ARES Cleaning System
Spring 2019 - Final Design Review

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Abstract
In this Final Design Review, the team outlines the general scope of the ARES Cleaning System project and the final design direction chosen and built. This team consists of a group of four mechanical engineering students who have been tasked with designing and manufacturing an autonomous ARES cleaning system to help their sponsor, Fracsun, better track soiling losses measured at large solar arrays. They designed, conceptualized, manufactured, and tested throughout the project as they looked to create a final, functioning product. In creating this Final Design Review, they have identified how the product will perform the desired functions and what materials and manufacturing methods need to be used for further development. The team has chosen a specific design, while creating a functional prototype that can be improved in the future or used immediately with Fracsun. The team has also identified future recommendations so that it can be implemented into a wider range of environments and be mass produced. While most of the specifications laid out by the team were met, they have reflected on the project and determined what worked during the year long project and what can be improved in the future.

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1. Introduction

Fracsun, a company built on helping solar array owners track soiling losses to save both time and money, has put forward the ARES Cleaning System project for our team at California Polytechnic State University, SLO. Fracsun provides owners of large solar arrays with an effective way to collect data and give feedback on the soiling losses in the arrays. The system consists of two panels, one control and one reference panel. The reference panel needs to be cleaned on a daily basis to be compared to the control that becomes dirty with the rest of the array. Our team, the Solar Patrollers, is a group of four mechanical engineering students: John Cunningham, Jack Glynn, Peter Greig, and Andy Sagers. We have taken on this project because of our interest in advancement in the solar industry and our desire to complete a year long senior project as we pursue a Bachelors degree in Mechanical Engineering. We have been tasked with designing and manufacturing a working prototype of the ARES cleaning system. This cleaner will be an autonomous cleaner that both eliminates the use of water and provides feedback as it cleans the 20x20 cm reference panel. We will aim to lower the cost and weight of the existing product used by Fracsun, with the purpose of helping Fracsun advance as they continue into Phase II of their overall design process. What follows in the Final Design Review is a background section, summarizing our preliminary findings, the objectives and goals of our scope, the ideation process, the chosen design direction, the manufacturing process for the final design, and the verification of this design.

2. Background

To begin this project, the team has done extensive research into what products and patents currently exist and what Fracsun desires. What follows in this background section is the findings of this research, with references to the exact articles and interviews in the appendices.

2.1 Sponsor Research

During the project presentation as well as our initial meeting with out project sponsor, we learned several things about Fracsun's current system and their experience in the solar industry. Firstly, Fracsun, as well as the solar industry as a whole, is very averse to moving parts and maintenance. Solar plants are often in very remote areas over vast land areas and panel arrays expected to operate for years at a time with little to no human intervention. This makes using any water and pumps which require refilling and frequent maintenance not tenable in this market. Fracsun, however, uses a water sprayer cleaning method on the current iteration of their device. This was because they needed a quick solution for their device in order to qualify for the Department of Energy grant they had been awarded. It uses a 25 gallon tank that water is drawn from using a pump and sprayed out of two nozzles onto the reference clean panel below. This method is not preferable and this limits the use of device to areas where the water will not freeze on the panel surface. Additionally, a 2' by 3' solar panel, separate from the device, is needed to power the pump cleaning system. Thus, Fracsun wants to eliminate the current wash extension entirely to a more maintenance-free friendly method.

Some other information we were told at our first sponsor meeting and additional meetings since then is that their current method is a 5th iteration design, with previous methods including a linear actuating manifold that used a lot of water. Additionally we have been told to stay away from from any sort of covers or lids for the reference clean panel for several reasons. One is that the solar panel is needed to charge the battery for the device as well as the panel needs to take measurements over the course of the day, so the lid would need to open and close several times throughout the day. This creates vortices that pull any dust from the outside into the closed off area that would negate the effectiveness of the lid and the panel would still need additional cleaning. We were told that industry acceptability for maintenance would be once a year with a five year lifetime without any major maintenance. In our most current meeting we asked about the possibility of using a clear cover, either plastic or glass, and we learned that any sort of clear covering would affect the irradiance of the panel which would affect the reading taken by their device. Anything above an irradiance of 1-2% would be enough to throw the entire measurement off. Additionally, placing a covering over both panels would cancel out the effect on the measurement, however the two covers would have to be attached the same way so if one had to move over the surface of the panel, we would not be able to adhesively attach a cover to the control panel. And without an adhesive attachment, there exists the very high possibility that water or dust could accumulate between the clear cover and the panel. And finally when taking into account their current system and designing our cleaner around it, though it would be efficient for them not to change the hardware or layout, but if need be they will design around our cleaning system.

