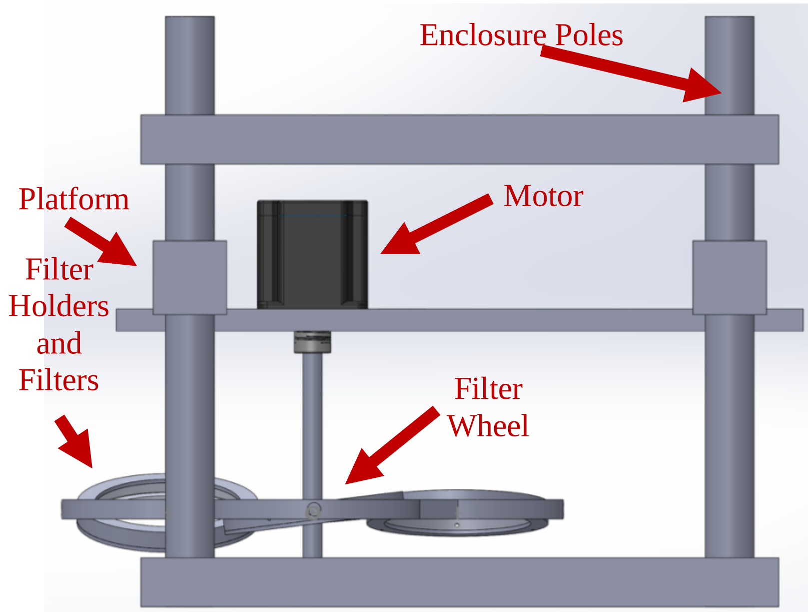


Figure 4.10. Concept CAD Side View

Lastly, there will be a mechanism to allow for the filter to be tilted in 0.2-degree steps. One option is the ratchet and gear-train mechanism in Figure 4.11. This mechanism would allow for the filters to be tilted in less than 0.2-degree increments but could be larger, heavier, and more complicated than other possible solutions. The steel gears can be bought standard from McMaster-Carr. The team is investigating other pre-made solutions that would provide a better filter tilting mechanism. This mechanism will be attached to the filter wheel or filter wheel shaft and will have a shaft that is connected to the filter holders. The team has chosen to use the PRM05, which will be further discussed in the next chapter.

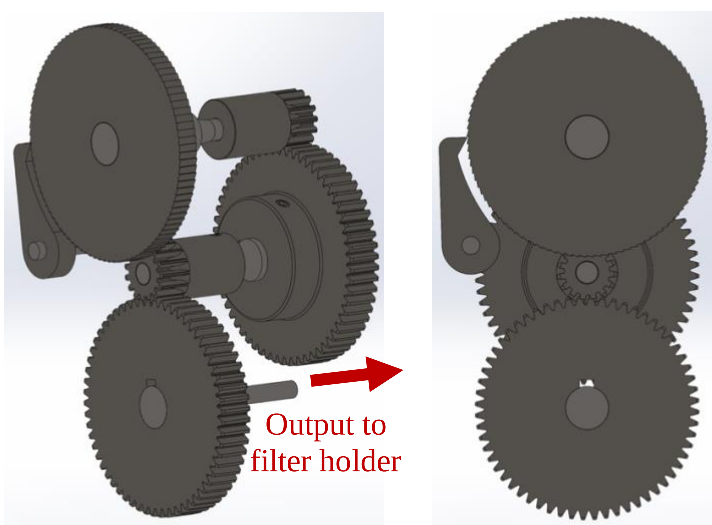


Figure 4.11. Ratchet and Gearing System

For this design, a 3D printed concept prototype was created to demonstrate the design structure and function. The concept prototype printed was split into two parts. One part showed the functionality of one filter holder, shown in Figure 4.12. The other part showed the structure of the filter wheel structure, printed at a much smaller scale, shown in Figure 4.13.

Figure 4.12. Concept Prototype of Filter Holder

Figure 4.13. Concept Prototype of Filter Wheel

The filter wheel will be machined with a CNC using aluminum as the main material. This will provide the required strength and fatigue resistance as well as ensure that the material will not severely expand or contract when heated. It is expected that the design of the filter wheel and filter holders will require CNC manufacturing, while the connecting rod can be done with a lathe by hand.

The heating system will be using an off the shelf heating control system, heating pads, and thermocouples. The enclosure itself will be cut and bent from aluminum sheet metal and insulated.

4.3 Preliminary Analyses

In order to determine the viability of the proposed design, several preliminary analyses were conducted. The first two were performed to determine whether the Smart Motor will be capable of directly driving the filter wheel. The first was a calculation to determine if the encoder resolution will allow the filters to be positioned within the necessary tolerance. The safety factor for this was 13.5. The second was a calculation to determine if the torque of the motor will be high enough to turn the filter wheel and the safety factor for this calculation was 58. Another analysis performed was to determine whether the main shaft would experience whirling failure, but the safety factor on this calculation was 1290. Lastly, a stress analysis was performed on the platform holding the motor, with the result being a safety factor of 1589. These calculations can be found in Appendix E.

The team does not have any major risks or challenges for completing the project. Some minor risks and challenges that will be addressed are included in the team's design hazard checklist in Appendix F. These challenges include: the revolving motion of the filter selector which can be hazardous if appendages are nearby, the threat of the filter selector falling down and harming other components within the system, sharp edges on the filter selector, and the environmental conditions harming the validity of the data. Methods to mitigate each of these risks are also provided in the design hazard checklist.

The following section will detail the final design and its function.

5.0 Final Design

The final design consists of three major subassemblies and can be viewed in Figure 5.1. The subassemblies are the filter wheel, the thermal enclosure, and the platforms.

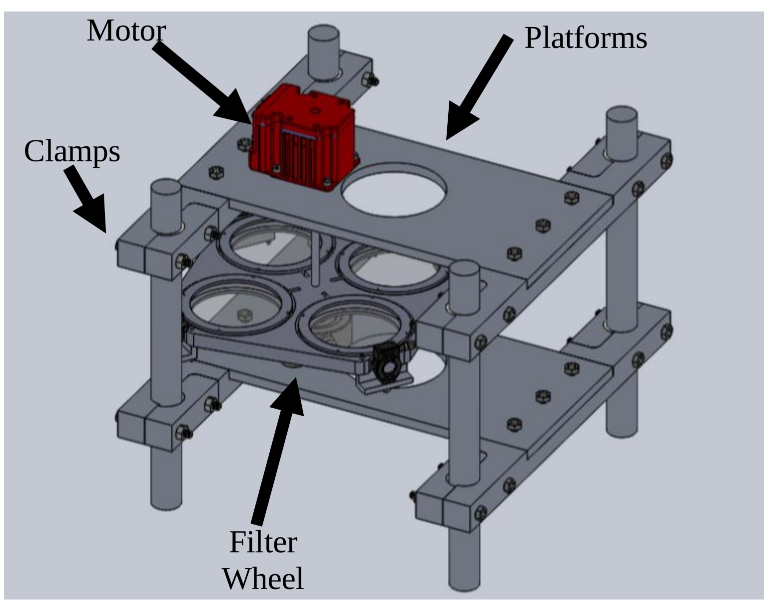


Figure 5.1. Isometric View of Main Assembly

The filter wheel subassembly contains the filter wheel itself, shaft coupling, PRM05 for precision tilting, bracket for the rotation mount, top and bottom of the filter holders, and shaft for the filter holders. The filter wheel will hold the top and bottom of the filter holders. The filter holders will hold the filters inside of them. The filter wheel will then rotate to center the filter that is needed. The PRM05 rotation mount is a product of ThorLabs and will provide the precision tilting of the filter shafts. This will allow the shaft that connects to the filter holders to rotate and tilt the filters as needed. The bracket that attaches to the PRM05 will hold the rotation mount in place so that it can be installed, used for calibration purposes, and then locked in place for regular use. This subassembly can be seen in Figure 5.2. The link to this specification sheet and those for other purchased materials are included in Appendix G.

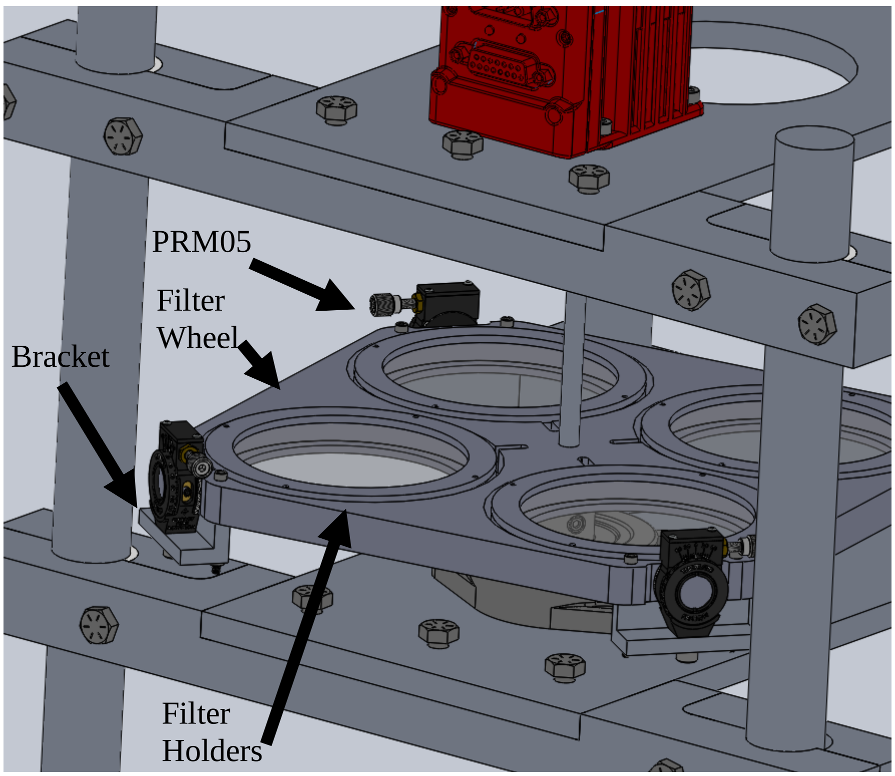


Figure 5.2. Filter Wheel Subassembly

Although the design does include a thermal enclosure, this is not included in the detailed drawings since the exact specifications will not be determined until after thermal testing has been done. The basic idea for the thermal enclosure is shown in Figure 5.3. The enclosure will be made of sheet metal that will be cut and bent to fit and then bolted together.

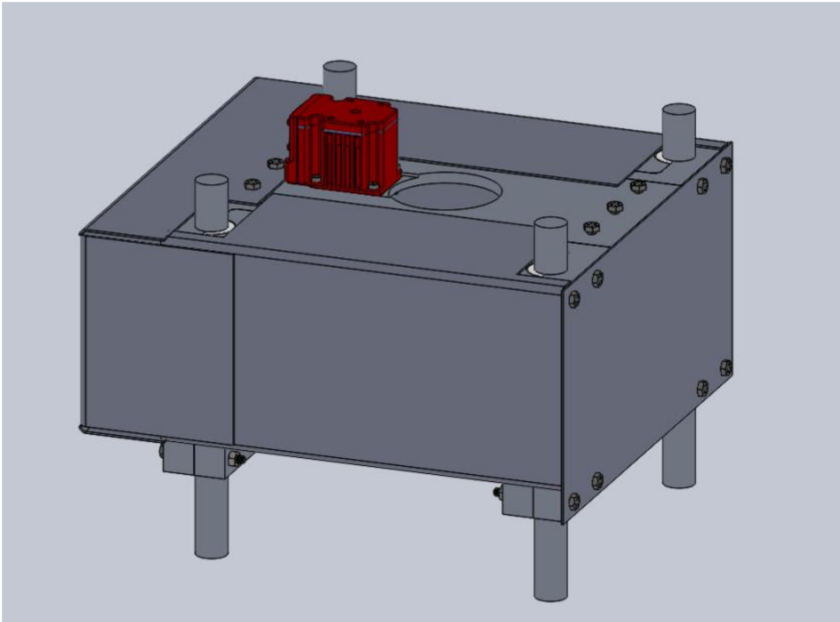


Figure 5.3. Thermal Enclosure

The platform subassembly consists of the clamps, the top and bottom platforms, and the rubber. This subassembly can be seen in Figure 5.4. The clamp works by bolting together and squeezing the poles with a small piece of rubber on one half of the clamp. The platforms will then be bolted to the clamps.

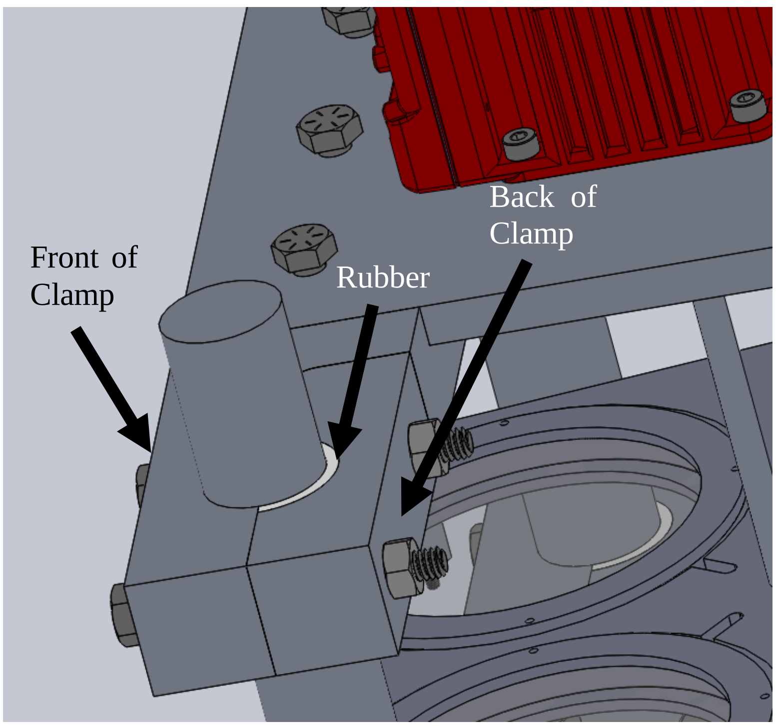


Figure 5.4. Clamp Subassembly

The motor subassembly consists of the coupling, shaft, motor, and the bearing. This subassembly is shown in Figure 5.5.

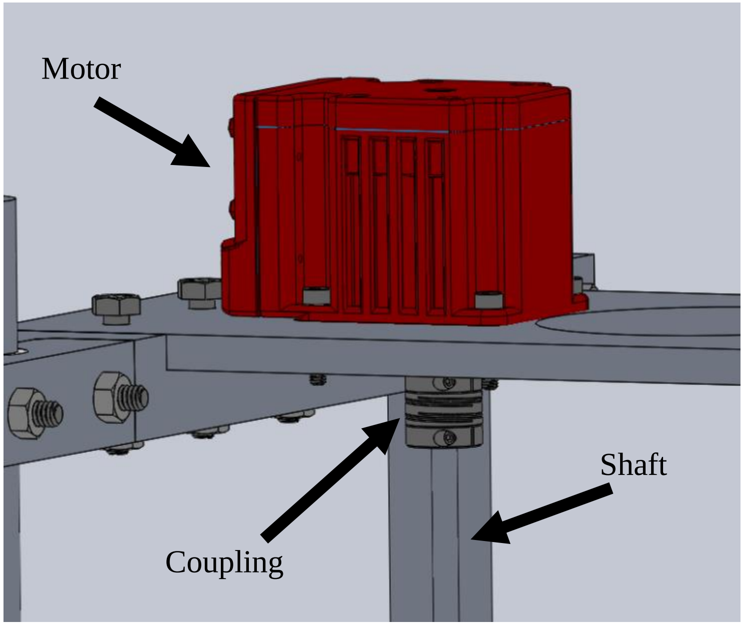


Figure 5.5. Motor Subassembly

A top view of the entire design is shown in Figure 5.6. This photo also shows the platform and how the active filter will align with the hole in the platforms.

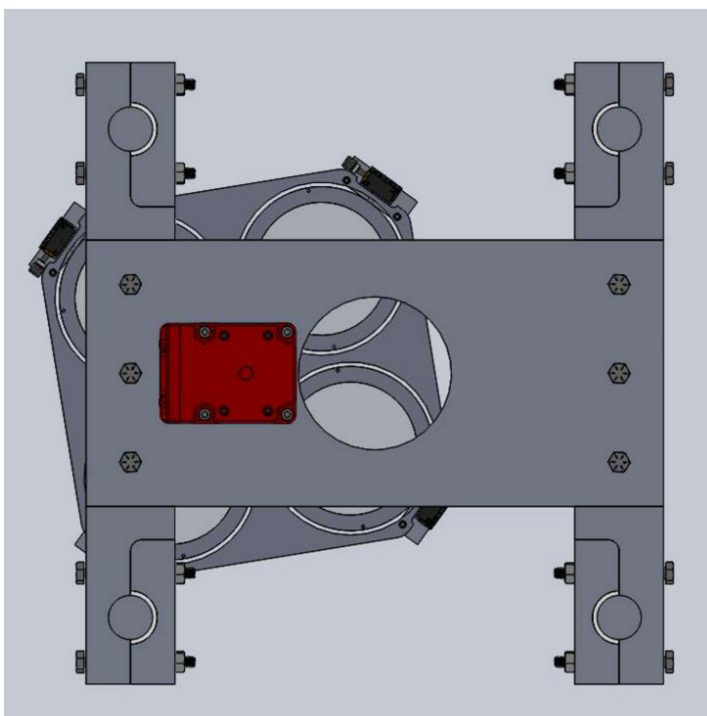


Figure 5.6. Top View of Platforms

While the design does require a motor, the wiring is trivial and still uncertain due to the placement of the design in a larger assembly. Wiring diagrams have been left out and deemed unnecessary. Additionally, no software is required for this design.

The final design was manufactured and assembled. It is pictured in Figure 5.7.

Figure 5.7. Final Prototype

This prototype does not include the sheet metal that will be added to form the thermal enclosure. Additionally, for this final design, many of the bolts that can be seen in the earlier iterations of the CAD have been replaced by tapped holes and screws.

5.1 Design Specifications

The final design fulfills all project specifications in a safe and cost-effective manner. The indented bill of materials for this design is shown in Appendix H, and the detailed drawings are included in Appendix I.

The design fits well within the limits of the size constraint, and the filter wheel clears the poles that the design clamps on to. The precision needed for the filter tilt is also achieved using the PRM-05 from Thorlabs which allows tilt changes of 10 arcmin. The active filter is also properly centered within the ±3 mm requirement, with consideration for tolerance stack-ups. A tolerance stack-up which consists of 0.005” stacked three times gives a maximum deviation of about 0.4 mm which is well within the requirement. The filter holds the required size of filters therefore meeting this specification.

While no loads are provided within the specifications and the low weight and rotation velocity of the system makes it unlikely for any system failures due to loading, a load case on the filter wheel was inspected. The results are shown in Figures 5.8 and 5.9. As shown in Figure 5.8, the deflection was a maximum of about 0.001 inches with point loads of 25 lbs. In Figure 5.9, the factor of safety for the filter wheel was over 15 with the same loading as before. This further confirms that the strength of the design is not a concern moving forward. Aluminum 6061-T6 will be used for the filter wheel and the rest of the system due to its light weight, beneficial mechanical properties, and relatively cheap cost.

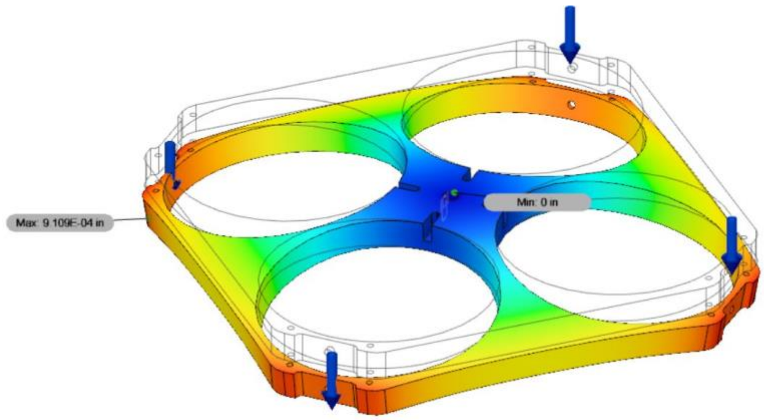


Figure 5.8. Deflection Test of the Filter Wheel

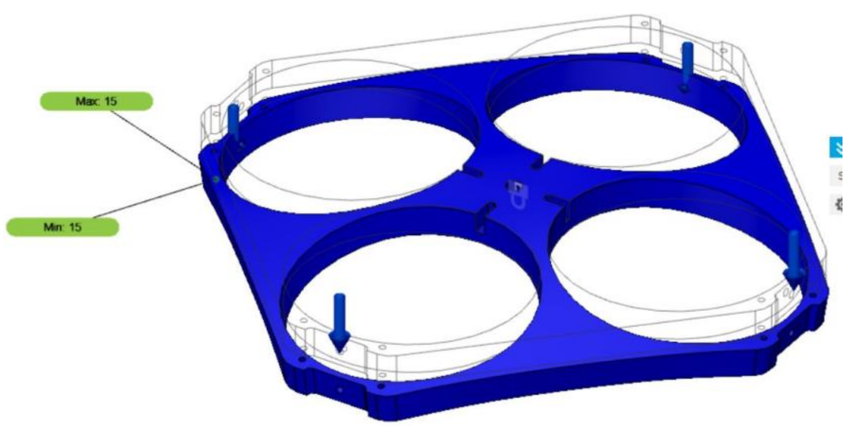


Figure 5.9. Strength Test of the Filter Wheel

The last specifications included within the design are the maintenance life cycle and temperature stability. The maintenance life cycle will still be empirically determined from testing and the temperature stability will also be determined from testing an insulated aluminum box with heating pads. However, preliminary calculations in Appendix J show that the design should be able to achieve the thermal stability specification.

In order to test the strength of the main shaft the team opted to analyze it using FEA. The failure mode examined was the case in which one of the PRMs were to get caught on one of the four poles. In this case the motor would be applying all of its available torque directly to the shaft. The team wanted to see if this torsion force would fracture the shaft. The figure below shows that even with a force applied with a two times safety factor, the max stress on the shaft is an order of magnitude below yield.

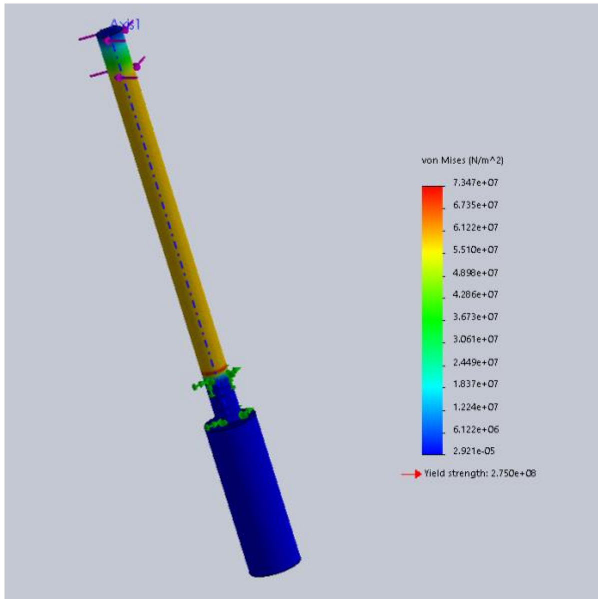


Figure 5.10. Strength Test of the Main Shaft

5.2 Design Safety Maintenance and Repair

To ensure that the design operates safely within the larger assembly a Failure Modes and Effects Analysis (FMEA) is included in Appendix K. All potential failure modes are quantified and tied to a specific system or function within the design. Preventative actions have been developed to mitigate these potential failures and ensure that all that can be done is done to create a robust design. Methods to enhance the safety of the design are provided in Appendix F.

The design has been made with the intention of easy assembly and disassembly with the use of screws to connect components together. This allows for easy maintenance and repair when a component is broken or needs to be replaced. The gap between the upper and lower bridges was sized to enable hands within the design to make any necessary modifications to the assembled system.

5.3 Design Cost Analysis

The cost of the design is calculated using a cost analysis in Appendix L. Note that the motor shows a cost of $0 because this was received at no cost. The cost of the project did surpass the budget at a total of $5,018. Since this is the prototype, Dr. Harding approved the project cost. Moving forward, some of the components can be reused again, such as the motor and the PRM05. Those were some of the more expensive components, so reusing them would reduce the cost of the next system by around $1,000.

The next section will detail the manufacturing of the final prototype.

6.0 Manufacturing Plan

The smart motor was purchased from Moog Animatics. The PRM-05 was purchased from Thorlabs. Components such as bolts, nuts, bearings, and any standard sized shafts were all sourced from McMaster-Carr, but equivalent components could be purchased from other vendors to be used in the final product. The stock aluminum 6061-T6 that will be used to machine most of the filter wheel can be procured from any vendor as well.

The machine shop at SSL will be manufacturing and assembling the parts for the filter wheel. It is expected that the main filter wheel and top platform will be machined using a CNC machine; however, SSL will be free to determine the manufacturing method that they will use to create the parts. The parts for the final prototype were outsourced to be manufactured by E&S Precision Machining Inc. because the machine shop at SSL was not going to be able to complete the parts within the necessary timeframe. The cost of the machined parts can be found in the final budget in Appendix L. For the verification prototype, the parts were assembled by the team.

Assembly instructions have also been provided in Appendix M. This filter selector assembly is split up into three main subassemblies. The first subassembly includes the four clamps which attach to the frame, and the bridges which extend from one clamp assembly to the other. The second subassembly involves the filter wheel itself along with the filters and the filter holders. The final subassembly is the vertical motor and shaft assembly which joins the two clamping assemblies and holds the filter wheel in place.

The next section will detail the design verification plan and the necessary testing procedures.

7.0 Design Verification Plan

In order to verify the final design of this optical filter selector system, the full system, vital subsystems, and specific components all need to be verified through testing. The types of tests and their purposes stem from the specifications table, Table 4. This table lays out the design requirements presented as specifications that the design needs to meet. The design presented in this report was chosen in order to satisfy these specifications, however, the design must be tested to confirm that it is satisfactory. The majority of the specifications tabulated will be tested, however the 7th specification, filter size, will not be tested as it is not something that the team has designed or has any control over. In addition to these specifications, three tests have been added to further validate the design, based on changes that have been made since the preliminary design review. These tests include a test of the clamping mechanism, a second thermal stability test (distinction between initial prototype and final design), and two adjustability tests to test the ease of tilting and replacing filters.

The remainder of this section will lay out a basic plan for each test in the DVR&P table presented in Appendix N, starting at the top of the table and working down.

In order to determine whether or not the system will fit within the restraints of the larger assembly, a test was completed on the fully built system. Since the size constraint is so tight, tests of concept prototypes were not sufficient to determine whether or not the size constraint was met. This is due to the larger tolerances that accompany rapid prototyping. Instead the team assembled the final prototype parts and used visual examination to determine whether the system fits within the space provided. If the system collided with its boundaries or if the team concluded that the space between the system and the boundaries is too small, < 2mm, then the test would have failed, and design changes would have needed to be made. However, the fit test, as outlined in Appendix O, was completed and the space between the system and the boundaries was acceptable for the given constraints. Because of this the final prototype of the design passed this test with a clearance of 3 mm as seen in Figure 7.1.

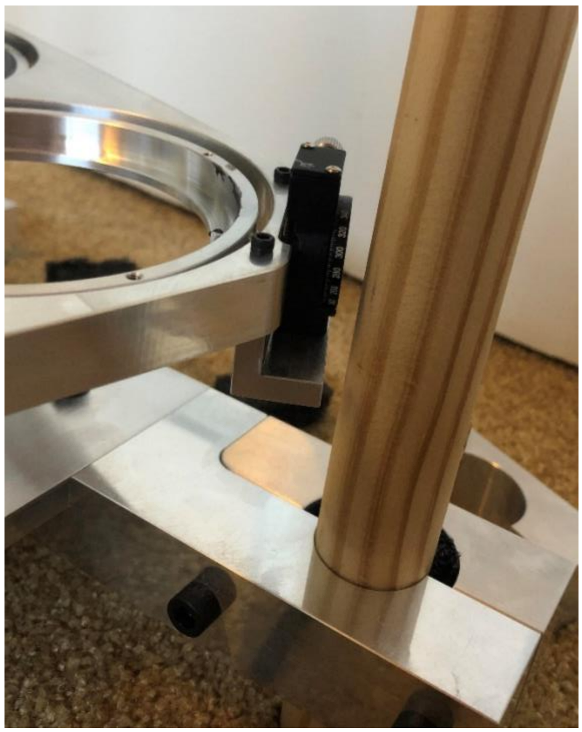
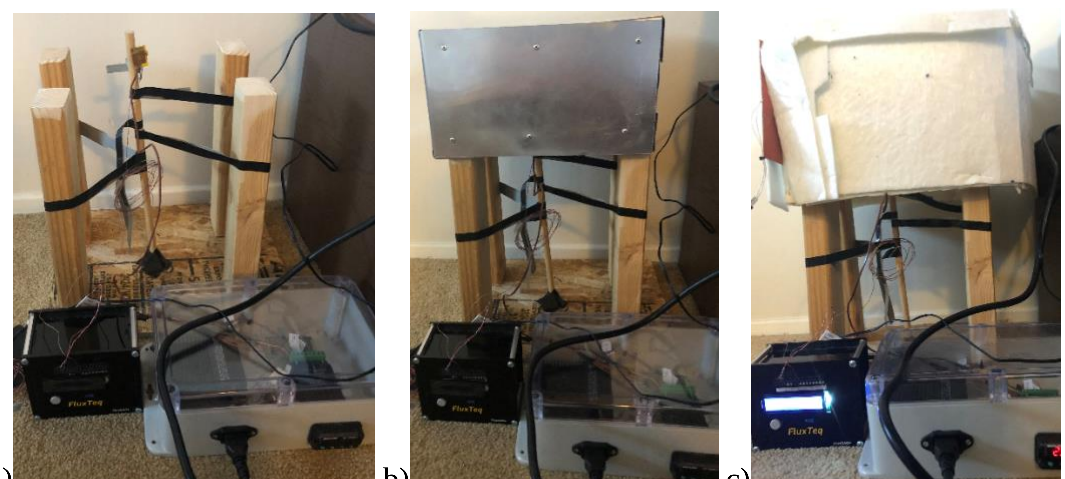


Figure 7.1. Clearance Achieved in Fit Test (3 mm)

One of the main requirements for this project was giving technicians the ability to accurately and repeatably tilt filters to collect the data they plan on acquiring. To do this, a tilting mechanism was designed with appropriate resolution; however, this functionality still needs to be tested. In order to test tilting, the filter wheel subassembly will need to be assembled with filter holders and filters in place. Next the rotation stage will be actuated, and the angle will be determined by eye. If the system seems to not be working properly then perhaps a sensor will be used to measure angular displacement. The failure modes for this test include; any catastrophic material or connection failure, inaccurate tilting, or insufficient tilting range.

The next three tests involve testing the system when it is fully assembled, minus the thermal stability. These tests are designed to see whether the system can perform its function for a lifecycle test. This test will be indicative of the real-life function of the device, as it will need to operate flawlessly for many months without maintenance. This test will require a room in which the system can run through 200,000 cycles which may take several days. The room will have to be able to supply the device with continuous power and must not be interrupted. The team may want to monitor the system with an external camera. Initial measurements of tilt angle, clamp height, filter position, and overall condition of the system will be recorded before the test is run. The test will have failed if; the angle of the tilt changes, the clamps slide down the poles, if the filters are not positioned centrally, or if any part of the system stops working or shows signs of imminent failure. The team was unable to complete this test since some of the equipment needed to run the motor did not arrive. An additional hinderance was that the team was not in the same city due to the last quarter being moved online. Therefore, the team at SSL will have to run the life test when the remaining parts arrive. Detailed instructions for this test are included in Appendix O.

A series of temperature stability tests will have to be passed in order to determine whether or not the specification of thermal stability is feasible. The first test, which is slated to happen in the first week of February, will be a concept test employing a mock-up of the area the system will occupy. This mock-up area will be built to closely mimic the conditions present in the final prototype. This test will allow the team to understand what it will take to achieve thermal stability. This test will require a sheet metal box with foam insulation and heating elements. It will also contain a data acquisition unit and thermocouple to track temperature over time. This test will fail once the team has exhausted all attempts to try and keep the box within 10 degrees Celsius. Most likely the team will have to iterate with different settings and configurations to determine the optimal layout for a thermal box. If this test proves that the concept of thermal stability for this system is possible then a subsequent test of the final prototype will determine if the first test is scalable. The actual system will have different results than the original test, so there will have to be more iteration to determine the optimal layout for the actual system. The test setup is shown in Figure 7.2.



a) b) c)

Figure 7.2. Thermal Test Set-Up
a) without thermal enclosure, b) with thermal enclosure, but without insulation, and c) with thermal enclosure and insulation

The test stand lifts the box off the ground in order to allow heat to escape from both the top and bottom holes that represent the holes that will exist in the final design to allow light to pass through. The dowel in the middle is slightly longer than the four corner posts so that the thermocouples taped to it will be approximately in the position that the active filter will be in. The two devices shown are a PID controller, that takes in temperature data from a thermocouple and controls the temperature of a heating pad, and a device to record the temperature from another thermocouple. Unfortunately, useful data was not able to be obtained both times that a thermal test was run with this setup. For the first test, Styrofoam was used as insulation because it was thought that it could be an inexpensive way to get initial data, but the Styrofoam contacting the heating pad began to melt before the temperature inside the box stabilized. For the second test, a composite paper insulation was used in place of Styrofoam, but this time the insulation was scorched where it touched the heating pad and began to smoke, so the test was cut short before useful data could be recorded. A more detailed document outlining the thermal test procedures can be found in Appendix O.

It is recommended that for future tests, SSL utilizes a more expensive type of insulation that they have used for thermal enclosures in the past. Additionally, the team believes that a more even heating inside the enclosure will result from heating pads being placed on all four sides of the thermal enclosure than with only one heating pad being used. Lastly, it is recommended that they use a controller that can be programmed to have a maximum temperature that the heating pad(s) is set to. This should prevent the heating pad from getting too hot and having a detrimental effect on the insulation contacting it.

A test of the clamps will be done to ensure that the entire system will stay suspended securely. This test will require a test stand that resembles the area in which the system will actually be placed. Weight will be added to the clamps until failure. This will allow the team to determine how the clamp fails, either material failure or displacement failure. If the clamp displaces more than .05 inches, then the test has failed.

The final two tests will be use tests. A technician will have to be able to easily and efficiently replace and tilt filters. This process must not only be possible, but it should also be straight forward and fast. This test can be running throughout the assembly process to allow for design change considerations; however, the final test will be done when the system is fully assembled. The final test will be considered a failure if the user is unable to tilt or replace any filter, or if they are unable to do it within a certain time period.

The next section will detail the project's overall process.

8.0 Project Management

The first steps for this project were to define the problem by performing the necessary background research and generating project requirements. This led to the definition of the scope of the project. Next, the creation phase began. This involved the ideation phase and creating concept models. The next phase involved evaluating ideas. To accomplish this, decision matrices, concept prototypes, and CAD were utilized. This phase ended with the preliminary design review where the basic design was presented to the sponsor. The design was specified by performing the necessary analysis, CAD, and creating a structural prototype. After this was the critical design review. After getting sponsor approval, the lab began the manufacturing of the design. The prototype was then be tested for safety and against the specifications as much as the current situation allowed and testing plans were created that will guide SSL in completing the remaining test. Finally, through the virtual design exposition, the team presented the final prototype and shared the work completed over the last 9 months. Table 5 highlights the major milestones on the project. Appendix P shows the Gantt chart for the project which shows the major milestones, the tasks leading to the milestones, and the timeline for the project.

For the design to be proven to be practical for use, the final prototype must pass a life test of 200,000 cycles. This test will be held at SSL and will also determine if the design can run autonomously while ensuring that the interface between the smart motor and the product works properly. In order to prepare for this test, extensive analysis was performed to ensure that the design can pass this test with no problems. To do this, hand calculations and software to test the strength and life of the product were implemented. There was also testing to see how often maintenance will need to be performed in order to keep the product in working condition. It is also required to design so that if part of the design fails, the filters will still be protected since they are fragile and expensive.

The lab at Berkeley will be purchasing all of the necessary materials. The concept prototype was 3D printed by the team, but the lab outsourced the manufacturing of the final prototype. The structural prototype was a thermal enclosure to be used for thermal testing.

Table 8. Project Schedule Overview

Deliverable	Description	Date
Scope of Work	Document describing the problem and project and defining the scope	10/18/2019
Preliminary Design Review	Presentation of the initial design	11/15/2019
Interim Design Review	Informal status update intended to receive feedback	1/16/2020
Critical Design Review	Presentation that includes final design, manufacturing plans, and testing plans	2/4/2020
Manufacturing and Test Review	Presentation to summarize the testing plan as well as update on the manufacturing status	3/12/2020
Final Design Review	Final report, prototype, and presentation of the project	5/29/2020

Since the last quarter of the project was virtual, some of the planned tests were not able to be performed. The life test could not be completed and although the team intended to run the thermal test, the insulation began smoking when the heating pads were on, so this test was not completed either. However, the parts were manufactured, and the system interface test verified that the parts fit together and that the system worked as intended. Moving forward, the team at SSL will have to run the life test and verify the thermal stability system by performing a thermal test.

For future projects the team would follow mostly the same process since it was successful. They would make sure to account for lead times of online orders and manufactured parts since it all took longer than expected. They would also reserve more time for the testing and assembly. Since this project had a clear design direction from the beginning, less time could have been spent in the ideation phase.

The next section will summarize this document and give the team's final recommendations.

9.0 Conclusion

This document outlined the research that was used to create a list of requirements that will fulfill the needs of the sponsor and the details of the final prototype. The main result of the research is that the list of requirements that need to be fulfilled are: a maintenance life of 200,000 cycles over 6 months, the ability to remotely position four filters, have a manufacturing cost of $4000 or less, and fit within the size constraint of 254 x 254 x 203.2 mm. After completing this research and understanding the problem, the design phase culminated with the chosen design. The process and design were detailed for approval. The chosen design consists of a simple filter wheel controlled by the smart motor with tilting mechanisms for each filter. The manufacturing and testing plan for the final design were created. With these the final prototype was constructed and tested.

9.1 Reflections

The team would like to use this section of the report to reflect on a few key points that capture the "lessons learned" from this project. Firstly, it was found that almost everything in a project takes longer than it is mapped out for. For instance, the team initially expected to have parts manufactured by an external source and shipped back in for building and testing. However, this process took a few weeks longer than expected. Similarly, when iterating designs to converge upon a final design, the process had many changes and took two to three weeks longer than expected. Allowing more time for tasks portrays the realities of working in an industry environment rather than an academic environment. When working on a project in an industry setting, adjustments need to be made for the timeline of a project.

It was also found that plans can constantly change, and the team and scope of the project must adapt to continue pushing the project towards completion. An instance of this occurred early on when developing the scope of the project. It was initially thought that temperature stability would not be a large concern to the project, but this changed to the point where it was critical. The team had to adapt their vision of the project as well as their approach to continue working on the project and create a successful product. With all projects, as the plans change the group must adapt to continue forward.

Lastly, the team found that the most forward movement for the project occurs when the team truly works as a team. As individuals, members of the team each have their weaknesses and skills. However, when the team is working together, the members cover the weaknesses of each other and contribute better work to the project.

9.2 Next Steps

There are several aspects of the design that deserve acknowledgment for future improvement. The first is the current design of the filter tilting. For the current design, a PRM05 is used for each individual filter to tilt and lock down the filter in the correct position. Because of this design choice, four PRM05s are required for each individual optical filter selector system. To reduce cost, it would be ideal to use a single PRM05 for each system to finely tilt a filter and then use a separate mechanism to lock it in place. The team was unable to develop a locking mechanism that could hold the filter in place at the required precision, so the PRM05 was used.

Another aspect of the design that could be improved is the manufacturing tolerances that are tied to each part. The team does not have enough manufacturing experience to inform a decision of how loose tolerances can be set on a part. However, the looser these tolerances are the cheaper the end product will be. Loosening tolerances on the parts that compose the design would reduce the manufacturing cost of the project.

In hand with loosening tolerances on the design as a whole, the gap that the upper and lower platforms fit into should be updated to be wider. This was initially a design choice to help fit the platform into place within the system. However, the platform screws will lock the platform into the proper place making the tight fit for the platforms unnecessary. The tolerance on the size of this gap could be significantly lowered to reduce manufacturing cost.

Another tolerance issue arose when using the clamps to attach the system to the four surrounding poles. The clamp blocks have cutouts for the insertion of rubber when being tightened to the locating clamp. This would compress the rubber generating a clamping force on the surrounding poles of the system. More research needs to be done into the type of rubber to use as well as the thickness of the rubber to provide an appropriate clamping force. The team believes this would improve the clamps and add to their reliability.

A design improvement that could also be made would be to change the bolts used for the motor and bearing to screws with tapped holes in the platform. The team struggled to find the appropriate hardware to fit the required specifications of the motor and the bearing and as such chose bolts. While the bolts are sufficient, they still present a risk of dropping out of the system that screws do not. Switching from bolts to screws in this part of the design would improve the system by minimizing the risk of harm to external systems.

Lastly, the largest improvement for the design would be the development and testing of a thermal enclosure. The team developed a thermal enclosure that is believed to work; however, testing was never conducted on the thermal enclosure due to untimely circumstances. The robustness of the design still needs to be verified through the life test, which SSL will have to complete.

Regardless of the next steps to be taken for the design, the team believes that this document presents a holistic approach to developing a filter selector for the given constraints. The team is thankful for all those at Cal Poly and SSL who have helped in not only the development of the project, but the personal development of the team members as well.

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Appendix A: SmartMotor Spec Sheet

SM23165DT Specifications

SM23165DT		
Continuous Torque	4.61	in-lb
	74	oz-in
	0.52	N-m
Peak Torque	7.40	in-lb
	118	oz-in
	0.84	N-m
Nominal Continuous Power	204	Watt
No Load Speed	5,200	RPM
Max. Continuous Current* @ 3800 RPM	5.074	Amps
Peak Power @ 3400 RPM	210	Watts
Voltage Constant	9.08	V/kRPM
Inductance	1.31	mH
Encoder Resolution	4,000	Counts/Rev
Rotor Inertia	0.001	oz-in-sec^2
	0.706	10^{-5} Kg-m^2
Weight	1.3	lb
	0.59	kg
Shaft Diameter	0.250	in
	6.35	mm
Shaft, Radial Load	7	lb
	3.18	kg
Shaft, Axial Thrust Load	3	lb
	1.36	kg
DeviceNet Available	Yes	
PROFIBUS Available	Yes	
CANopen Available	Yes	

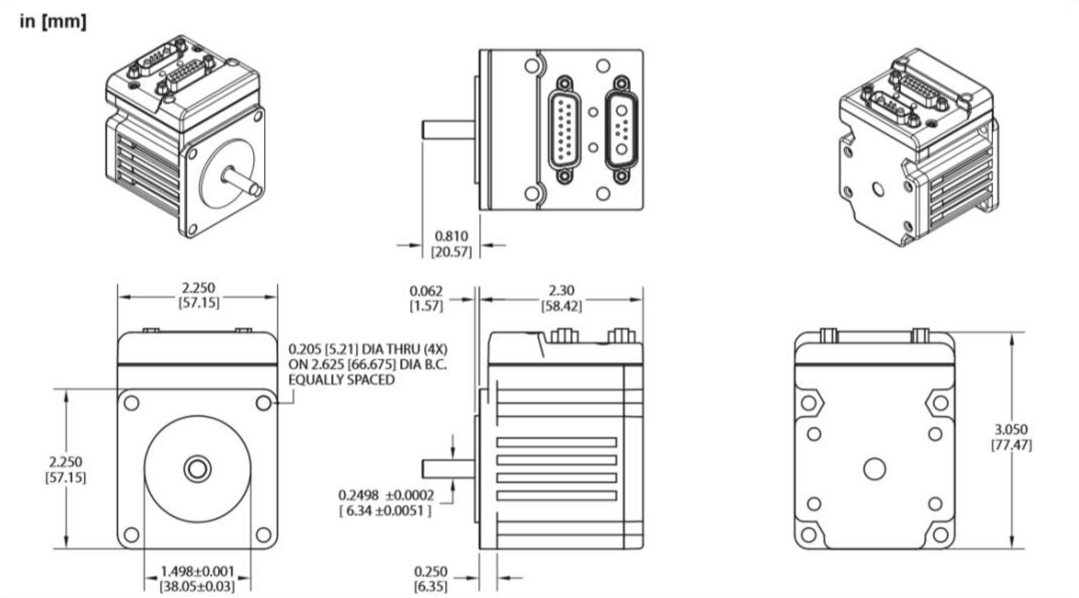
*Default voltage is 48V. See graphs for additional voltages.