2.2 Product Research

Five competitors of the ARES Cleaning system were researched and compared to Fracsun's product. All five of these products are soiling measurement devices. In Table 1, the vendor and name are listed aside a description of the product. The products are evaluated in the two paragraphs following Table 1.

Table 1. Product Research Descriptions

Product	Description
Atonometrics - PV Device Soiling Measurement Systems for PV Power Plants  (Atonometrics)	The Atonometrics soiling measurement device measures soiling loss and soiling rate of PV power plants. This data is used for pre construction purposes or to optimize cleaning schedules of preexisting solar plants. The device has a control cell, accumulating dirt over time, and a reference cell, that is autonomously cleaned every day. The reference cell is a small PV cell about 1/60 the size of the control cell. The control cell's energy output powers the system. A water solution and pump is used to clean the reference cell. This water solution does not freeze in cold temperatures and the reference cell has its own heating system. These features allow the product to be utilized in cold and snowy locations. In the photo, the black reference cell can be seen at the base of the control cell. The pump system runs tubing from the large white box to the reference cell. When deployed in the field, the device is either placed at a new possible solar plant site or next to an existing array.
NRG Systems - Soiling Measurement Kit  (NRG Systems)	The NRG Systems Soiling Measurement Kit measures the impact of soiling on PV plants. The product can be used to optimize cleaning and maintenance schedules or provide pre construction data for PV plants. The device consist of three PV cells, a control, reference, and logger power cell. The control cell collects dirt over time. The reference cell is regularly cleaned, by an onsite worker, with deionized water. The logger power cell provides a 12V signal to power the device. All three of the cells are mounted to a pole and cable structure. This device can be installed with NRG Systems SRA System attachment. The SRA System is another device providing data to improve PV plant efficiency.

Table 2. Continued Product Research Descriptions

Product	Description
Kipp & Zonen - DustIQ Soiling Monitoring System  (DustIQ for PV Solar Monitoring)	The DustIQ Soiling Monitoring System collects soiling measurement data to find out when and where PV plants need to be cleaned. The system does this by tracking the loss of light transmission caused by dirt on PV panels. Furthermore, the device does not have a control or reference cell. Instead it uses two light monitoring systems that accumulate dirt over time. These are the blue lights in the photo. The 990 x 160 mm PV cell in the middle of the two lights powers the system. This design requires no maintenance and no moving parts. The voltage required to power the device is 12-30 Volts DC. It takes measurements in one minute intervals throughout the day. The system is mounted in alignment with existing PV arrays.
Kintech Engineering - Soiling Measurement Kit  (Kintech Engineering)	The Kintech Engineering Soiling Measurement Kit provides data to learn the exact effect soiling has on PV arrays. The device compares a clean reference to a dirty control cell. The reference cell is cleaned manually, by an onsite worker. The system is powered by its own solar power running at a voltage of 12 Volts DC. The temperature range of this product is -40 to 85 degrees C. It is commonly implemented in the field with other meteorological devices measuring temperature, pressure, and wind speed. To accommodate the extra devices the product is supported by a large metal structure. Because this device is built for a wide range of environments, it is commonly used to survey solar possibilities in extreme weather locations.
Campbell Scientific - SMP100  (SMP100: Solar Module Performance Monitoring System)	The Campbell Scientific SMP100 is an in field soiling measurement device for operational or pre construction PV sites. The device consists of a clean reference cell, dirty dirty control cell and control box. The control cell must be cleaned manually by an onsite worker. The product is marketed mainly as an add-on to other Campbell Scientific meteorological systems, measuring other variables affecting solar panel efficiency. However, it can be used on its own as a soiling measurement device.