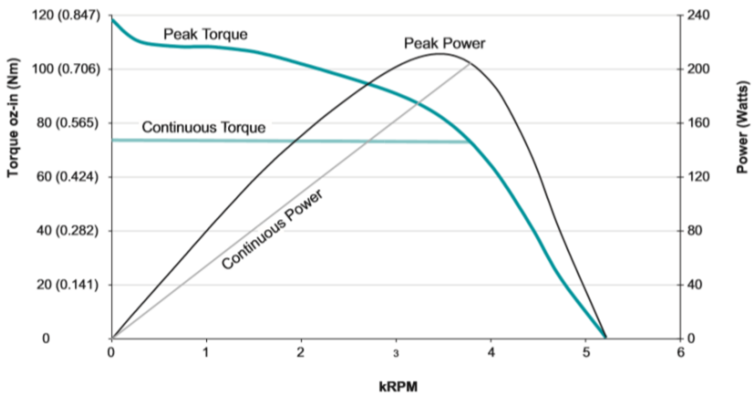
Operating temperature range: 0°C–85°C

Storage temperature range: -10°C–85°C, noncondensing

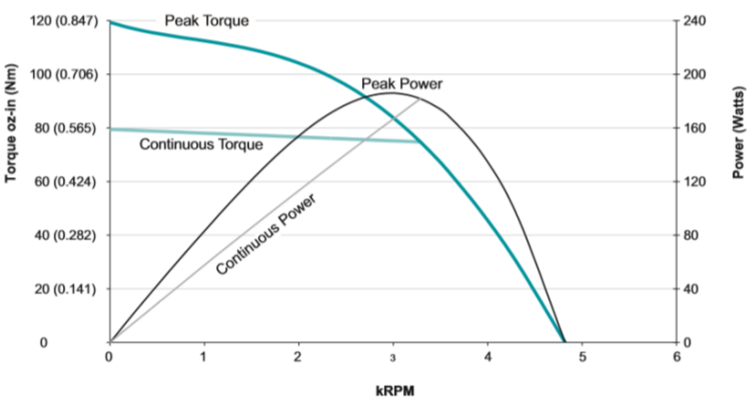
NOTE: Motor specifications are subject to changes without notice. Consult website and factory for latest data.

Moog Animatics SmartMotor™ SM23165DT (No Options) CAD Drawing

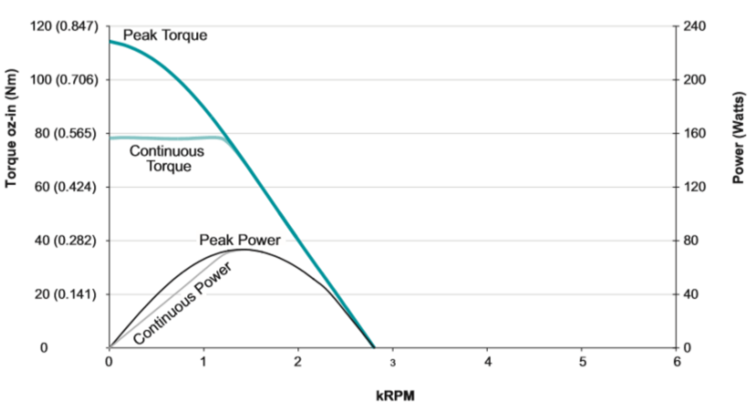




SM23165DT
at 48 VDC
at rise to 85°C



SM23165DT
at 42 VDC
at rise to 85°C



SM23165DT
at 24 VDC
at rise to 85°C

All torque curves based on 25°C ambient.

Motors were operated using MDT (Trapezoidal Drive Mode) Commutation.

For ambient temperatures above 25°C, Continuous Torque must be linearly derated to 0% at 85°C.

Appendix B: QFD

Correlations	
Positive	+
Negative	−
No Correlation	

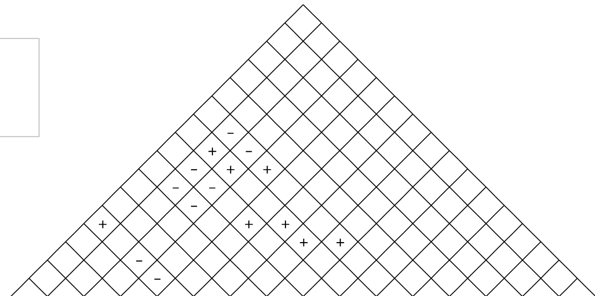
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Optical Filter Selector

Revision Date: 10/16/2019



Row #	Weight Chart	Relative Weight	SSL Scientists	Manufacturers	Maintenance Workers		Maximum Relationship	WHAT: Customer Requirements (Needs/Wants)
1		8%	7	3	3		9	fits into available space
2		5%	10	1	1		9	ability for filters to tilt
3		9%	7	2	8		9	robust
4		5%	9	1	1		9	low cost
5		9%	7	1	10		9	easy to change filters
6		9%	7	1	10		9	easy to perform maintenance
7		10%	10	1	10		9	secure connections
8		8%	5	1	10		9	easy to install/uninstall
9		15%	1	10	1		9	manufacturability
10		6%	10	1	3		9	easy to use
11		9%	10	1	8		9	autonomous
12		5%	10	1	1		9	filter location

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Direction of Improvement	▼	◇	▼	▲	▼	▼	▼	▲	▲	▲	◇					
HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	size	total tilt angle	tilt angle increments	lifecycle	cost	time to change filters	time to do maintenance	FEA	Manufacturability Survey	User Survey	Run Test for Life					
fits into available space	●															
ability for filters to tilt		●	●													
robust				●				●			●					
low cost					●				○							
easy to change filters						●										
easy to perform maintenance							●									
secure connections								●			●					
easy to install/uninstall	▽						●									
manufacturability	▽								●							
easy to use										●						
autonomous											●					
filter location		○	○					●			●					
HOW MUCH: Target Values	10" x 10" x 7'	0-10 degree	0.2 degree steps	2 million cycles	$4,000	quick and easy (<3mins)	quick and easy (<3mins)	Filter location within ± 5mm	Easy to manufacture. Minimize parts	How easy to use?	Passes "life test"					
Max Relationship	9	9	9	9	9	9	9	9	9	9	9					
Technical Importance Rating	96.7	65.74	65.74	83.94	46.08	80.54	154.6	223.5	148.1	58.39	304.6	0	0	0	0	0
Relative Weight	7%	5%	5%	6%	3%	6%	12%	17%	11%	4%	23%	0%	0%	0%	0%	0%
Curr. Products: SSL has no current product	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A					
Curr. Products: Motorized wheel	2	0	0	3	5	2	2	5	3	4	N/A*					
Curr. Products: 5-position Multi Selector	2	0	4	5	4	4	4	5	5	2	N/A*					
Curr. Products: Fast Indexing Wheel	4	1	5	4	4	3	3	5	2	2	N/A*					
Curr. Products: Filter Selector System	5	5	2	1	4	3	3	5	3	3	N/A*					
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

NOW: Curr. Products	SSL has no current product	*Motorized wheel*	5-position *Multi Selector*	*Fast Indexing Wheel*	*Filter Selector System*	Row #
	N/A	2	3	1	5	1
	N/A	0	1	2	4	2
	N/A	0	4	0	2	3
	N/A	3	4	3	5	4
	N/A	5	3	4	3	5
	N/A	2	4	4	3	6
	N/A	2	3	3	4	7
	N/A	5	5	5	5	8
	N/A	4	2	3	5	9
	N/A	3	3	3	2	10
	N/A	1	1	1	1	11
						12

* data was unable to be found for life tests for current products and it would be prohibitively expensive to purchase each product and test them

Appendix C: Idea List

Filter Selection

- A filter that can change color
- Vertical filter wheel
- Little arms
- Linear movement
- Straight filter wheel
- Magnets
- Individual motors
- Pivots
- Pendulum
- Stacking filters
- Some obscure 3D array of filters
- Fold down into middle
- Super-filter
- Pulleys
- Cut filters into pieces
- Filter wheel
- Filters on slide
- Filter sphere
- Mirrors
- Quarter wheel
- Centrifugal spinner
- Filter mill
- Gears
- Filter pyramid
- Conveyor belt
- Smaller filters
- Filter flipper
- Ring toss
- Set screws

Temperature Stability

- Small heater
- Insulation
- Fans
- Heated coils
- Refrigeration
- AC unit
- Water cooling system with pipes
- Steam

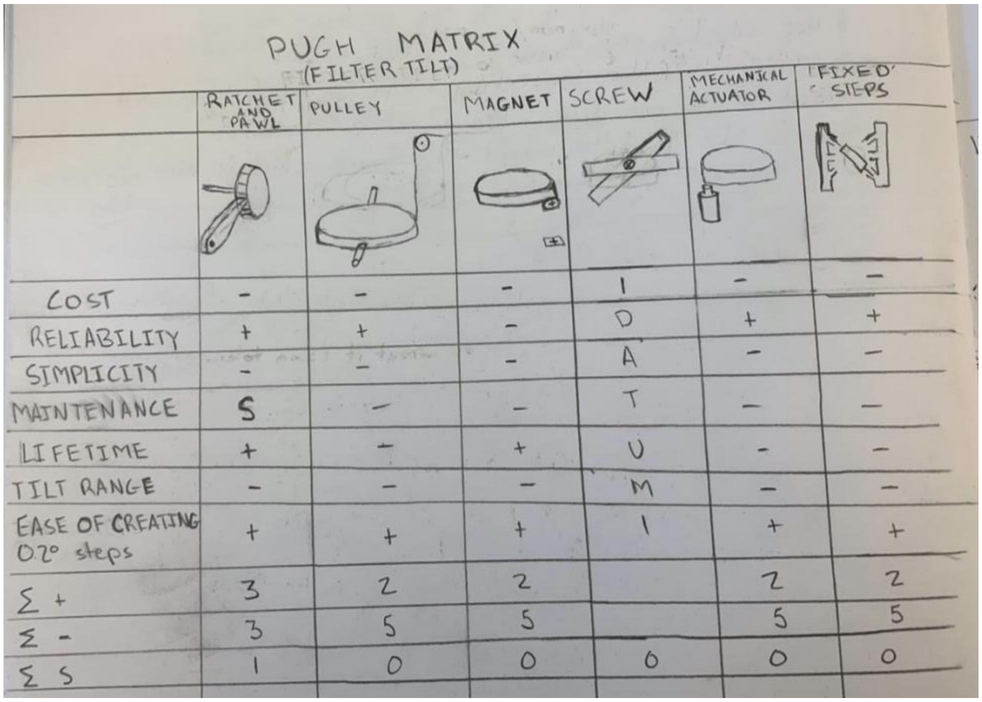
Filter Rotation

- Set screws
- Latching system
- Push on one side
- Pulley
- Magnetic steps
- Gears
- Pressurized lifts
- Differential magnet
- Notches
- Gears continuous stuff
- Bearings that lock/unlock
- Ratchet
- Screws on one side
- Hooks
- Hinges
- Micrometer
- Linear thing tilts
- Use vertical wheel
- Screw holds in place
- Adjustable legs
- Steps
- Electronic level
- Laser leveler
- Magnets
- Stepper motor
- Filters click into spaces
- Tilt the whole thing
- Filters tilt freely and lock into space
- Solenoid pushes on one side
- Control tilt with expansion due to heat

Connection to Poles

- Hose clamps
- Vise
- Bolted Clamps
- Weld plate
- Bike Seat Pole Clamp
- Velcro strap
- Bolt into pole
- Pinch grip
- Duct tape
- Bracket Clamp
- Set Screws

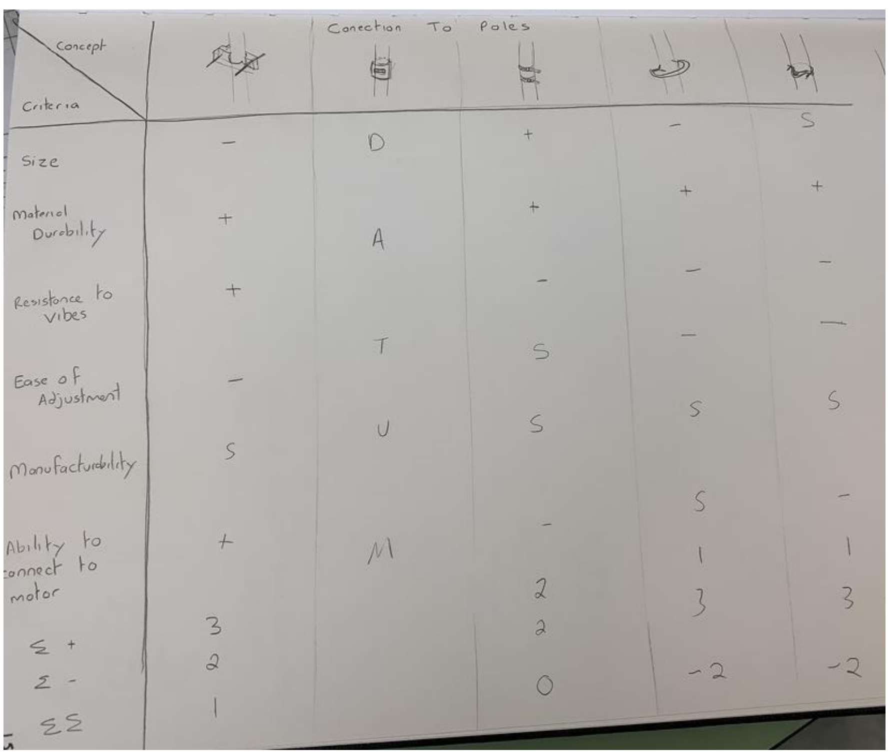
Appendix D: Pugh Matrices



PUGH MATRIX (FILTER TILT)

	RATCHET AND PAWL	PULLEY	MAGNET	SCREW	MECHANICAL ACTUATOR	"FIXED" STEPS
COST	-	-	-	|	-	-
RELIABILITY	+	+	-	D	+	+
SIMPLICITY	-	-	-	A	-	-
MAINTENANCE	S	-	-	T	-	-
LIFETIME	+	-	+	U	-	-
TILT RANGE	-	-	-	M	-	-
EASE OF CREATING 0.2° steps	+	+	+	|	+	+
Σ +	3	2	2		2	2
Σ -	3	5	5		5	5
Σ S	1	0	0	0	0	0

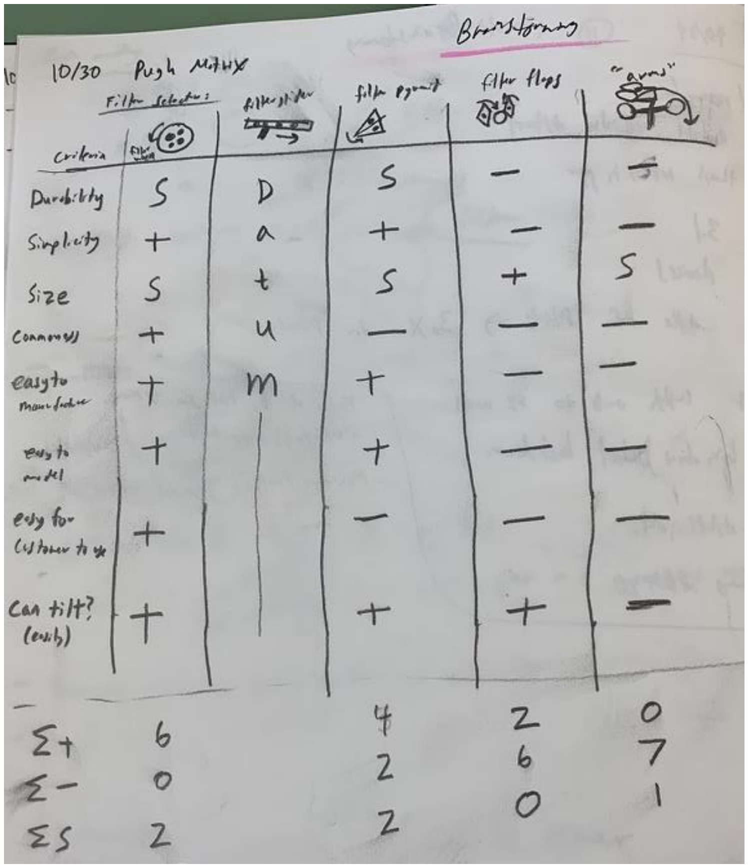
Filter Tilt Pugh Matrix



Conection To Poles

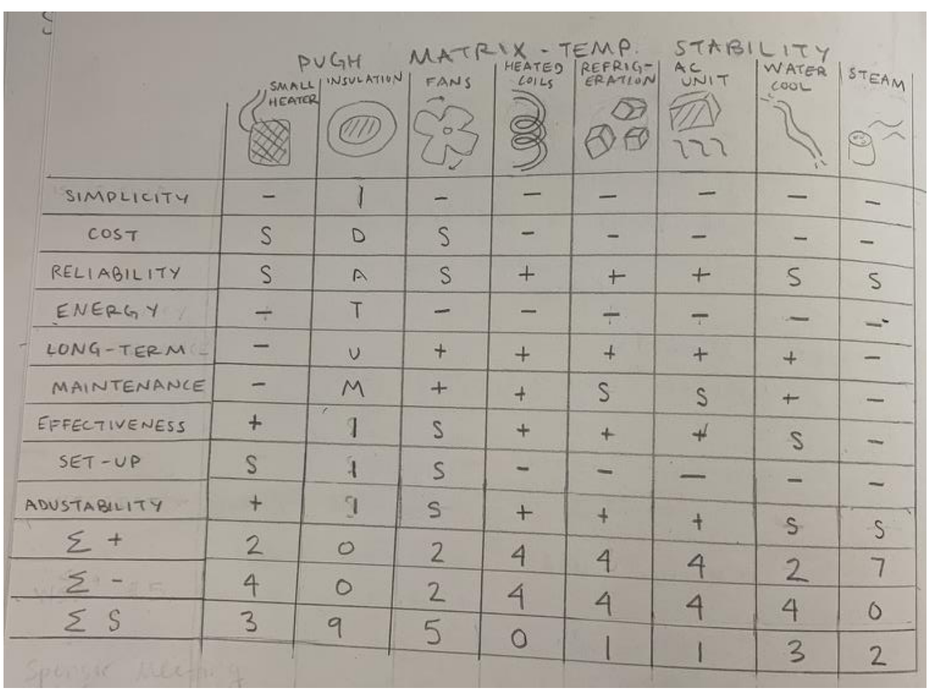
Concept / Criteria					
Size	-	D	+	-	S
Material Durability	+	A	+	+	+
Resistance to vibes	+	T	-	-	-
Ease of Adjustment	-	U	S	-	—
Manufacturability	S	M	S	S	S
Ability to connect to motor	+		-	S	-
Σ +	3		2	1	1
Σ -	2		2	3	3
Σ S	1		0	-2	-2

Connection to Poles Pugh Matrix



Criteria	Filter selector	filter slider	filter pyramid	filter flaps	"arms"
Durability	S	D	S	−	−
Simplicity	+	a	+	−	−
Size	S	t	S	+	S
Commonness	+	u	−	−	−
easy to manufacture	+	m	+	−	−
easy to model	+		+	−	−
easy for customer to use	+		−	−	−
Can tilt? (easily)	+		+	+	−
Σ+	6		4	2	0
Σ−	0		2	6	7
ΣS	2		2	0	1

Filter Selection Pugh Matrix



	SMALL HEATER	INSULATION	FANS	HEATED COILS	REFRIGERATION	AC UNIT	WATER COOL	STEAM
SIMPLICITY	−		−	−	−	−	−	−
COST	S	D	S	−	−	−	−	−
RELIABILITY	S	A	S	+	+	+	S	S
ENERGY	−	T	−	−	−	−	−	−
LONG-TERM	−	U	+	+	+	+	+	−
MAINTENANCE	−	M	+	+	S	S	+	−
EFFECTIVENESS	+		S	+	+	+	S	−
SET-UP	S		S	−	−	−	−	−
ADJUSTABILITY	+		S	+	+	+	S	S
Σ +	2	0	2	4	4	4	2	7
Σ −	4	0	2	4	4	4	4	0
Σ S	3	9	5	0	1	1	3	2

Temperature Stability Pugh Matrix

Appendix E: Hand Calculations

Whirling Failure Spreadsheet:

	shaft inputs				Calculated Shaft Properties					rad/s	rpm
	gravity (m/s^2)	9.81			mass/length (kg/m)	0.632245522			whirling of shaft	19550	186689
	shaft length (cm)	8			moment of inertia(m^4)	4.90874E-10			whirling of weights (no shaft)	4157.96	39705.56
	shaft diameter(cm)	1							Dunkerleys	4066.99	38836.9
	density (kg/m^3)	8050									
	elastic modulus (Gpa)	207									
	Weights				influence coefficient matrix (m/N)						
	location(cm)	weight(N)		1.04976E-07	0	0					
x1	4	5.40531		0	0	0					
x2	0	0		0	0	0					
x3	0	0									
					Deflections						
b1	4				y1	5.67426E-07					
b2	8				y2	0					
b3	8				y3	0					
a1	4										
a2	0										
a3	0										

Ratchet Gear Train:

$\theta_F \leq 0.2°$ (angle that the filter shaft turns for each tooth on the ratchet gear)

$N_R = 100$ (# of teeth on ratchet gear) ← max I could find on 2 catalogs. Maybe can go larger!

$\theta_R = \frac{360°}{N_R} = \frac{360°}{100 \text{ teeth}} = 3.6°/\text{tooth}$ (angle that the ratchet gear turns per tooth)

N_G = (# of teeth on gear - connected to filter shaft)

N_P = (# of teeth on pinion - connected to ratchet shaft

$$\theta_F = \frac{N_P}{N_G}\theta_R$$

$$\frac{N_G}{N_P} = \frac{\theta_R}{\theta_F} = \frac{3.6°}{0.2°} = 18$$ ← need a gear ratio of 18

Encoder Resolution:

$$\frac{1\text{ rev}}{4000\text{ counts}}\left(\frac{360°}{\text{rev}}\right) = 0.09\,°/\text{count}$$

$\tan\theta = \frac{d}{x}$

$x = d\tan\theta$

$= (70.65\text{ mm})\tan(0.09°)$

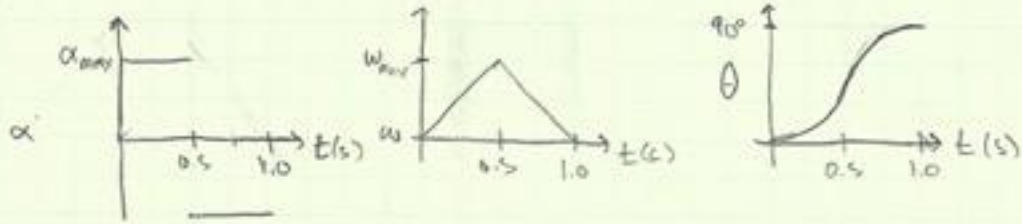
$x = 0.111\text{mm}$

For each count of the encoder, the wheel will rotate 0.09° which corresponds to a position change of 0.111 mm at the center of the Filter.

$$SF_{position} = \frac{1.5\text{mm}}{0.111\text{mm}} = 13.5$$

Rotation Time: Want 1 sec for 90° rotation

If we have the motor accelerate for 0.5 sec then decelerate for 0.5 sec what does the acceleration need to be?



Need to get 45° rotation during acceleration if acceleration & decceleration are symmetric

$$\alpha = \frac{d\omega}{dt} \qquad \omega = \frac{d\theta}{dt}$$

$$\int_0^{0.5s} \alpha \, dt = \int_0^{\omega_{max}} d\omega \qquad \int_0^{0.125rev} d\theta = \int_0^{0.5s} \omega \, dt$$

$$(0.5s)\alpha_{max} = \omega_{max} \longrightarrow 0.125 rev = \tfrac{1}{2}(0.5s)(\omega_{max})$$

$$0.125 rev = \tfrac{1}{2}(0.5s)(0.5s)\alpha_{max}$$

$$\alpha_{max} = \frac{0.125 rev}{\tfrac{1}{2}(0.5s)(0.5s)}$$

$$\alpha_{max} = 1 rev/s^2 = 2\pi \, rad/s^2$$

$$\omega_{max} = (0.5s)\alpha_{max} = (0.5s)(1 rev/s^2)$$

$$\omega_{max} = 0.5 rev/s = 30 rpm$$

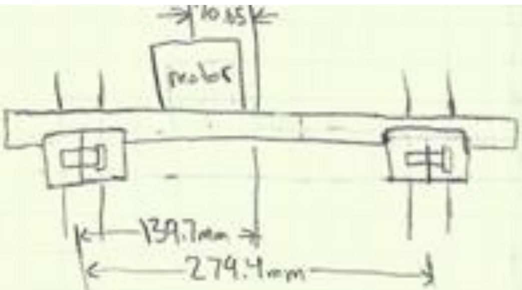
From Solidworks: $I = 2.2843 \times 10^{-3} \, kgm^2$

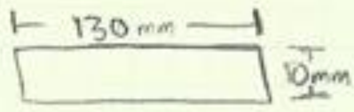
$$T = I\alpha = (2.2843 \times 10^{-3} \, kgm^2)(2\pi \, rad/s^2)$$

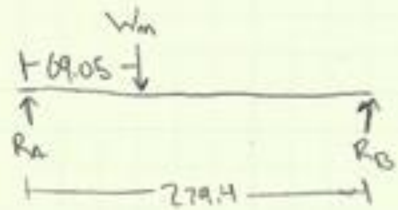
$$T = 0.0144 \, Nm$$

Even for worst case scenario of running at 24 VDC
$T_{stall} = 0.847 \, Nm$

$$SF_{torque} = \frac{T_{stall}}{T} = \frac{0.847}{0.0144} = 58.8$$







$W_m = (0.59\text{ kg})(9.81\text{ m/s}^2)$

$W_m = 5.788\text{ N}$

Using Excel Spreadsheet: $R_A = 4.38\text{ N}$

$R_B = 1.43\text{ N}$

Max moment ≈ 300 Nmm

$C = 5\text{ mm}$

$I = \frac{1}{12}(130\text{ mm})(10\text{ mm})^3$

$I = 10833\text{ mm}^4$

$\sigma = \frac{Mc}{I} = \frac{(300\text{ Nmm})(5\text{ mm})}{10833\text{ mm}^4}$

$\sigma = 0.1385\text{ N/mm}^2$

Von Mises: $\sigma' = (\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2)^{1/2}$

$\sigma' = \sigma$

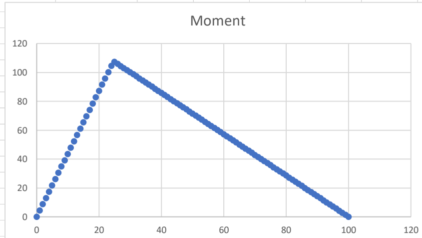
For 1018 annealed steel: $S_y = 220\text{ MPa}$

$n = \frac{S_y}{\sigma'} = \frac{220\text{ MPa}}{0.1385\text{ MPa}}$

$n = 1589$

Beam Bending Spreadsheet:

	magnitude	location
F1	5.788	24.714
F2	0	55
F3	0	78
q	0	
start	30	
stop	70	
Ra	4.357554	
Rb	1.430446	



	mag	loc
max moment	107.2835	25

x	Moment
0	0
1	4.357554
2	8.715107
3	13.07266
4	17.43021
5	21.78777
6	26.14532
7	30.50288
8	34.86043
9	39.21798
10	43.57554
11	47.93309
12	52.29064
13	56.6482
14	61.00575
15	65.36331
16	69.72086
17	74.07841
18	78.43597
19	82.79352
20	87.15107
21	91.50863
22	95.86618
23	100.2237
24	104.5813
25	107.2835
26	105.853
27	104.4226
28	102.9921
29	101.5617
30	100.1312
31	98.7008
32	97.27035
33	95.8399
34	94.40946
35	92.97901
36	91.54856
37	90.11812
38	88.68767
39	87.25723
40	85.82678
41	84.39633
42	82.96589
43	81.53544
44	80.10499
45	78.67455
46	77.2441
47	75.81365
48	74.38321
49	72.95276
50	71.52232
51	70.09187
52	68.66142
53	67.23098
54	65.80053
55	64.37008
56	62.93964
57	61.50919
58	60.07875
59	58.6483
60	57.21785
61	55.78741
62	54.35696
63	52.92651
64	51.49607
65	50.06562
66	48.63517
67	47.20473
68	45.77428
69	44.34384
70	42.91339
71	41.48294
72	40.0525
73	38.62205
74	37.1916
75	35.76116
76	34.33071
77	32.90027
78	31.46982
79	30.03937
80	28.60893
81	27.17848
82	25.74803
83	24.31759
84	22.88714
85	21.45669
86	20.02625
87	18.5958
88	17.16536
89	15.73491
90	14.30446
91	12.87402
92	11.44357
93	10.01312
94	8.582678
95	7.152232
96	5.721785
97	4.291339
98	2.860893
99	1.430446
100	0

Appendix F: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: Team 75 – Optical Filter Selector   Advisor: Dr. Elghandour   Date: 11/06/19

Y	N	
✓	☐	1. Will the system include hazardous revolving, running, rolling, or mixing actions?
☐	✓	2. Will the system include hazardous reciprocating, shearing, punching, pressing, squeezing, drawing, or cutting actions?
☐	✓	3. Will any part of the design undergo high accelerations/decelerations?
☐	✓	4. Will the system have any large (>5 kg) moving masses or large (>250 N) forces?
✓	☐	5. Could the system produce a projectile?
☐	✓	6. Could the system fall (due to gravity), creating injury?
✓	☐	7. Will a user be exposed to overhanging weights as part of the design?
☐	✓	8. Will the system have any burrs, sharp edges, shear points, or pinch points?
☐	✓	9. Will any part of the electrical systems not be grounded?
☐	✓	10. Will there be any large batteries (over 30 V)?
☐	✓	11. Will there be any exposed electrical connections in the system (over 40 V)?
☐	✓	12. Will there be any stored energy in the system such as flywheels, hanging weights or pressurized fluids/gases?
☐	✓	13. Will there be any explosive or flammable liquids, gases, or small particle fuel as part of the system?
☐	✓	14. Will the user be required to exert any abnormal effort or experience any abnormal physical posture during the use of the design?
☐	✓	15. Will there be any materials known to be hazardous to humans involved in either the design or its manufacturing?
☐	✓	16. Could the system generate high levels (>90 dBA) of noise?
✓	☐	17. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, or cold/high temperatures, during normal use?
☐	✓	18. Is it possible for the system to be used in an unsafe manner?
☐	✓	19. For powered systems, is there an emergency stop button?
☐	✓	20. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, add (1) a complete description, (2) a list of corrective actions to be taken, and (3) date to be completed on the reverse side.

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
The filter selector, will involve a revolving action to switch the filters out. This can be hazardous if fingers are placed near the selector while it is moving.	The system will be kept in an enclosed compartment which serves to prevent unwanted light from entering the optical equipment. This compartment will also serve to prevent fingers from being injured by the rotating equipment while the filter selector is operating.	Summer 2020	Summer 2020
The filter selector has the potential to fall and damage systems which are held below the filter selector.	The system will be attached to two rigid platforms preventing it from falling and damaging equipment beneath it.	Spring 2020	Spring 2020
The system will likely have burs and sharp points when first being manufactured that could cause cuts on hands.	Notes will be included within the drawings asking for parts to be deburred and sharp points will be rounded if necessary.	Spring 2020	Spring 2020
The system will be exposed to changes in temperature which could harm the data taken with the optical instruments.	The system will have a heater implemented within the filter selector compartment that will ensure that the temperature does not fluctuate enough to harm the data recorded.	Summer 2020	Summer 2020

Appendix G: Product Links

PRM05:
https://www.thorlabs.com/thorproduct.cfm?partnumber=PRM05

McMaster Carr:
https://www.mcmaster.com/

Smart Motor:
https://www.animatics.com/products/smartmotor/sm23165dt

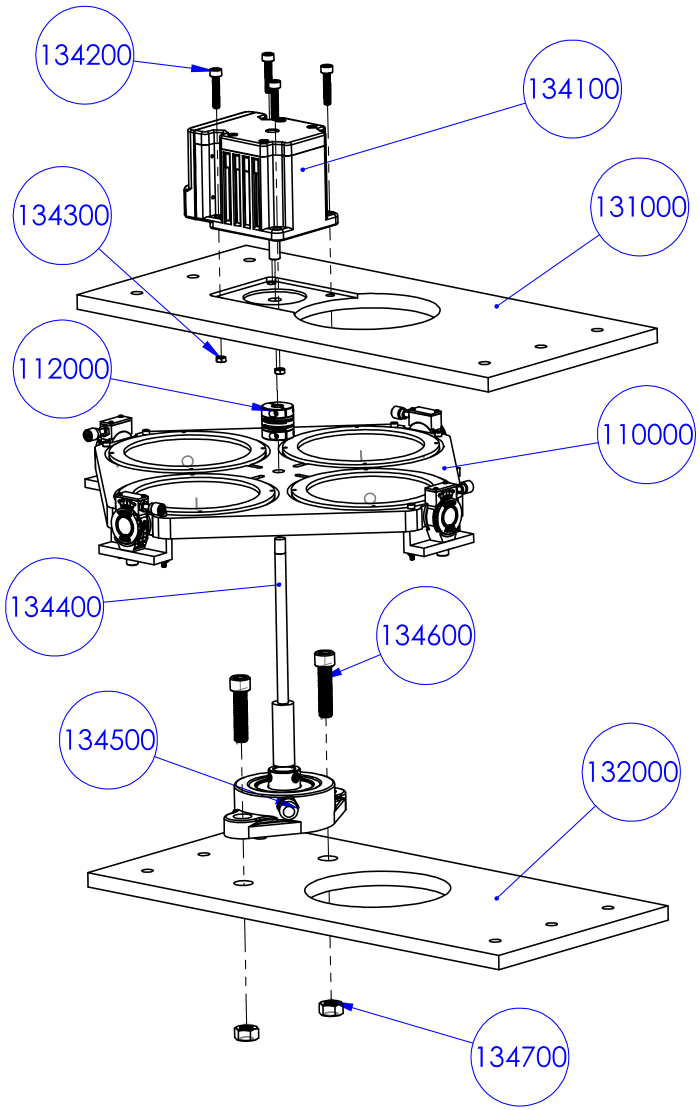
Appendix H: Indented Bill of Materials

Optical Filter Selector

Indented Bill of Material (iBOM)

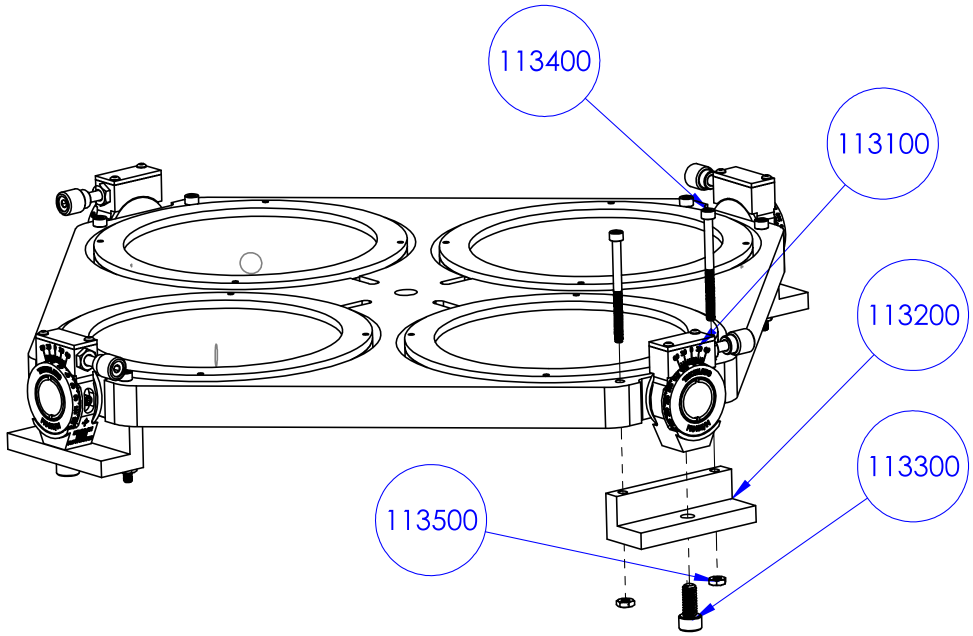
Assembly Level	Part Number	Description Lvl0	Lvl1	Lvl2	Lvl3	Qty	Cost	Ttl Cost	Source	More Info
0	100000	Final Assy							------	
1	110000		Filter Wheel Assembly						------	
2	111000			Filter Wheel		1			Custom	Aluminum 6061
2	112000			Coupling		1	41.50	41.50	McMaster	6208K433, 1/4" - 1/4"
2	113000			Tilting Assembly					------	
3	113100				Rotation Mount	4	177.47	709.88	Thorlabs	PRM05
3	113200				Holding Bracket	4			Custom	Aluminum 6061
3	113300				Bolts	4	1.30	5.21	McMaster	8-32, 3/8" long
3	113400				Bolts	8	1.03	8.27	McMaster	3-48, 1-1/4" Long
3	113500				Nuts	8	0.40	3.20	McMaster	18-8 Hex
2	114000			Filter Holders					------	
3	114100				Filter Holder - Top	4			Custom	Aluminum 6061
3	114200				Filter Holder - Base	4			Custom	Aluminum 6061
3	114300				Small Tilting Shaft	4	6.66	26.64	McMaster	1/8"
3	114400				PRM Shaft	4	7.84	31.36	McMaster	Altered from 1/2"
2	120000		Thermal Enclosure Assembly						------	
3	121000			Side		2			Custom	Aluminum Sheetmetal
3	122000			Front		1			Custom	Aluminum Sheetmetal
3	123000			Back Panel		1			Custom	Aluminum Sheetmetal
1	130000		Platforms						------	
2	131000			Top		1			Custom	Aluminum 6061
2	132000			Bottom		1			Custom	Aluminum 6061
2	133000			Clamps					------	
3	133100				Front	4			Custom	Aluminum 6061
3	133200				Back	8			Custom	Aluminum 6061
3	133300				Rubber	8	2.10	16.80	McMaster	
3	133400				Bolts	16	0.25	4.00	McMaster	1/4-20, 1-3/8" long
3	133500				Nuts	16	0.05	0.80	McMaster	1/4-20
2	134000			Motor Assembly					------	
3	134100				Motor	1	500.00	500.00	Moog Animatics	SmartMotor
3	134200				Bolts	4	0.63	2.52	McMaster	8-32, 3/4" long
3	134300				Nuts	4	0.05	0.20	McMaster	8-32
3	134400				Main Shaft	1	7.84	7.84	McMaster	Altered from 1/2"
3	134500				Bearing	1	43.64	43.64	McMaster	5968K71, 1/2" shaft
2	134000			Bolts		12	0.25	3.00	McMaster	1/4-20, 1-3/8" long
2	135000			Nuts		12	0.05	0.60	McMaster	1/4-20
	Total Parts					**139**				

Appendix I: Drawing Package



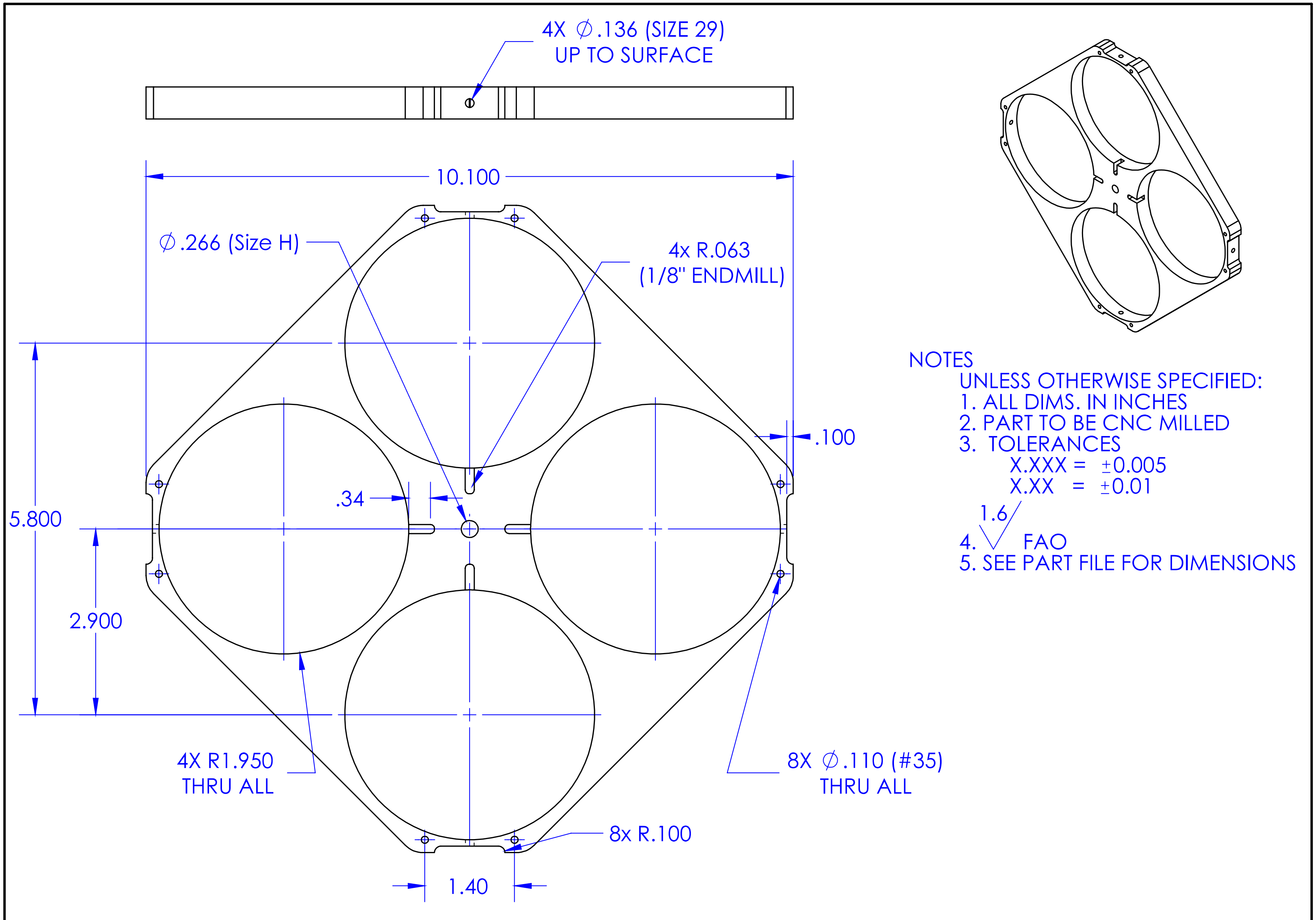
ITEM NO.	PART NUMBER	QTY.
134100	Smart Motor	1
131000	Top Motor Bridge	1
132000	Bottom Bearing Bridge	1
134400	Main Shaft	1
134500	Bearing	1
110000	Filter Wheel with Filters	1
112000	Coupling	1
134200	M4 x 0.7mm, 20mm long bolts	4
134300	M3 x 0.5mm Hex Nut	4
134600	5/16"-24, 1-1/4" Long Bolts	2
134700	5/16"-24 Hex Nut	2