Analyzing the five products listed above, only two can be declared major competitors of the ARES Cleaning System, the Atonometrics PV Device and Kipp and Zonen's DustIQ. These are the only fully autonomous low maintenance products that provide soiling data to PV plants. Atonometrics accomplishes this with a system very similar to the ARES Cleaning System. Both have a dirty control and self cleaning reference cell combination; however, Atonometrics' control cell is much larger. This inhibits the product from being installed directly on an existing solar array. The advantage of this device is that it can be used in cold environments. The reference cell can be heated and the pump system runs with an antifreeze water solution. Atonometrics' patent information can be found in Appendix A. The other stand-out Fracsun competitor was Kipp and Zonen's DustIQ. This device autonomously collects soiling data using a light monitoring system that tracks loss of light transmission due to soiling. Thus, no reference must be cleaned in order for the DustIQ to run. In addition, the self powered product has no moving parts and requires no maintenance. As one can see, DustIQ's unique design satisfies many of the design requirements the ARES Cleaning System is working toward. The major concern is how light transmission data compares to that of ARES's control and reference cell data. Moreover, because this technology is new and not used by many, Kipp Zonen's product has not gone through enough testing to prove reliability.

As for the remaining three devices from Kintech Engineering, NRG Systems and Campbell Scientific, the primary need to self clean is not satisfied. While this classifies the products as poor competitors to the ARES Cleaning System, knowledge can still be gained from these systems. The designs of these devices are robust and permit flexibility. They can be placed in any environment and are often sold as attachments to more complex meteorological measuring systems. If the ARES Cleaning System could implement these design features, the product would reach more customers throughout the world.

2.3 Technical Research

With our technical research, we looked at several articles with case studies ranging from automatic solar panel cleaning solutions to any waterfree method of cleaning a surface. For solar panel cleaners, several methods were investigated that included wipers, roller wipers, lasers, static electricity, and acoustic systems. Some methods still used water but we specifically looked for cleaning solutions without water. Some systems utilized wind or solar energy to power their device while others relied on external power sources.

The final design for the photovoltaic panel cleaner is required to meet certain codes and regulations including an International Protection rating, the National Electrical Manufacturers Association (NEMA) 4X rating, and the Underwriters Laboratories (UL) listing. These are important to the design because the product needs to be safe for anyone interacting with the system. It is also important that that all the electrical components are enclosed so that they are protected from dust, debris, and water. Further information on these codes and regulations can be found in Appendix B.

Case studies by Lu and Qiang utilized driven drag-wipers with pressure applied between the wiper and the panel. The movement was driven with a linear actuator and the wiper was able to reach the edges of the panel for complete coverage. A rolling, rotating wiper was a very popular cleaning method seen in case studies from Wang, Jawale, Qiang, and Aly. Some just used a nylon brush whereas the case study from Aly used three separate rotating rollers. In a 4 stage cleaning process, compressed air first cleans the surface, followed by a foam roller and an additional pass of the compressed air before finally brushed with a finishing pass of a rotating ostrich feather roller. Additional research was done in looking into case studies that detailed any water-free cleaning methods such as laser cleaning for windows and compressed air cleaning for apricots. There was mention that the laser system could have use cleaning a solar panel but additional research would have to be done in observing how the laser would affect the solar panel and its performance.

Overall, it was helpful into researching what can feasibly be done and tested, as well as what has and has not been done for cleaning methods. These case studies also gave us inspiration for possible cleaning methods during our ideation phase of the project. Further information into the case studies presented here can be found in Appendix C.

2.4 Additional Research

Additional research was done after the broad scope of the project had been addressed. The below research focuses on specific functions of the desired product and how these functions might be incorporated.

2.4.1 Alternative Cleaning Methods

The first step in performing additional research was to look into alternative cleaning methods that don't use any water. The patents for each of these methods can be found in the Patent Research Table in Appendix A. It was found that a remote controlled vacuum system could be used to remove dust, debris and liquids from our panel, and a radio controlled transmitter could be used to power the device on and off. A lint roller with a disposable adhesive sheet could be used to remove dust and debris, but would be ineffective in the removal of liquids and would create a lot of waste. A squeegee brush combination tool provides both scrubbing and scraping capabilities that could effectively remove almost any debris or liquid without the use of a motor driven blower that is required for a vacuum system.