TEAM OFS			Motor Assembly		Drwn. By: Matthew Allen
	Dwg. #: 134000		Date: 1/24/20	Scale: 1:4	Chkd. By: Niko Banks

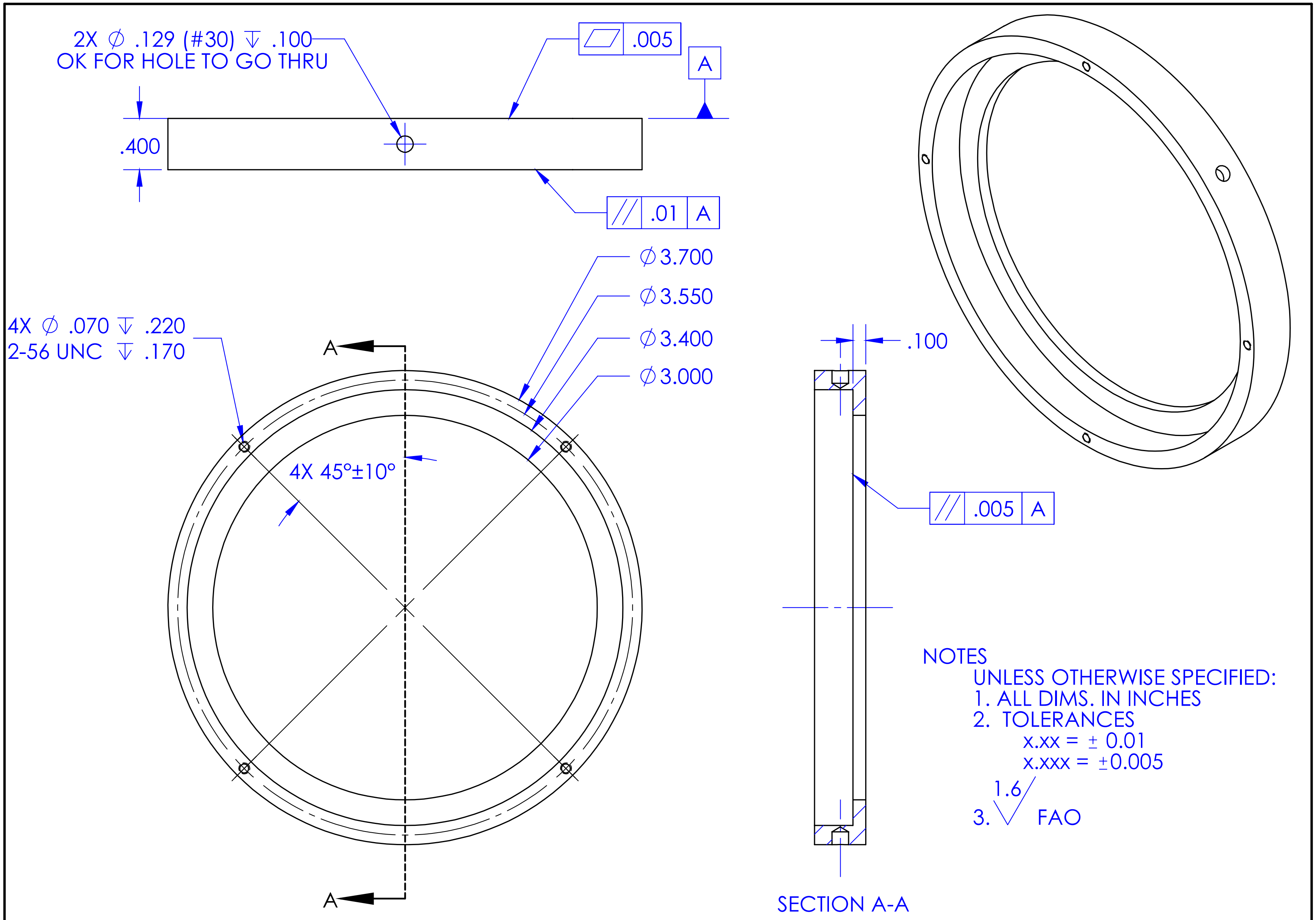


ITEM NO.	PART	
113200	Holding Bracket	4
113100	Rotation Mount	4
113300	8-31, 3/8" Long Bolt	4
113400	3-48, 1-1/4" Long Bolt	8
113500	18-8 Hex Nut	8

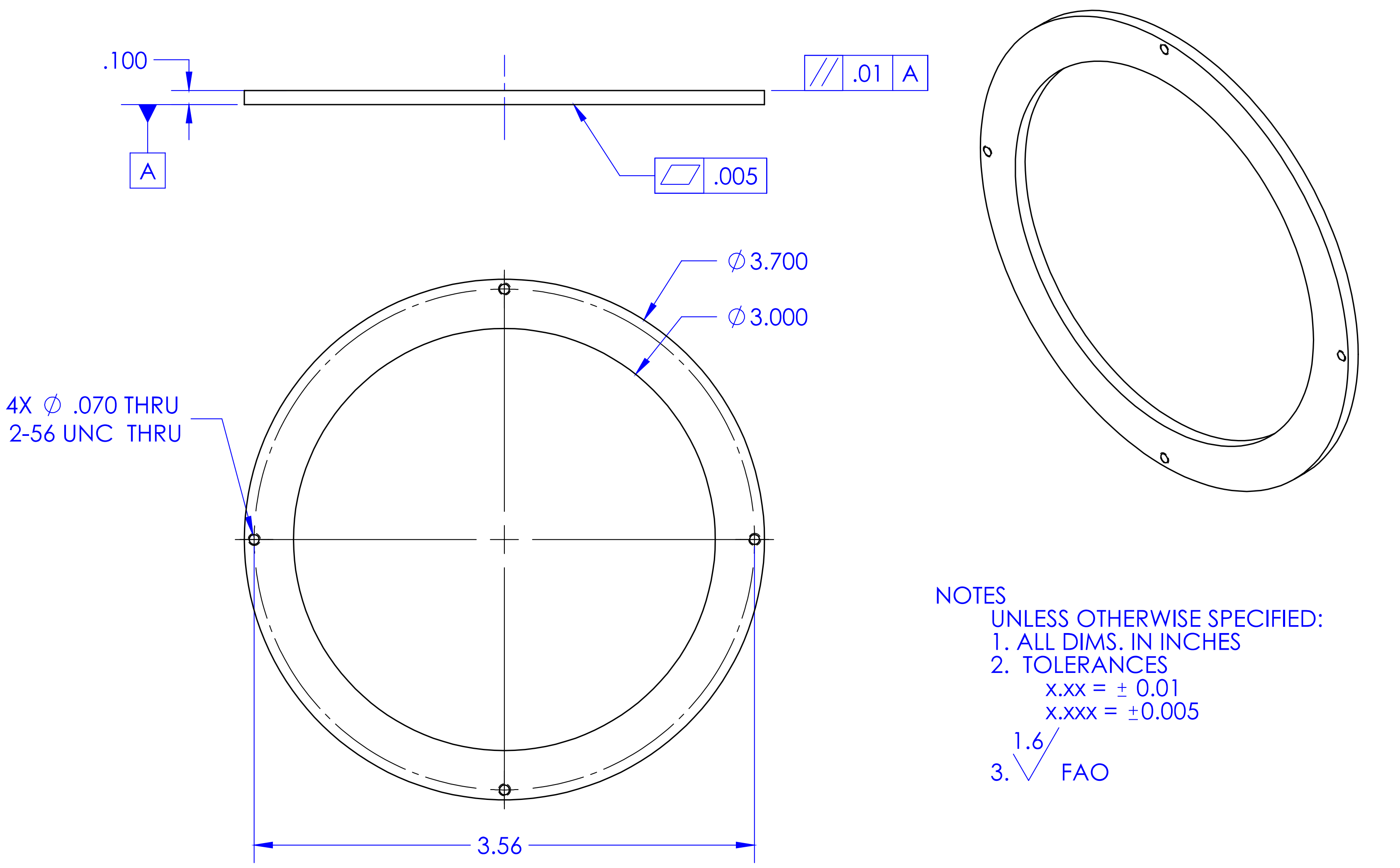
Team OFS			Filter Wheel Assembly	Drwn. By: Matthew Allen
	Part No: 110000		Date: 2/5/20 Scale: 1:2	Chkd. By: Niko Banks



Team OFS			Title: Filter Wheel		Drwn. By: Cal Schwefler
	Part No. 111000		Date: 2/05/20	Scale: 1:2	Chkd. By: Niko Banks



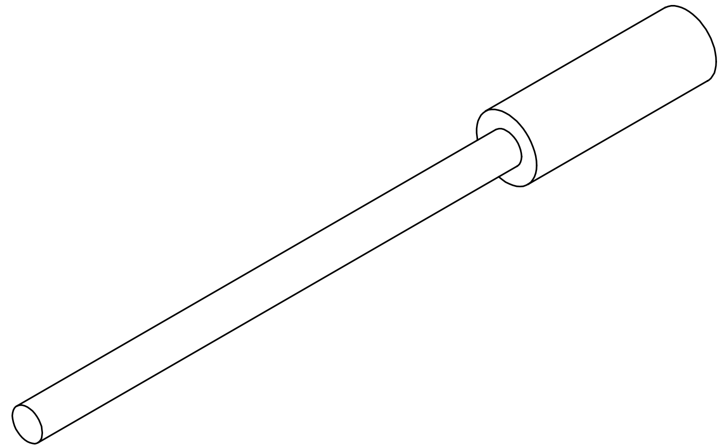
TEAM OFS			Title: Filter Holder - Base	Drwn. By: Joel Pitzer
	Part #: 114200		Date: 1/24/20 / Scale: 1:1	Chkd. By: Niko Banks

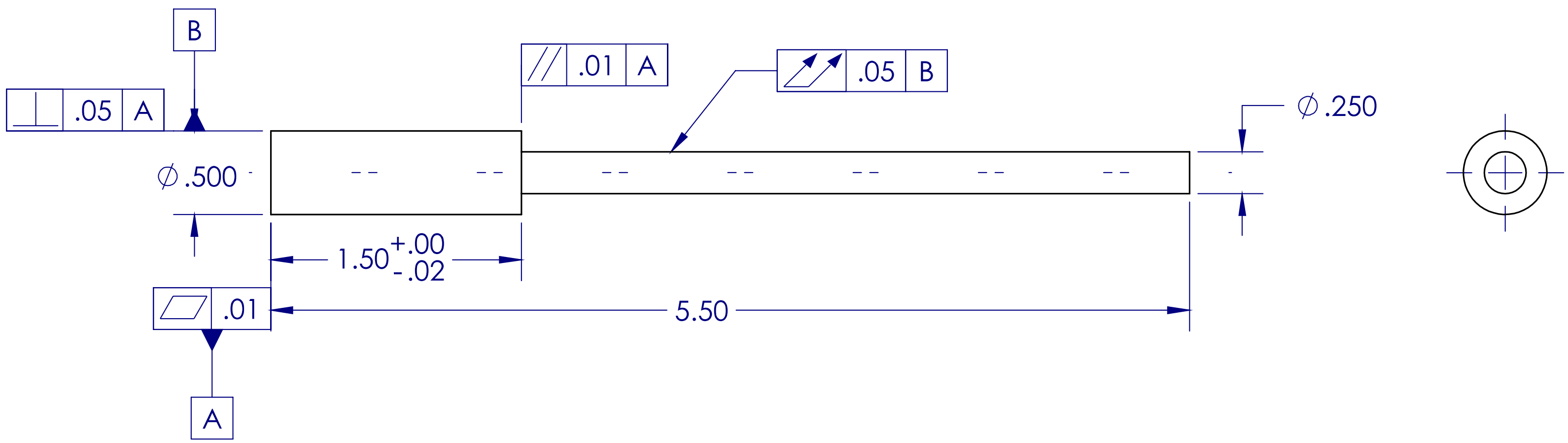


NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
x.xx = ± 0.01
x.xxx = ±0.005
3. 1.6 √ FAO

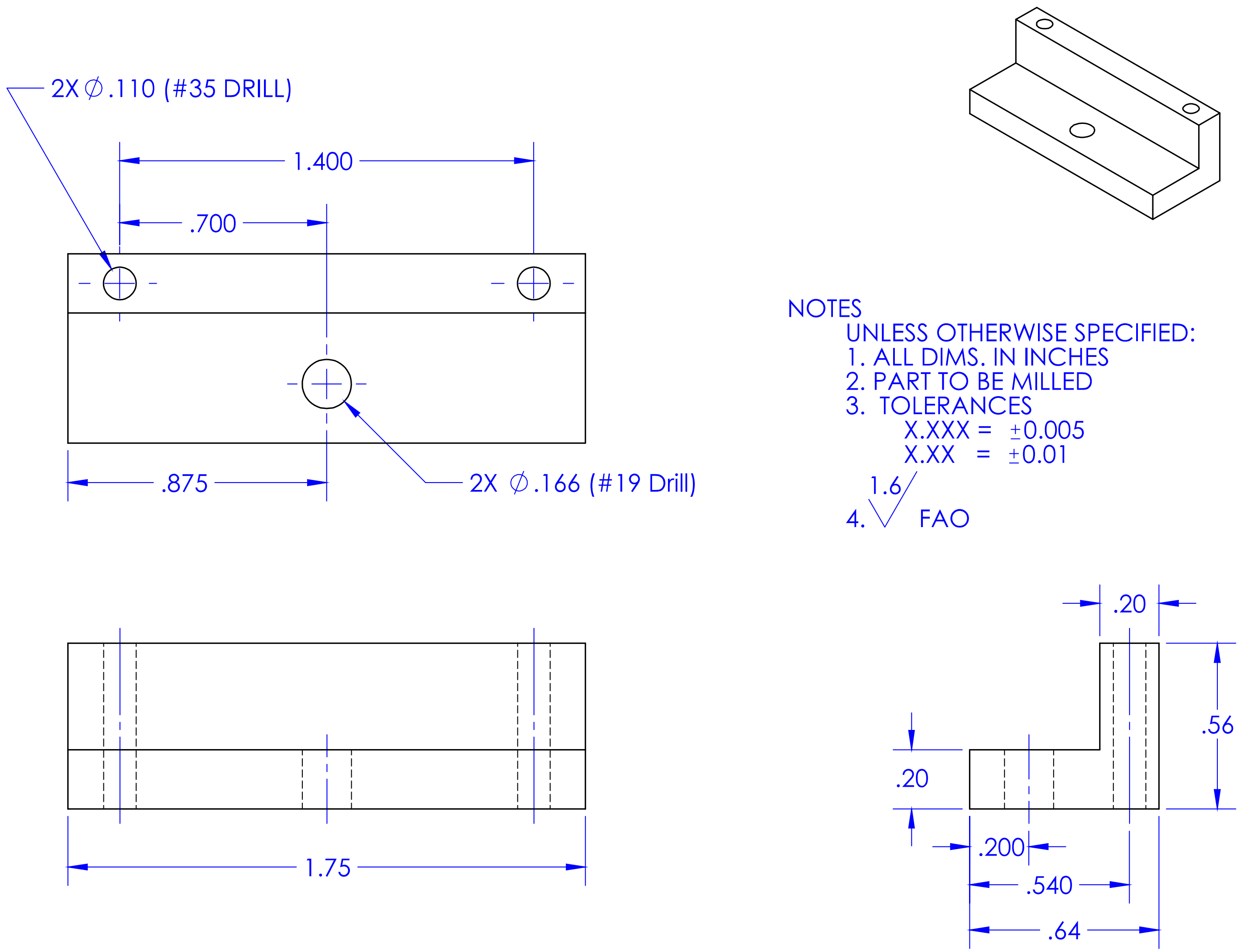
TEAM OFS			Title: Filter Holder - Top		Drwn. By: Joel Pitzer
	Part #: 114100		Date: 1/24/20	Scale: 1:1	Chkd. By: Niko Banks

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES
x.xx = ± 0.01
x.xxx = ±0.005
3. 1.6 √ FAO

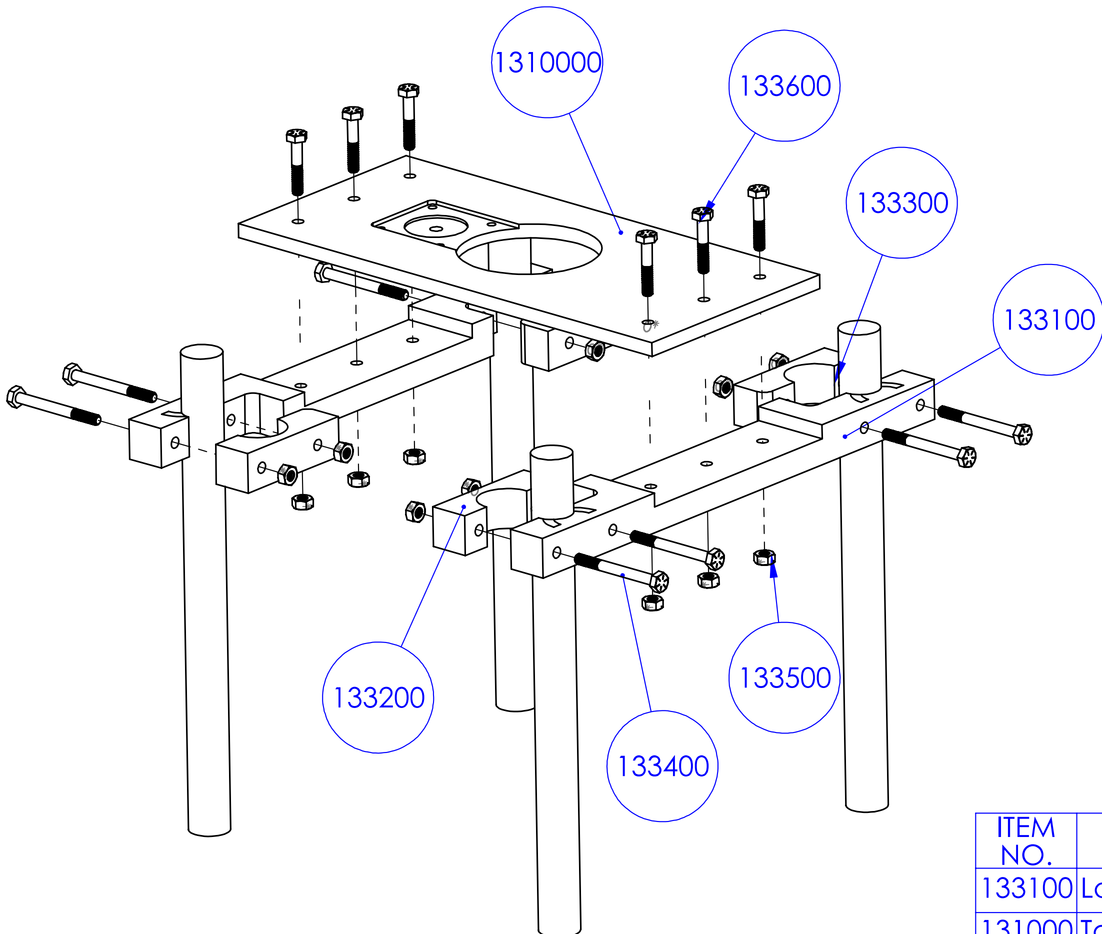




TEAM OFS			Title: Main Shaft	Drwn. By: Joel Pitzer
	Dwg. #: 134400		Date: 1/29/20 / Scale: 1:1	Chkd. By: Niko Banks



Team OFS			Holding Bracket	Drwn. By: Matthew Allen
	Part No. 113200		Date: 2/5/20 / Scale: 2:1	Chkd. By: Niko Banks



ITEM NO.	PART NUMBER	QTY.
133100	Locating Clamp	2
131000	Top Platform	1
133200	Clamp Block	4
133300	Rubber C	4
133600	1/4 - 20, 2-1/2" Long Bolts	8
133500	1/4-20 Hex Nuts	14
133400	1/4 - 20, 1-3/8" Long Bolts	6

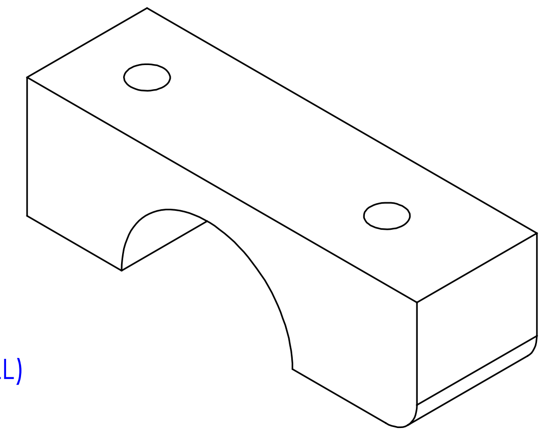
Team OFS			Clamps Assembly		Drwn. By: Matthew Allen
	Part No. 133000		Date: 2/5/20	Scale: 1:4	Chkd. By: Niko Banks