Additional research looking into the use of a microfiber material and ostrich feathers was done. Microfibers are commonly used in dust mops that use static electricity to pick up dust. These mops are completely cleaned by washing them with water and soap however, a less thorough cleaning is done by simply shaking the mop out. (Simply Good Stuff) Ostrich feathers have been used in the automotive industry to clean. They are also used in feather dusters, where the duster is made up of 100% ostrich feather. When this is the case, these feathers have a very good rate of attracting dust and are resistant to static charge. Due to the collection and not elimination of dust, these feathers would need to be cleaned in order to continue performing over long periods of time. (Speed Cleaning)

2.4.2 Sensor Research

Our cleaning system is going to require some sort of sensor in order to provide Fracsun's microcontroller with feedback. There are multiple options for sensor selection, and each has its own advantages and disadvantages that will be taken into account when the overall design is completed. The following list provides each sensor type along with benefits and drawbacks of each.

Video
- Provides live monitoring, but is expensive, and requires lots of cellular data

Infrared
- Cheap and requires low power, but could be affected by debris crossing the sensor's path (Thonti)

Ultrasonic
- Utilizes the sound of the system as feedback, but could easily be disturbed by outside noise (Thonti)

Magnetic
- Commonly used for security systems, and is readily available, but would require components in two locations (Thonti)

Contact
- Simple and reliable, but would require custom design

Vibration
- Utilizes the vibration of the system, but could easily be affected by external vibrations

Microwave
- Can distinguish movement toward and away from sensor, but requires more power than other sensors (Thonti)

DC Motor Potentiometer
- Device is built into DC motors of actuation devices providing feedback of the device's angle, speed and displacement (Resistor Guide)

2.4.3 Linear Actuation Research

In order to develop solutions for the cleaning function of the ARES Cleaning System, further linear actuation research needed to be completed. While it is not guaranteed actuation will be needed for the cleaning system, additional research has helped us identify practical ways to move a cleaning device up and down a panel. The following list consists of different linear actuation methods with the benefits and drawbacks of each.

Lead Screw Actuator

- Robust design able to hold medium to large size loads
- Actuation requires power screw and guiding mechanism to be fixed onto system (Firgelli Automations)

Worm Drive Actuator

- Robust design able to hold very large size loads
- Used for heavy duty applications thus expensive (Firgelli Automations)

Reciprocating Motor Actuator

- Provides repeating linear motion with simple system
- Hard to control and limited to one single cycle motion

Rack and Pinion

- Robust design good for long travel lengths
- Manufacturing can be costly (Collins)

Chain Drive

- More commonly used to transmit power but in this case actuation moves with chains
- Requires a full loop to be made around two sprocket gears (Encyclopaedia Britannica)

Rigid Chain Actuator

- Rigid chain is fed out of sprocket enclosure and is completely enclosed when not in use
- Chain system is complex and expensive (Collins)

Gravity and Pulley System

- Custom actuation system using gravity to advantage
- Cable system would be custom and require excessive maintenance

Hydraulic or Pneumatic System

- High force, fast responding, liquid and air systems
- High cost systems that often required excessive maintenance (Collins)

3. Objectives

This objectives section outlines the project goals and specifications, a problem statement and boundary diagram to depict the specific problem, and a Quality Function Deployment - House of Quality (QFD) to help analyze the desired specifications.

3.1 Problem Statement

Fracsun analyzes power loss due to the soiling of solar cells to help solar plant operators refine their wash schedules for cost effectiveness. For their ARES system, Fracsun needs a way to autonomously clean a reference solar panel at a daily interval with minimal maintenance while eliminating the use of water or other liquids, due to concerns with freezing and pump upkeep.

3.2 Boundary Diagram

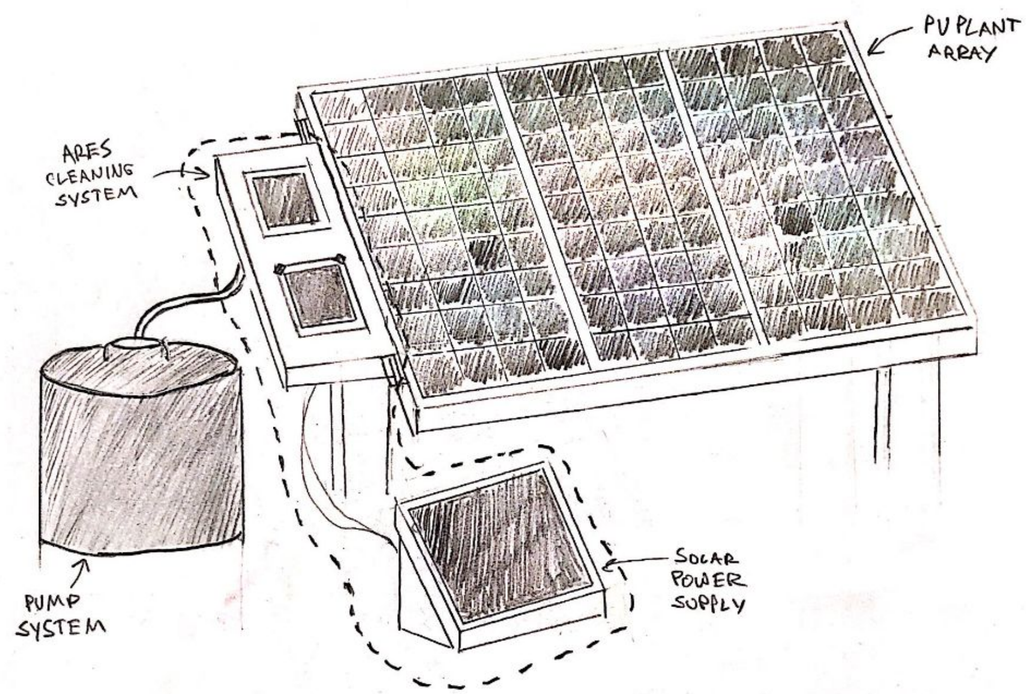


Figure 1. ARES Cleaning System Boundary Diagram

The boundary diagram in Figure 1 offers a visual representation of the scope of the ARES Cleaning System project. The dashed line serves as a boundary to what our project has a direct influence on. Inside the boundary is the cleaning system itself and the solar cell that powers the pump and cleaning system. The final product of this project will alter these two components. Outside the boundary are elements related to these components that will not be in our design. These include the solar plant array and the pump system. The pump system will be removed from Fracsun's product due to elimination of water usage.

3.3 Needs/Wants List

The customer needs/wants list is outlined in the Customer Requirements section of the QFD House of Quality located in Appendix D. Ten customer needs were chosen based on discussions with our sponsor and team research conducted and documented in the background section. The following bulleted list provides the ten needs and wants chosen for analysis in order of importance beginning with the most important. The importance is defined by the House of Quality as a relative weight in the customers section.

- An autonomous system
- The capacity to clean a 20x20cm piece of glass on a daily basis
- Maintenance on a yearly basis
- The ability to provide accessible cleaning feedback
- The elimination of water or other liquids
- Powered by a DC voltage supply
- Clean on a nightly basis
- Easy to install
- Cheap/affordable
- Works in critical temperatures

3.4 QFD House of Quality Analysis

QFD (Quality Function Deployment) is an analytical method used to define a customer's needs and requirements. The full House of Quality resulting from the QFD analysis can be found in Appendix B. It incorporates given needs, engineering specifications, and QFD analysis into one specifications table found below in Table 3. The results of the analysis show that our most important specification is the ability of our system to provide a feedback voltage to Fracsun's microcontroller. The relative weights of the specifications also indicate that the maintenance and cleaning schedules are critical requirements to the design when compared to install time and critical temperature range. Needless to say, we believe all of the needs and specifications are important, and we plan to meet all of our target values assigned in Table 3. The four competitors listed in the far right of our House of Quality each have products with unique design features and specifications. We plan to use a similarity comparison of these products against our own along with analysis and testing to ensure our product meets all the needs and specifications required by our customers and sponsor.