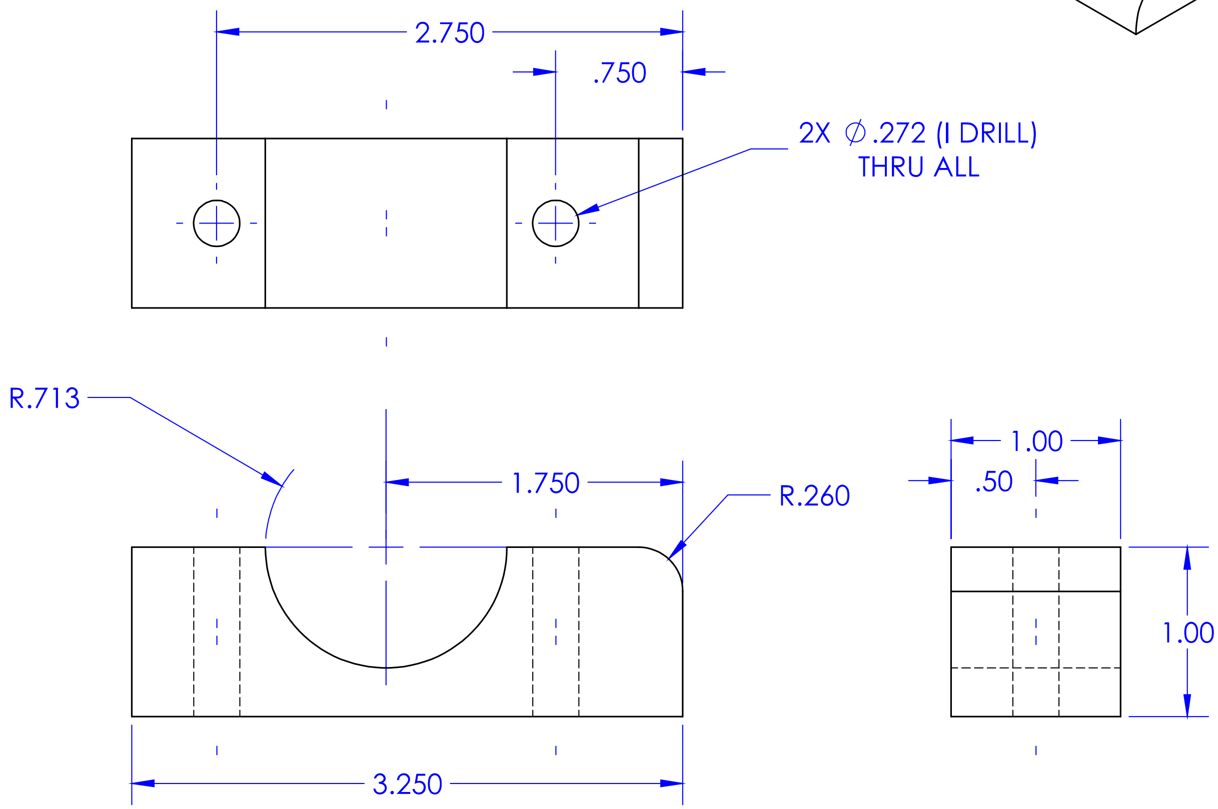
NOTES

UNLESS OTHERWISE SPECIFIED:

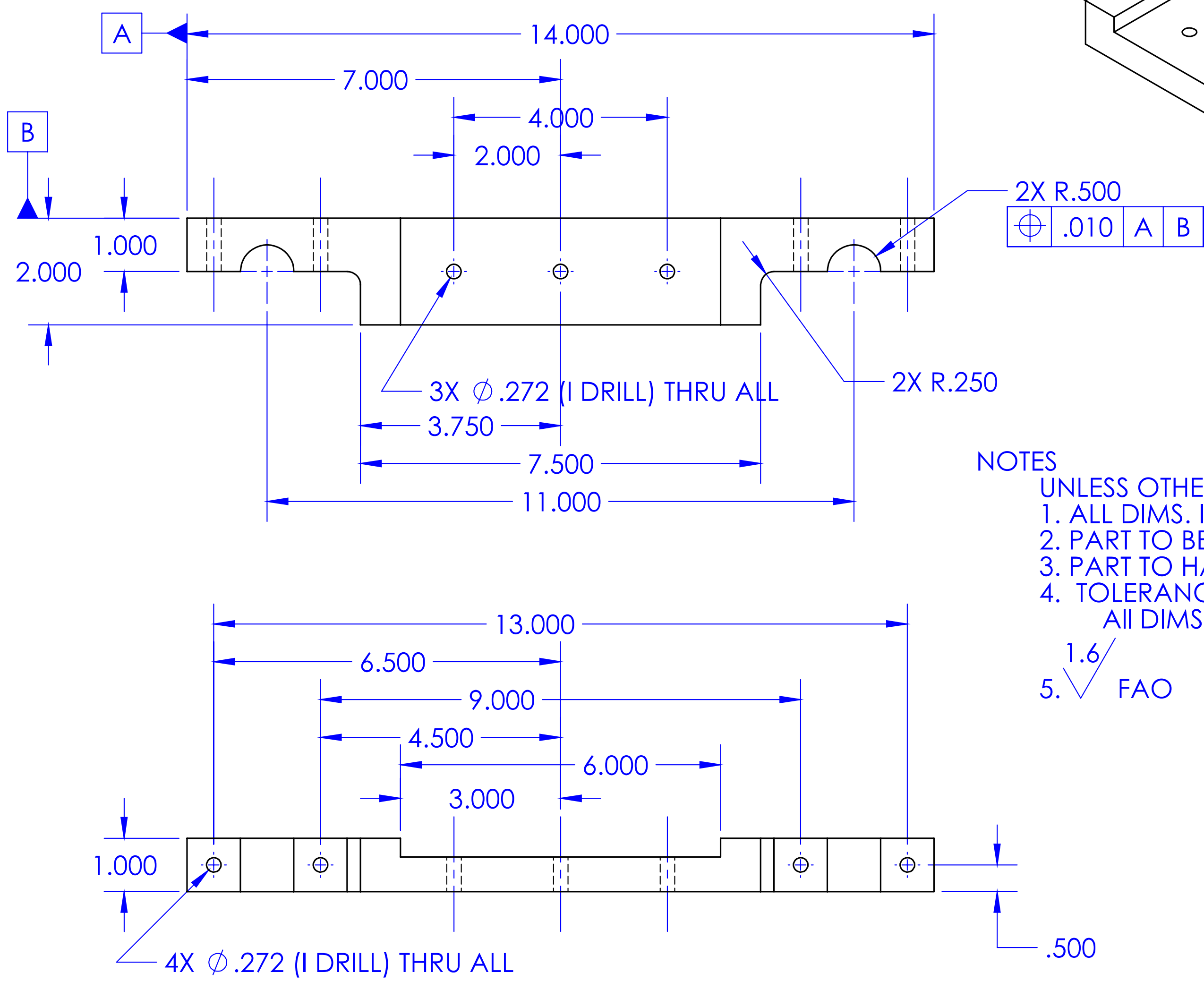
1. ALL DIMS. IN INCHES
2. PART TO BE CNC MILLED
3. PART TO HAVE HOLES DRILLED WITH SIZE I
4. TOLERANCES

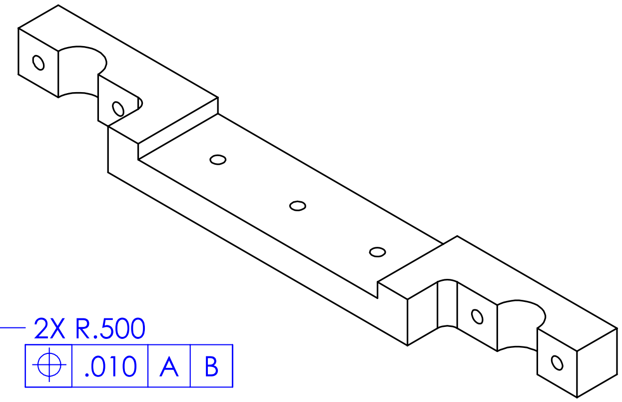
   All DIMS HELD TO ±0.005
5. 1.6 √ FAO





Team OFS			Title: Clamp - Back	Drwn. By: Cal Schwefler
	Part #: 133100		Date: 1/24/20	Scale: 1:1	Chkd. By: Niko Banks





NOTES

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. PART TO BE MILLED
3. PART TO HAVE HOLES DRILLED WITH SIZE I
4. TOLERANCES
   All DIMS HELD TO ±0.005
5. 1.6 √ FAO

Team OFS			Title: Clamp - Front	Drwn. By: Cal Schwefler
	Part #:133100		Date: 1/24/20	Scale: 1:3	Chkd. By: Niko Banks

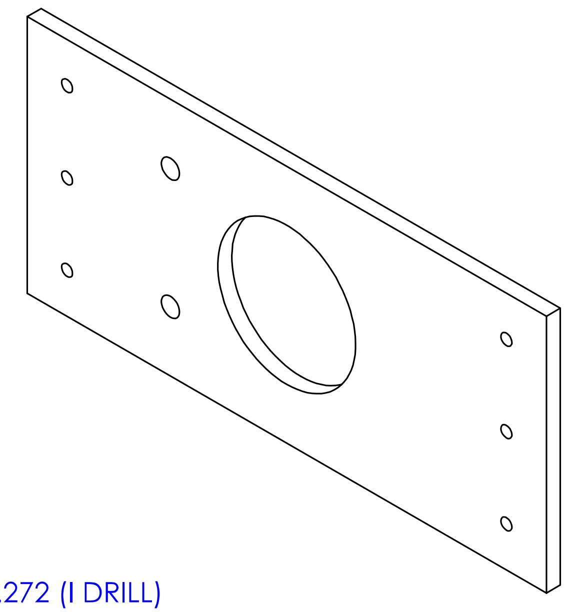
NOTES

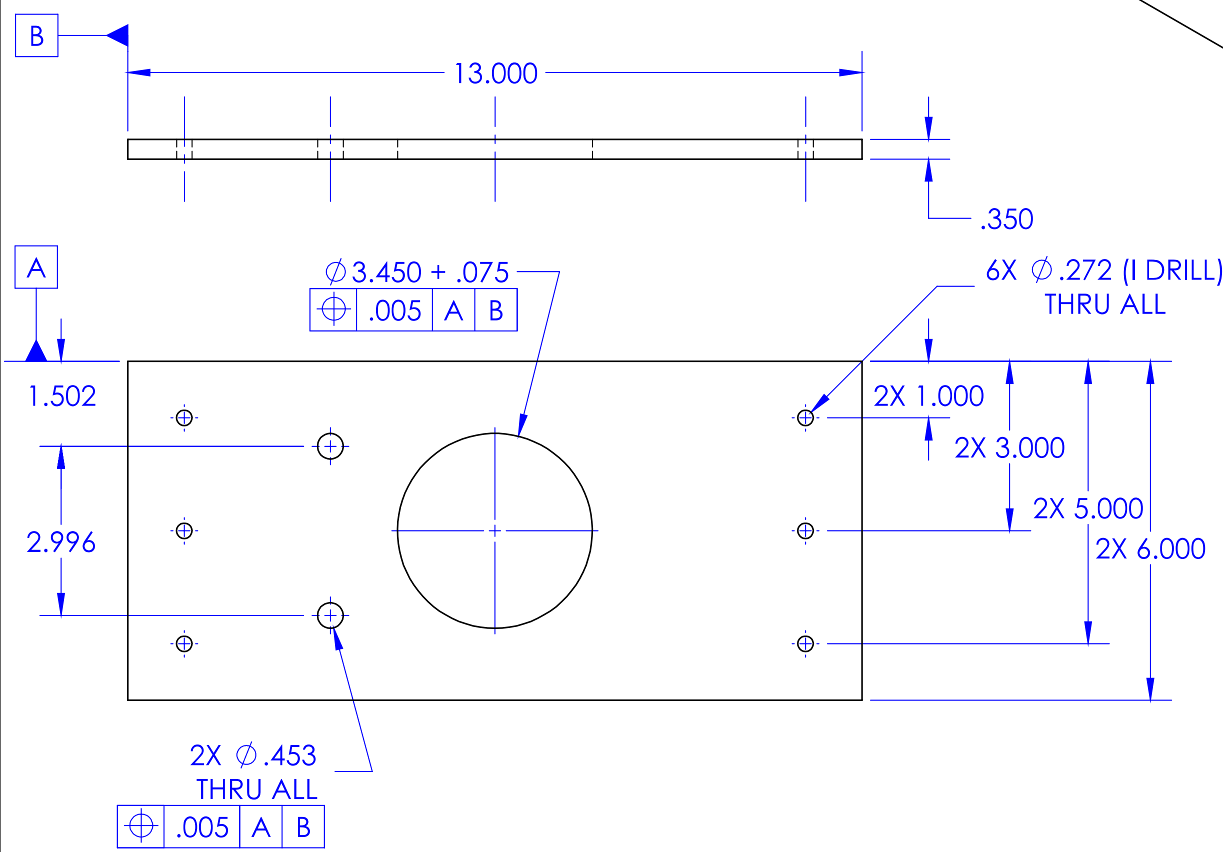
UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. PART TO BE CNC MILLED
3. PART TO HAVE HOLES DRILLED WITH SIZE I
4. TOLERANCES

   All DIMS HELD TO ±0.005 UNLESS SPECIFIED

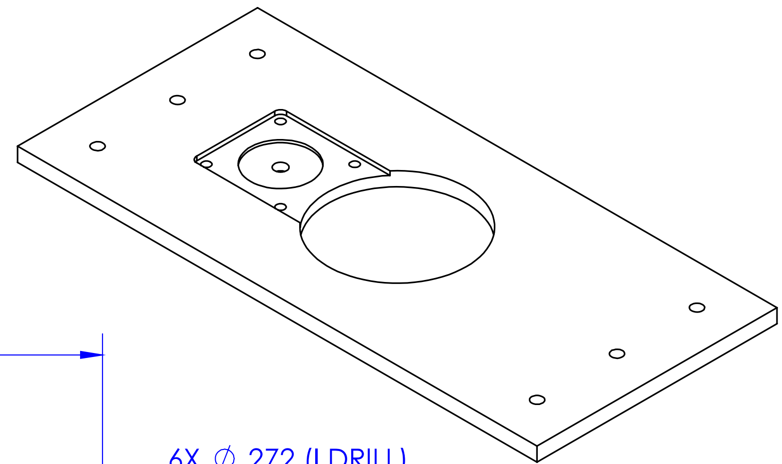
5. 1.6 √ FAO
6. REFERENCE CAD FOR DIMENSIONS

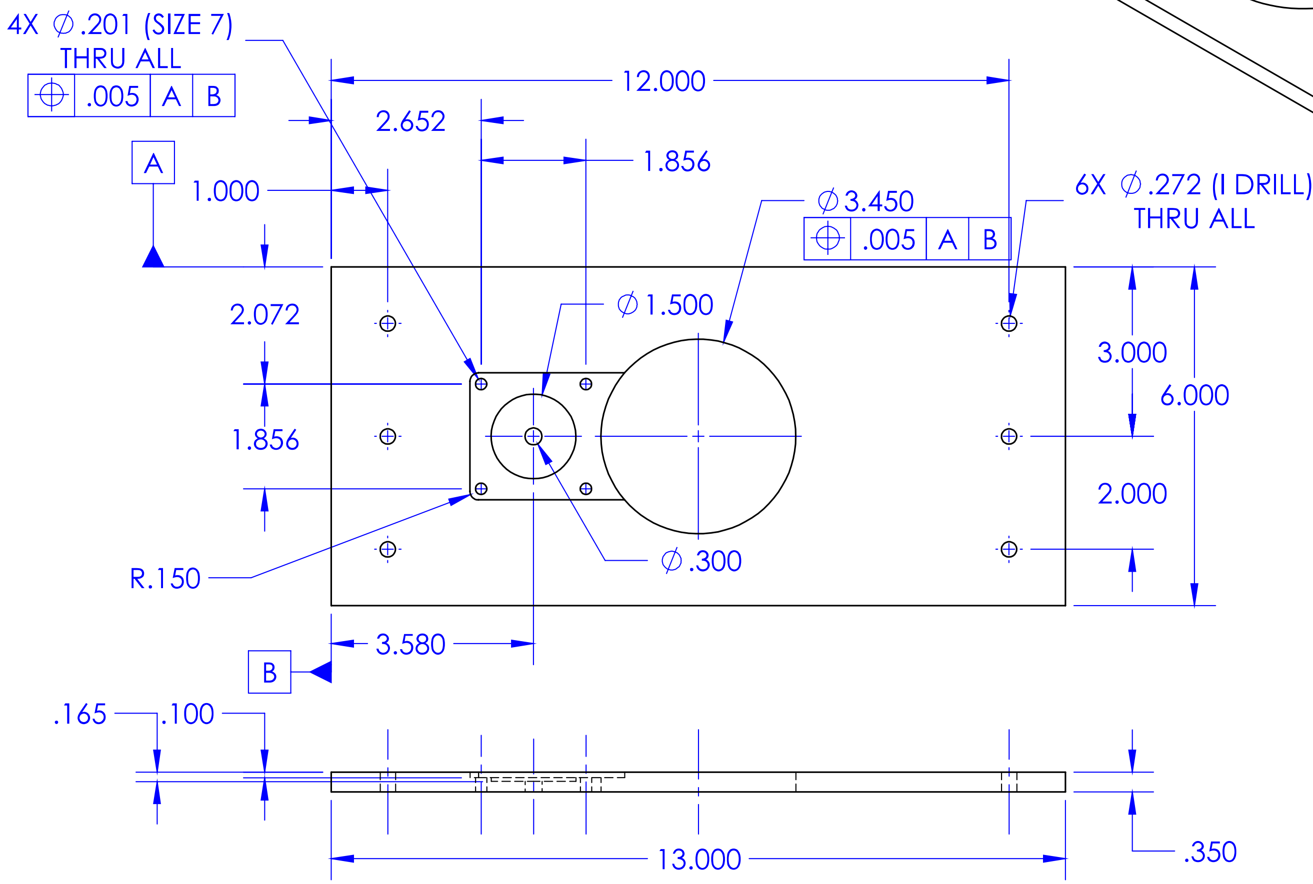




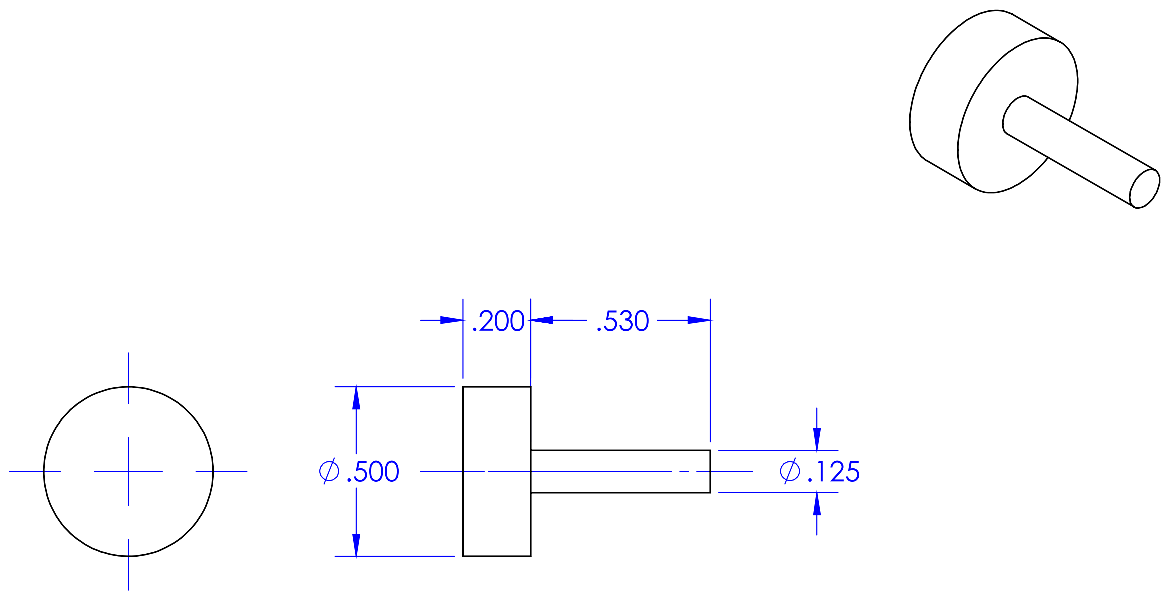
Team OFS			Title: Platform - Bottom	Drwn. By: Cal Schwefler
	Part #: 132000		Date: 1/24/20 · Scale: 1:3	Chkd. By: Niko Banks

NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. PART TO BE CNC MILLED
3. PART TO HAVE HOLES DRILLED WITH SIZE I
4. TOLERANCES
All DIMS HELD TO ±0.005 UNLESS SPECIFIED
5. 1.6 √ FAO
6. REFERENCE CAD FOR DIMS





Team OFS			Title: Platform - Top		Drwn. By: Cal Schwefler
	Part #: 131000		Date: 1/24/20	Scale: 1:3	Chkd. By: Niko Banks



NOTES

UNLESS OTHERWISE SPECIFIED:

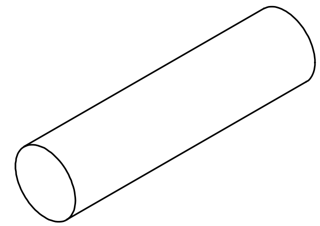
1. ALL DIMS. IN INCHES
2. TOLERANCES
   All DIMS HELD TO ±0.005
3. 1.6 √ FAO