Every specification listed in Table 3 needs to be verified by one of four methods: Analysis (A), Test (T), Similarity to existing designs (S), Inspection (I). In addition each specification is given a risk factor of either High (H), Medium (M), or Low (L) indicating how hard it will be to meet each specification.

Table 3. Design Specifications

Spec #	Specification	Target	Tolerance	Risk (H, M, L)	Compliance (A,T,S,I)
1	Maintenance Schedule	Once/Year	Max	M	A,T
2	Install Time	15 Minutes	Max	L	S,T
3	Power Requirement	12-24 VDC and 30 A	Max	L	A,T
4	Cleaning Schedule	Once/day	Min	L	T
5	Weight	6 lbf	Min	M	A,T
6	Cost	$600	Max	M	A
7	Area Cleaned	400 cm^2	Min	L	T
8	Temperature Range	-40-185 °F	Min	H	A
9	Lifetime	10 Years	Min	M	A
10	Amount H_2O	0 mL	Max	H	I,T
11	Feedback Voltage	50 mV	Max	L	T

Specifications:

- Maintenance Schedule: This maintenance schedule through testing to determine how often our product will need to be maintained.
- Install Time: The install time will be measured through testing, by timing how long it takes to install the product in the field.
- Power Requirement: The power used by our product will be measured through voltage analysis and testing with a digital voltmeter.
- Cleaning Schedule: The cleaning schedule will be measured through testing how often our product autonomously cleans the solar cell.
- Weight: The weight of our product will be measured through analysis using 3D modeling as well as testing with a scale.
- Cost: The cost of our product will be measured through a cost analysis for both a single product as well and wholesale.
- Area Cleaned: The area cleaned will be measured through testing and visual inspection of our solar cells.
- Temperature Range: The temperature range will be measured through analysis of selected materials. This is listed as a high risk specification because it could cost more to design something that withstand critical temperatures.
- Lifetime: The lifetime of our product will be measured through fatigue analysis.
- Amount H_2O: The amount of water used will be measured by inspection and testing (if necessary) the volume of water used per cleaning cycle. This is listed as a high risk specification because if any water is used, we will have failed to meet a critical design requirement.
- Feedback Voltage: The feedback voltage will be tested by monitoring the voltage across a microcontroller.

4. Concept Design

The team began by choosing three main product designs that utilize cleaning methods in different ways. Once the effectiveness of the methods were tested, a specific design route would be selected. In this section the selection process is explained and three initial designs are presented as well as additional, alternate designs that were considered but not selected.

4.1 Concept Generation

In deciding how to move forward in the project, the first step was to determine the functions of the desired product and how to best use the research that had been done. The primary functions that were determined were: the cleaning method, the source of actuation, and the sensor. These functions, when working in unison, would meet the specifications. Ideation sessions were scheduled at different times, allowing for brainstorming. Each day during the meeting, the team picked one of the three functions and came up with at least twenty ideas for how to provide the desired function. Ideas were generated sporadically with no confinement or judgement from the other team members. Following the ideation session, and the recording of the results, the team moved forward in deciding how to implement these ideas into the concept design.

4.2 Selection Process

From the chosen functions, three Pugh matrices were created that would weigh the possibilities against each other. The Pugh matrices were made by selecting a "best idea" and setting it as the datum, then comparing all other ideas to this chosen idea. These Pugh matrices can be seen in Appendix E. When working through these Pugh matrices, it was clear that the cleaning method would need to be tested. Although research provided many possibilities for cleaning materials, because of the specific conditions of soiling, testing would further show what materials were best. The two other functions were combined into three unique ideas that would be the starting point in choosing the final design direction.

Following the creation of the Pugh matrices, a decision matrix was made to weigh the best system ideas. The two cleaning methods that were compared were ostrich feathers and a scraper. These were the most desirable in the Pugh matrix, and although testing has not yet been done, the team used these two to compare the other functions. The weighted decision matrix can be seen in Appendix F. The results of this show little differences between the top three choices. It appears that using multiple cleaning tools in combination will be the best choice. Although the assumed cleaning tools are ostrich feathers and a scraper, testing will allow for stronger certainty in what cleaning tool should be used. Other options that will be tested include micro fibers, bristles, and the material lining the inside of baby diapers.