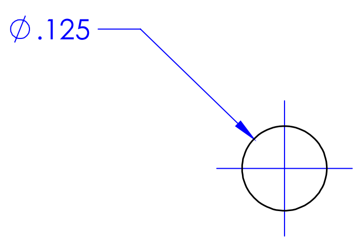
Team OFS			PRM Shaft		Drwn. By: Matthew Allen
	Part #: 114400		Date: 2/5/20	Scale: 2:1	Chkd. By: Niko Banks

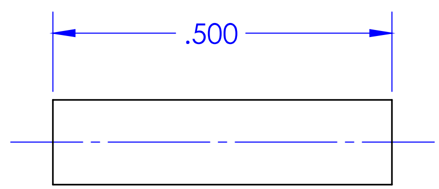
NOTES

UNLESS OTHERWISE SPECIFIED:

1. ALL DIMS. IN INCHES
2. TOLERANCES
   All DIMS HELD TO ±0.005 UNLESS SPECIFIED
3. √ 1.6 FAO

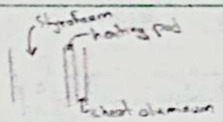






Team OFS			Title: Small Tilting Shaft		Drwn. By: Camaryn Chambers
	Part #: 114300		Date: 1/29/20	Scale: 4:1	Chkd. By: Niko Banks

Appendix J: Thermal Analysis



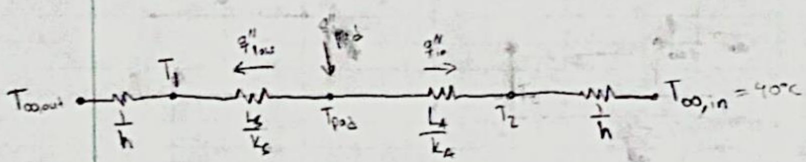
Styrofoam: $k_s = 0.03\,\frac{W}{mK}$ (engineering toolbox) ← melts @ 240°C

$L_s = 1\,in = 0.0254\,m$

Aluminum: $k_A \approx 180\,\frac{W}{mK}$ (ASM Mat'l Data Sheet & Fundamentals of Heat and Mass Transfer Bergman, Lavine)

$L_A = 0.019\,in = 4.826 \times 10^{-4}\,m$

Heating Pad: $q_{pad,max} = 360\,W$, $A = (12\,in)(6\,in) =$



Assumptions:
- contact resistance is negligible
- radiation from Al to filter is negligible
- ignoring heat loss out of thermal enclosure
- ~~$T_{\infty,out} = 0°C$ is lowest temp the trailer will be on the inside~~
- $h = 100\,W/m^2K$
- $T_{pad} = 200°C$ (so that the styrofoam doesn't melt)

$$q''_{loss} = \frac{T_{pad} - T_{\infty,out}}{\frac{1}{h} + \frac{L_s}{k_s}}$$

$$q''_{in} = \frac{T_{pad} - T_{\infty,in}}{\frac{1}{h} + \frac{L_A}{k_A}}$$

$$q''_{pad} = q''_{loss} + q''_{in}$$

$$q''_{loss} = \frac{200°K - 0°K}{\frac{1}{100\,\frac{W}{m^2K}} + \frac{0.0254\,m}{0.03\,\frac{W}{mK}}}$$

$$q''_{loss} = 233.5\,\frac{W}{m^2}$$

$$q''_{in} = \frac{200°K - 40°K}{\frac{1}{100\,\frac{W}{m^2K}} + \frac{4.826 \times 10^{-4}\,m}{180\,W/mK}}$$

$$q''_{in} = 15995.7\,W/m^2$$

$$q''_{pad} = q''_{loss} + q''_{in}$$

$$\boxed{q''_{pad} = 16230\,W/m^2}$$

Appendix K: FMEA

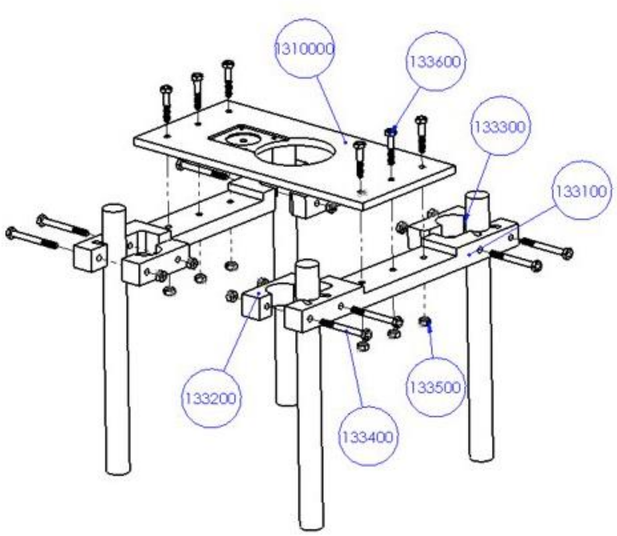
System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality	RPN
(Filter Wheel System) Position filter precisely	filters get out of position	Data collected becomes skewed or useless	8	1) Slots for filters aren't high tolerance. 2) Filter wheel is too heavy and moves out of alignment	1) Verification testing over an expected cycle of the system	2	Checked by operator when set up, final testing	3	48	Use sufficiently high tolerances	Cal 12/10	Toleranced drawings properly	8	1	3	24
(Tilting System) Tilts filter to capture correct wavelength	Incorrect wavelength is captured	data could be interpreted incorrectly	7	1) Tilting mechanism doesn't lock in place strongly enough. 2) Angle reading is incorrect	1) Verification testing over an expected cycle of the system	2	Checked by operator when set up, final testing	2	28	Choose accurate tilting method	Joel 12/10	Use PRM-05 for fine tuning	7	1	2	14
(Temperature Control System) Prevents wavelength modification	temperature isn't stable to plus or minus 5 degrees Celsius	Wrong wavelength is observed	7	1) It gets very hot or very cold in the trailer. 2) The heater cuts out from over use. 3) High heat causes structural members to fail	1) Thermal analysis of the system 2) Use of insulation to minimize heat transfer to the system	3	Checked by operator when set up, final testing	2	42	Perform sufficient testing and analysis	Matt 1/15	Analysis Performed	7	2	2	28
(Filter Holding System) Precisely locates filters	Wheel over or under rotates	filters wont line up accurately over the instrument below	8	1) Too much torque on the motor 2) Software has bugs.	1) Stress analysis of the shaft 2) Verification testing over an expected cycle of the system	2	Checked by operator when set up, final testing	1	16							

(Tilting System) tilt individual filters	Tilting angle changes during operation	User is unaware and so data collected over 6 months is erroneous	8		1) Verification testing over an expected cycle of the system	2	Checked by operator when set up, final testing	1	16							
(Filter Wheel System) hold tilting system	Tilting system falls out or shifts	Possibly damages the expensive. Instrument below	8	1) The filter holding components are improperly sized 2) The platform holding the filter and other components is improperly attached to the rest of the sytem	1) Verification testing over an expected cycle of the system	2	Checked by operator when set up, final testing	2	32	Add protective cover to design, ensure pieces can't drop out	Camaryn 12/10	Platforms added to protect lower areas	8	1	2	16
(Filter Wheel System) Moves filters	inaccurately rotates filters	filters wont line up accurately over the instrument below	7	1) Software has bugs 2) Improper positioing of filter wheel within the system 3) Filter wheel does not lock in place once moved	1) Verification testing over an expected cycle of the system	1	Checked by operator when set up, final testing	1	7							
(Platform System) Generates Rotation of filter wheel	smart motor fails	data collection stops and repairs have to be made	5	1) Software has bugs 2) Improper rotation of filter wheel so it blocks the lens	1) Verification testing over an expected cycle of the system	1	Checked by operator when set up, final testing	1	5							

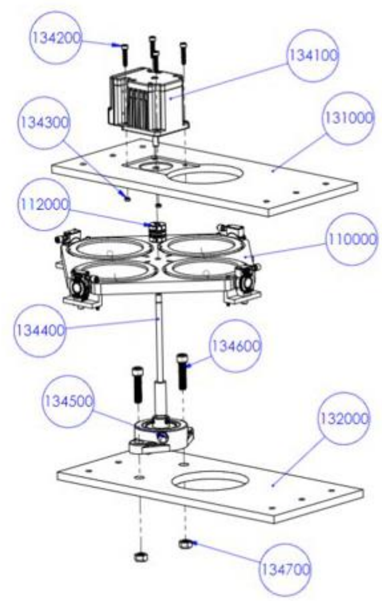
Appendix L: Final Budget

Assembly	Hardware	Description	Qty	Cost	Source
Filter Wheel					
	Bracket Screws	3-48 1" Socket (Alloy Steel)	8	$ 10.72	McMaster
	PRM Screw	8-32 3/8" Socket (Alloy Steel)	4	$ 5.21	McMaster
	Filter Holder Screws	2-56 1/4" Socket (Alloy Steel)	16	$ 6.37	McMaster
	Filter Wheel	Custom Part	1	$ 474.02	E&S Precision Machine Inc.
	PRM Shaft	Custom Part	4	$ 113.04	E&S Precision Machine Inc.
	Holding Bracket	Custom Part	4	$ 291.36	E&S Precision Machine Inc.
	Filter Holder - Base	Custom Part	4	$ 597.28	E&S Precision Machine Inc.
	Filter Holder - Top	Custom Part	4	$ 329.96	E&S Precision Machine Inc.
	Small Tilting Shaft	Custom Part	4	$ 95.00	E&S Precision Machine Inc.
	PRM	Tilting Device	4	$ 709.88	ThorLabs
Platforms					
	Bridge Screws	1/4"-20 1" Socket (Alloy Steel)	12	$ 8.55	McMaster
	Clamping Screws	1/4"-20 2" Socket (Alloy Steel)	16	$ 8.42	McMaster
	Rubber C	Polyurethane Rubber Round Tube	8	$ 43.30	McMaster
	Motor Bolts	M4 .7mm (Alloy Steel)	4	$ 10.86	McMaster
	Motor Nuts	M4 7mm Width Hex (HSS)	4	$ 8.71	McMaster
	Bearing Bolts	5/16"-24, 1-1/4" Socket (Alloy Steel)	2	$ 7.01	McMaster
	Bearing Nuts	5/16"-24, Grade 8 (HSS)	2	$ 5.86	McMaster
	Coupling	1/4" to 1/4" (7075 Aluminum)	1	$ 41.50	McMaster
	Clamp - Back	Custom Part	8	$ 525.60	E&S Precision Machine Inc.
	Clamp - Front	Custom Part	4	$ 737.08	E&S Precision Machine Inc.
	Platform - Top	Custom Part	1	$ 499.39	E&S Precision Machine Inc.
	Platform - Bottom	Custom Part	1	$ 359.91	E&S Precision Machine Inc.
	Main Shaft	Custom Part	1	$ 85.64	E&S Precision Machine Inc.
	Motor	SmartMotor	1	$ -	Moog Animatics
	Bearing	Mounted Sealed Ball Bearing	1	$ 43.64	McMaster
				$ 5,018.31	

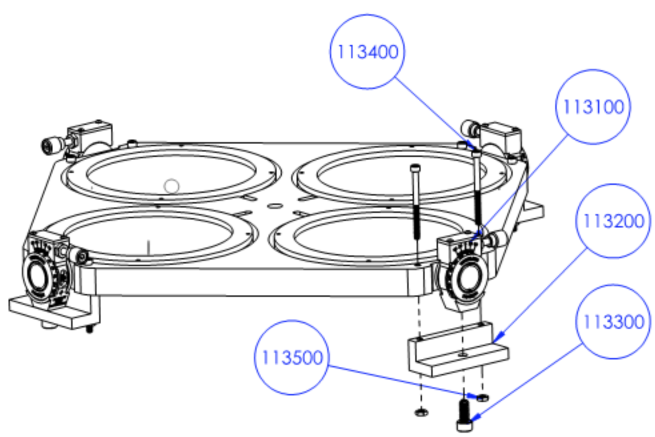
This filter selector assembly is split up into three main subassemblies. The first subassembly includes the four clamps which attach to the frame, and the bridges which extend from one clamp assembly to the other. The second subassembly involves the filter wheel itself along with the filters and the filter holders. The final subassembly is the vertical motor and shaft assembly which joins the two clamping assemblies and holds the filter wheel in place.



Single Clamp Assembly



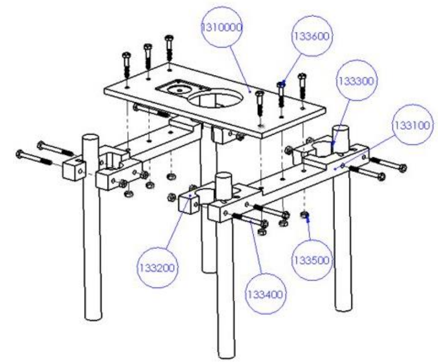
Vertical Motor and Shaft Assembly



Filter Wheel Assembly

For the assembly process we recommend a bottom up approach starting with the bottom clamping assembly. This document is meant to be followed chronologically starting with the following page. However, if two technicians are available, they can save time by having one technician work on assembling the filter wheel separately.

Bottom Clamping Assembly

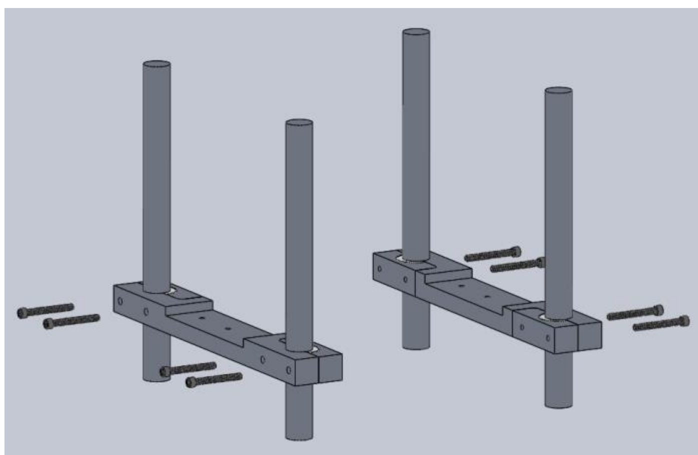


Parts List:

- x2 Locating Clamp (133100)
- Bottom Platform (131000)
- x4 Clamp Block (133200)
- x4 Rubber C (133300)
- x8 ¼-20, 2-1/2” Long Bolts (133600)
- x14 1/4-20 Hex Nuts (133500)
- x6 2 1/4 - 20, 1-3/8" Long Bolts (133400)

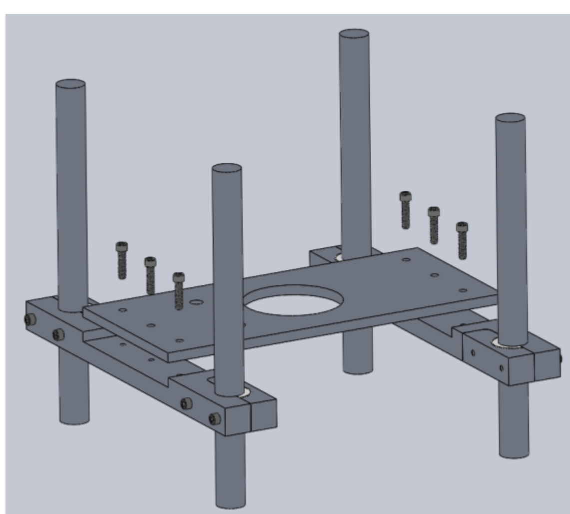
Instructions:

1. Hold the clamp block to the two poles adjacent to one another. Attach the locating clamp to the clamp block (with a piece of rubber against the pole) using 2 1/4 - 20, 1-3/8" Long Bolts and 2 1/4-20 Hex Nuts for each locating clamp.



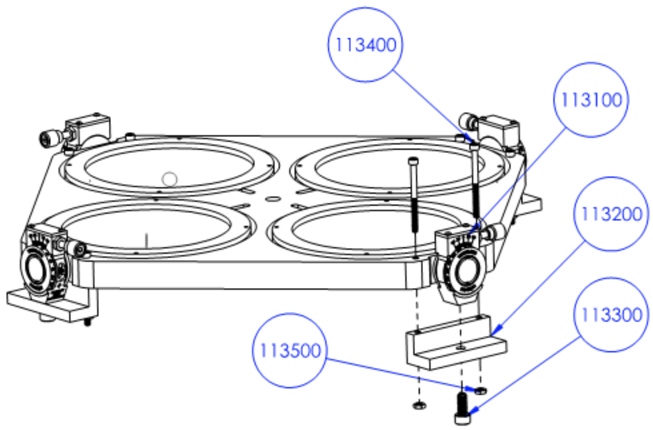
2. Repeat for the other set of poles.

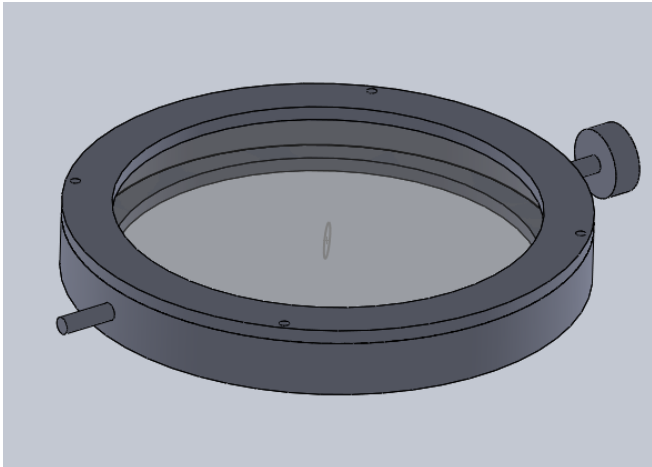
3. Place the bottom platform into the indentation on the clamp blocks. Secure with 6 1/4 - 20, 2-1/2" Long Bolts.



Filter Wheel Assembly

The filter wheel assembly contains two different types of subassemblies which both attach to the filter wheel itself. The first are the filter holder assemblies. These assemblies are identical and hold the four filters in place and allow them to be rotated within the filter wheel. The other subassemblies are the brackets for holding the PRM tilting devices. These brackets attach to the filter wheel and hold the PRM's in place so they can rotate the filters.





This assembly will be handled in three steps. First, the operator should assemble the four filter holders. Second, the operator should attach the PRM brackets to the filter wheel. Third, the operator should adhere the PRM devices to the shafts extending from the filter holder assemblies.

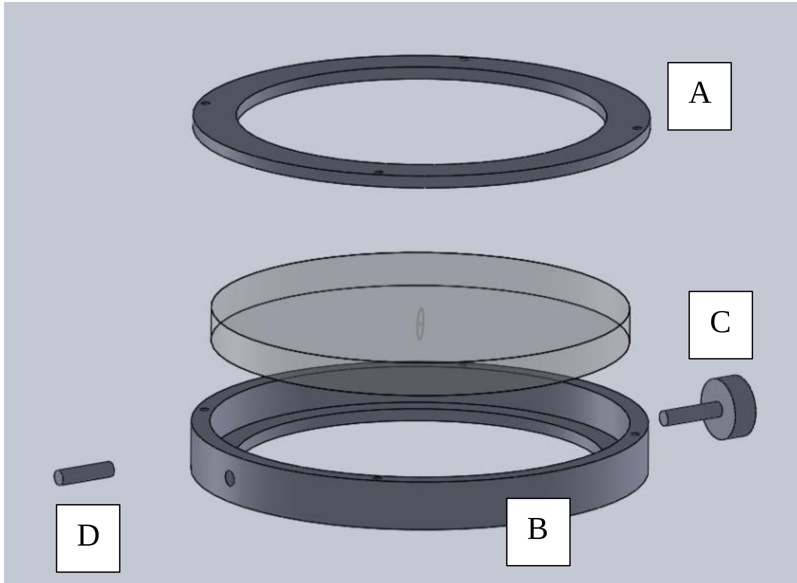
Step 1: Filter Holders

Part List:

- Filter Holder Top (A)
- Filter Holder Bottom (B)
- Screws
- PRM Shaft (C)
- Small Tilting Shaft (D)

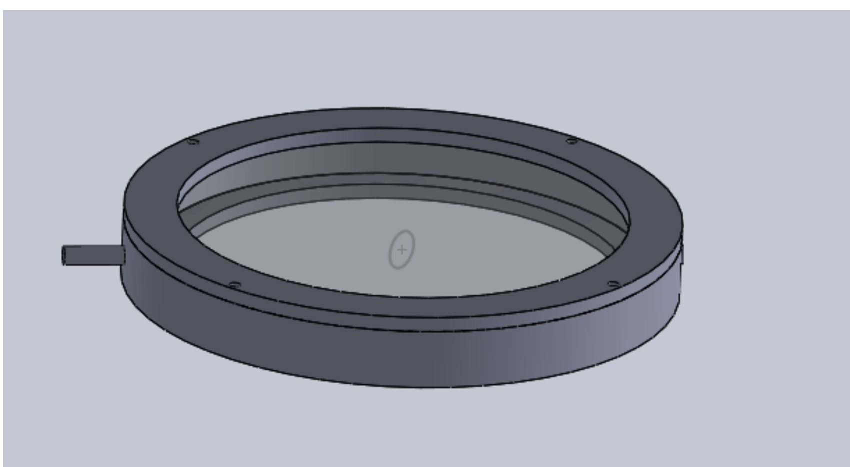
Instructions:

1. Place filter into the bottom filter holder (B)



2. Place the top filter holder on top of the filter and line up the holes with the bottom filter holder. Screw the top filter holder (A) into the bottom filter holder (B) using the screws.

3. Insert the small tilting shaft (D)) into the bottom filter holder and adhere with jbWeld. **Do not insert the PRM shaft (C) yet.**

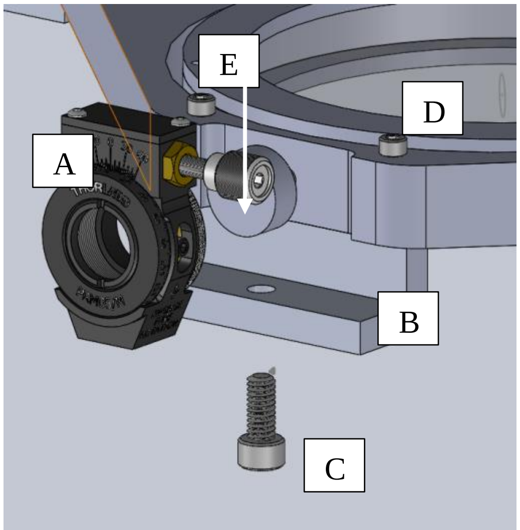


4) Repeat for all four filters

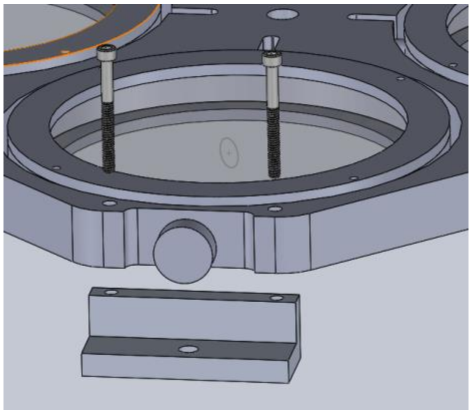
Step 2: PRM Brackets

Part List:

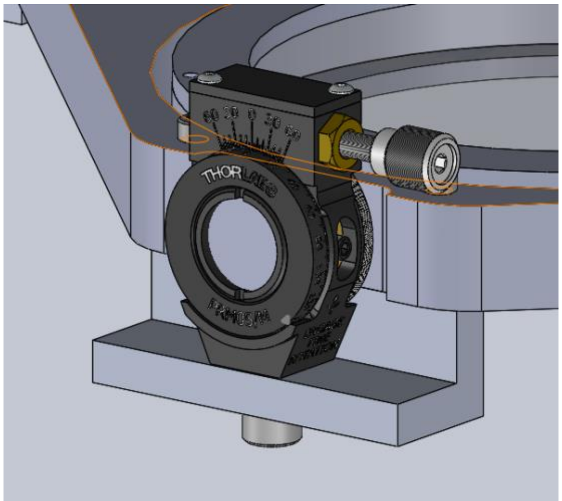
- PRM (A)
- PRM Bracket (B)
- PRM Screw (C)
- Bracket Screws (D)
- PRM Shaft (E)



Step 1: Attach the PRM Bracket (B) to the filter wheel using the Bracket Screws (D). Insert the PRM Shaft (E) though the filter wheel into the filter holder. Secure with jbWeld. Repeat for all four brackets

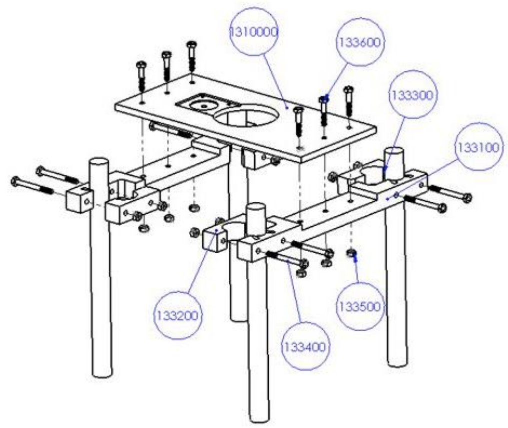


Step 2: Slide the PRM over the PRM Shaft and then insert the PRM screw into the bottom of the Bracket. Repeat for all four PRM's



Top Clamping Assembly

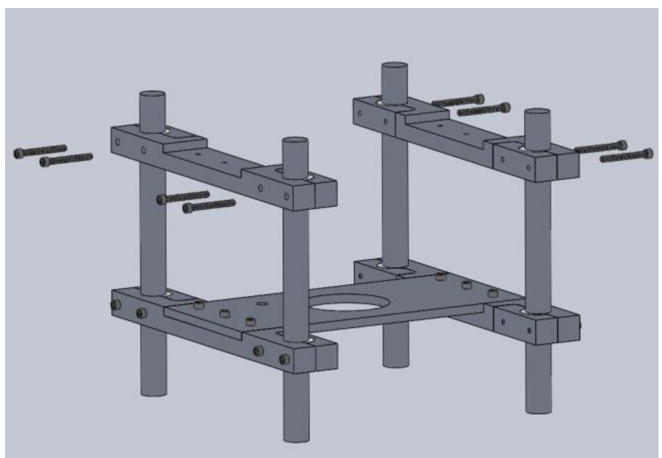
Parts List:



- x2 Locating Clamp (133100)
- Top Platform (131000)
- x4 Clamp Block (133200)
- x4 Rubber C (133300)
- x8 ¼-20, 2-1/2" Long Bolts (133600)
- x14 1/4-20 Hex Nuts (133500)
- x6 2 1/4 - 20, 1-3/8" Long Bolts (133400)

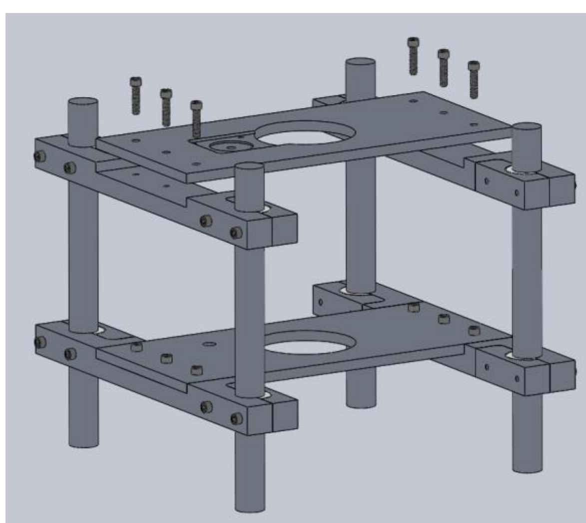
Instructions:

1. Hold the clamp block to the two poles adjacent to one another. Attach the locating clamp to the clamp block (with a piece of rubber against the pole) using 2 1/4 - 20, 1-3/8" Long Bolts and 2 1/4-20 Hex Nuts for each locating clamp.



2. Repeat for the other set of poles.

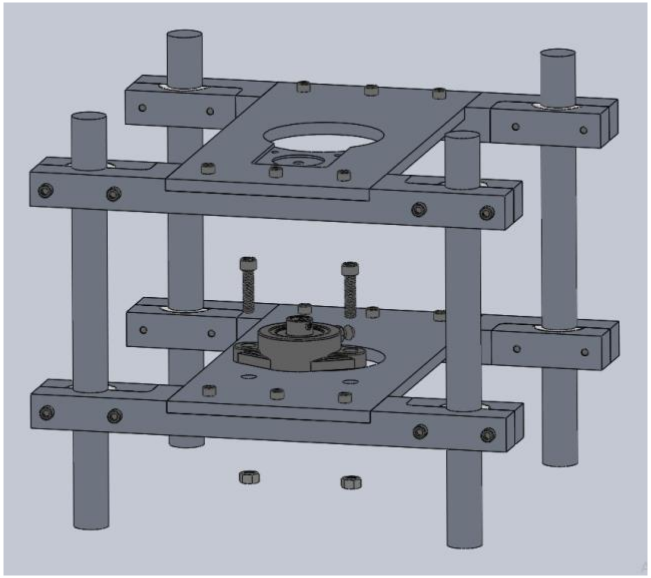
3. Place the top platform into the indentation on the clamp blocks. Secure with 6 1/4 - 20, 2-1/2" Long Bolts.



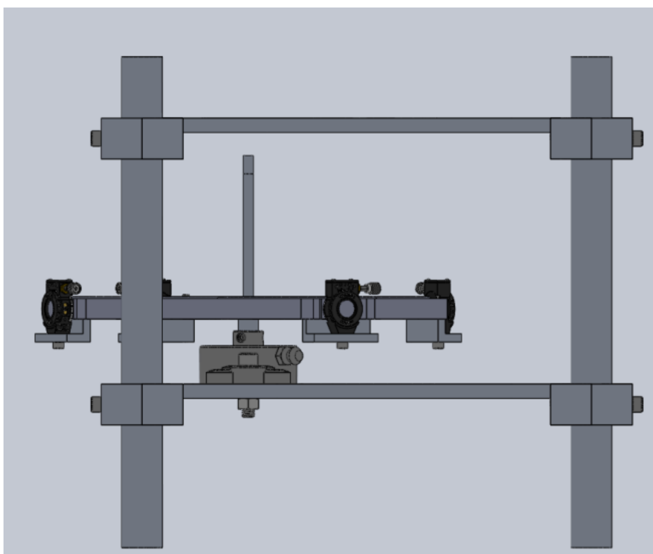
Vertical Motor and Shaft Assembly

The assembly of the rotating shaft and motor is a bottom up process beginning with the bottom platform that is already assembled.

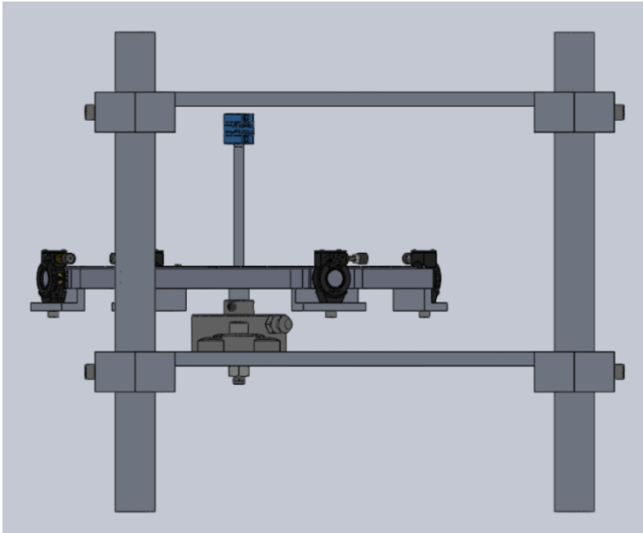
Step 1: Attach the bearing to the bottom platform using 5/16"-24, 1-1/4" Socket (Alloy Steel) Bolts and 5/16"-24, Grade 8 (HSS) nuts.



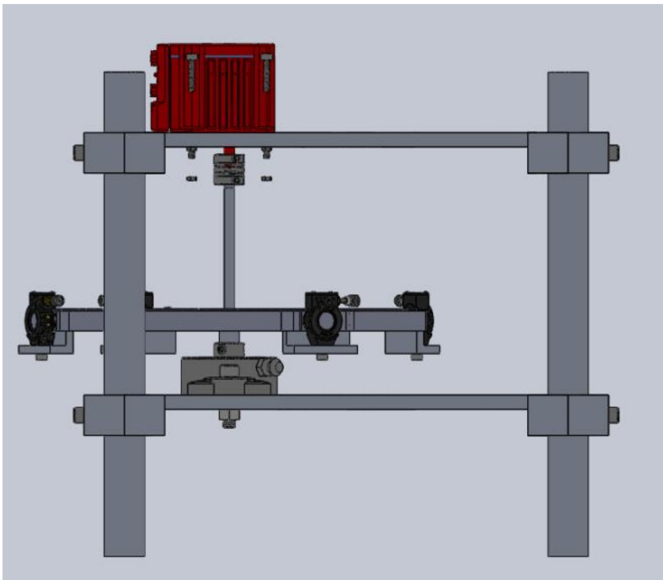
Step 2: Secure the larger diameter of the main shaft into the bearing and secure with set screw. The upper clamping assembly can be moved higher up the poles to allow room for the installation of the filter wheel onto the main shaft. Adhere the filter wheel to the main shaft using jbWeld.



Step 3: Attach the coupling to the main shaft. Make sure that the shaft only inserts halfway through the coupling to allow room for the motor shaft.



Step 4: Bolt the motor to the top platform using M4 .7mm (Alloy Steel) bolts and M4 7mm Width Hex (HSS) nuts. There is a cutout in the top bridge which lines up with the motor. Once the motor is secure lower the upper clamping assembly until the motor shaft is halfway through the coupling and secure the motor shaft in the coupling using the setscrew.



Important tests before operation:

In order to avoid any damage to the system before operation, it is important to perform basic collision detection. Begin by rotating the filter wheel by hand to make sure that the PRM's do not collide with the four poles. Next rotate each filter to make sure that they can rotate freely (plus or minus 20 degrees) without any interference. Make sure all bolts are secure before powering the motor.

Appendix N: DVP&R

Senior Project DVP&R

Date: June 2nd, 2020	Team: 75 - Optical Filter Selector	Sponsor: Space Science Laboratory, UC Berkley	Description of System: A thermally stable enclosed assembly which automattically and remotely rotates a wheel of filters and allows each individual filter to be acurately tilted	DVP&R Engineer: Matthew Allen, Cal Schwefler, Joel Pitzer, Camaryn Chambers

TEST PLAN										TEST REPORT			
						SAMPLES		TIMING		TEST RESULTS			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	NOTES
1	System Test 1	Size Constraint	254 x 254 x 203.2 mm	Joel	CP	1	Sys	4/15/2020	4/16/2020		X		
2	Tilt Test	Filter Tilt	0-10 deg (0.2 deg steps)	Cal	SP	4	Sub	3/10/2020	3/11/2020		X		
3	System Test 2	Active Filter Centered	127 mm from x and y edges	Matt	SP	1	Sys	4/15/2020	4/16/2020		X		
4	System Test 3	Maintenance Life Cycles	200,000	Camaryn	FP	1	Sys	4/20/2020	4/21/2020				Life Test was not able to be conducted
5	Cost	Cost Per Device	$4000	Matt	FP	1	Sys	4/20/2020	4/21/2020	$5,018		X	
6	System Test 4	Temperature Stability - Initial concept and test of feasibility	Target Temperature TBD, stable to within 10 degrees celcius	Cal	SP	1	Com	2/15/2020	3/16/2020				Temperature Stability Test was not able to be conducted
7	System Test 5	Temperature Stability - Final prototype with filter tilting	Target Temperature TBD, stable to within 10 degrees celcius	Cal	FP	1	Sys	4/25/2020	4/25/2020				Temperature Stability Test was not able to be conducted
8	Clamp Test 1	Continous clamping	Minimal deflection with 2x safety factor	Joel	FP	4	Sub	4/10/2020	4/11/2020		X		Wooden poles were used instead of steel
9	Adjustability Test 1	Feasibility of changing filters	Filter changing is posibile and takes less than 5 mins	Matt	SP	1	Sub	4/12/2020	4/13/2020				The team was not able to obtain filters to perform this test with
10	Adjustability Test 2	Feasibility of tiliting filters	Filter tilting is posibile and takes less than 5 mins	Cal	SP	1	Sub	4/12/2020	4/13/2020		X		

Appendix O: Test Procedures

Test 1: Life Test (200,000 cycles)

Description of Test:

Run the filter selector for 200,000 cycles to test the maintenance life cycle.

This will test the structural stability of the design and also ensure that the position of the filters stays as intended.

Required Materials:

- Filter Selector
- SmartMotor
- Ruler
- Level

Testing Protocol:

1. Set up the Optical Filter Selector assembly with the smart motor and clamps attached to the poles. Assemble according to the assembly instructions.
2. Run the SmartMotor at the desired RPM for 200,000 cycles. (Recommended to use 1 RPM)
3. Take measurements every 50,000 cycles.
   a. Check the position of the filters by measuring the distance from the center of the filter holder to each edge of the platform.
   b. Check the angle of each of the filters.
   c. Check the performance of the clamps by measuring the distance from the top of the poles to the top of the clamps.
   d. Check that no small parts or screws have fallen out or onto the ground.
4. After running for 200,00 cycles, perform the last measurements and calculate difference in positions.
5. If the positions of the filters have changed position by more than 3 mm, the filters have changed angle by more than 0.3 degrees, or any parts have fallen, the design automatically fails.

Data:

Number of Cycles	Distance to X Edge [in]	Distance of Y Edge [in]	Angle of Filter [deg]	Clamp Position 1 [in]	Clamp Position 2 [in]	Clamp Position 3 [in]	Clamp Position 4 [in]	Fallen Parts? [Y/N]
0								
50,000								
100,000								
150,000								
200,000								

Pass / Fail

Description of Test

To see if thermal stability of our system can be maintained.

Location: A room with access to electricity and a window that can be opened (or other method of simulating the outside temperature during the night)

Required Equipment:

- Thermal Enclosure Box with insulation
- Heating pads with controller
- Data recording thermocouples
- Computer for data recording

Safety:

The heating pad will be surrounded by insulation to ensure that no one is burned, and it will be ensured that the heating pad does not exceed the melting temperature of the insulation. No PPE should be required for this test.

Data Collection:

Data on system temperature and room temperature will be collected using thermocouples and a data acquisition system. This will enable viewing of data within excel to observe fluctuations in temperature and the thermal stability of the system. An uncertainty analysis will be conducted on the temperature data after it has been collected.

Testing Protocol:

1. Test the system before the desired test weekend to ensure that data is being properly collected and stored and that the heating pad is not melting the insulation.
2. Set up the system in a room to be run for a weekend. This will involve clearing out the room and perhaps leaving some windows open to allow the temperature to fluctuate.
3. Leave the system set up recording data over the weekend. A team member will check in on the experiment every 8 hours to ensure that it is running as desired.
4. The test will be ended at the end of the weekend by unplugging all the data collection equipment and inserting an SD card from the data collection system into a computer for analyzing data.
5. The equipment will be removed from the room and the data will be processed to see if thermal stability was achieved.

Data:

Maximum Temperature Difference from Set Point [ºF]	

Test Procedures

Test 3: System Interface Tests

Description of Test:

Ensure that the optical filter assembly interfaces properly with and fits within the overall assembly.

- Clamps
- Filter Wheel

Required Materials:

- Filter Selector
- Clamps
- Mockup of overall assembly (4 poles and a spacing plate)

Testing Protocol:

1. Attach the clamps to the poles to ensure that they fit as intended and do not slide down the poles once the screws are tightened.
2. Attach the platforms and filter wheel and rotate the filter wheel a full rotation to ensure that the poles do not interfere with the rotation of the filter wheel.

Data:

System Test	PASS/FAIL
Clamps	
Filter Wheel	

Appendix P: Gantt Chart

Team 75 Optical Filter Selec...	start	end	100%
Scope of Work	**09/27/19**	**10/21/19**	**100%**
Search 5 Current Products	09/27	10/04	100%
Research 5 Relevant Literatures	09/27	10/04	100%
Search 5 Patents	09/27	10/04	100%
Interview Customer	09/27	10/04	100%
Write Problem Statement	10/08	10/08	100%
Perform QFD	10/10	10/10	100%
Create Specification Table	10/11	10/11	100%
Create Initial Project Plan	10/14	10/15	100%
Create Gantt Chart	10/21	10/21	100%
Write Background Information	10/18	10/18	100%
Write Scope of Work Draft	10/14	10/17	100%
Turn in Scope of Work	10/18	10/18	100%
Submit Scope of Work to Sponsor	10/21	10/21	100%
Preliminary Design Review	**10/18/19**	**11/21/19**	**100%**
Brainstorm	10/18	10/24	100%
Build Concept Models	10/25	10/29	100%
Evaluate and Choose Idea	10/29	10/31	100%
Build Concept Prototype	11/01	11/07	100%
Create Concept CAD Model	11/01	11/07	100%
Create Risk Hazard Checklist	11/01	11/07	100%
Create Presentation	11/07	11/11	100%
Update Report	11/11	11/14	100%
Present PDR	11/12	11/12	100%
Present PDR to Sponsor	11/15	11/15	100%
Complete FMEA	11/20	11/21	100%
Interim Design Review	**12/17/19**	**01/16/20**	**100%**
Design Platforms	12/17	12/24	100%
Select Tilting Mechanism	12/19	12/26	100%
Design Enclosure	01/06	01/15	100%
Design Connector to Tilting	01/06	01/15	100%
Create Function Overview	01/06	01/15	100%
Create Manufacturing Overview	01/13	01/15	100%
Update Testing	01/13	01/15	100%
Compile Concerns/Feedback	01/14	01/15	100%
Present IDR	01/16	01/16	100%
Critical Design Review	**12/24/19**	**02/05/20**	**100%**
Perform Fatigue Analysis	12/24	12/30	100%
Finish Design Analysis	01/17	01/27	100%
Analyze Temperature Stability Syst...	01/17	01/27	100%
Design Locking Mechanism	01/21	01/27	100%
Build Structural Prototype	01/20	01/27	100%
Choose Final Parts/Materials	01/23	01/30	100%
Complete Detailed CAD	01/23	01/30	100%
Create Manufacturing Plan	01/28	01/30	100%
Create Drawings	01/28	02/03	100%
Prepare Presentation	01/30	02/03	100%
Present CDR	02/04	02/04	100%
Present CDR to Sponsor	02/05	02/05	100%
Manufacturing and Testing Review	**02/05/20**	**05/22/20**	**100%**
Send Drawings to SSL	02/05	02/12	100%
Complete Risk Assessment	02/11	02/14	100%
Perform Safety Review	02/11	02/14	100%
Review for Safety	02/17	02/24	100%
Prepare Detailed List of Standard Par...	02/20	02/27	100%
Order Parts	02/27	03/05	100%
Compile Test Procedures	03/05	03/12	100%
Finalize Test Procedures	04/01	04/17	100%
Assemble Parts	05/13	05/20	100%
Complete System Interface Test	05/21	05/22	100%
Final Design Review	**05/12/20**	**06/05/20**	**100%**
Design Website	05/12	05/19	100%
Create Videos for Virtual Expo	05/18	05/21	100%
Finish Writing Report	05/26	06/05	100%