4.3 Alternate Designs

Table 4 displays the alternative project designs that were considered during the ideation process. Provided are sketches and descriptions of the designs.

Table 4. Alternative Project Designs

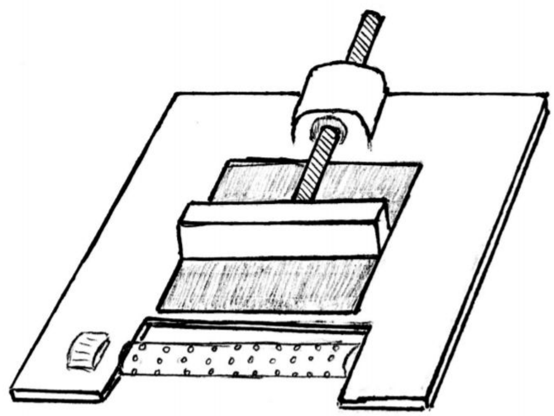
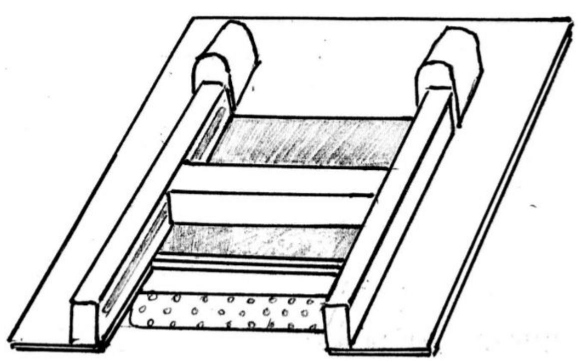
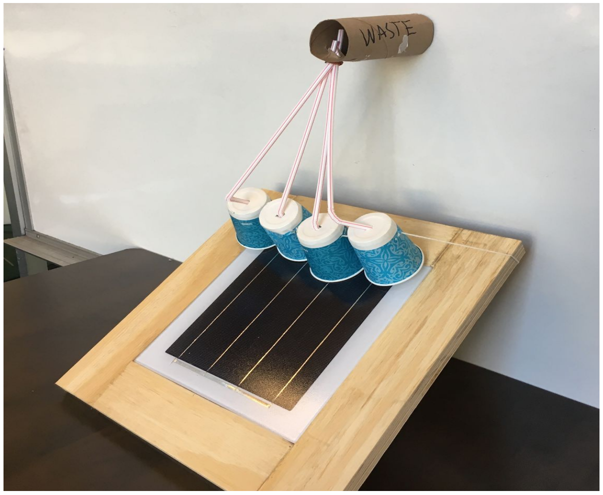
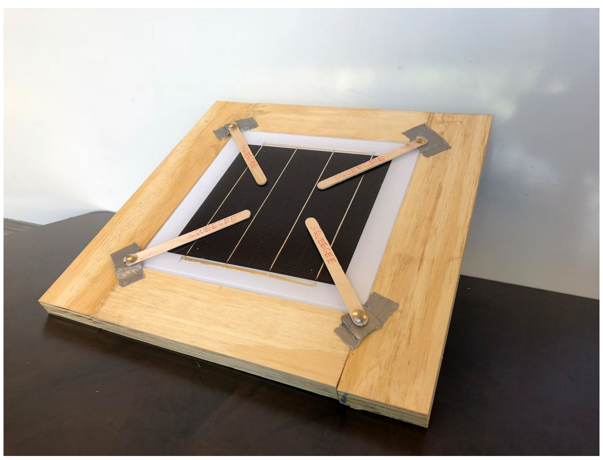
Sketch	Description
	Worm Drive Actuator A worm gear and motor system actuates a power screw, and attached cleaning system, across the solar panel. The actuation stops when the cleaning system is on top of the cylindrical cleaning bar. The bar rotates, forcefully removing the cleaning system of any dust or dirt. The actuation system reverses and returns the cleaning system to its resting state above the solar panel.
	Double Slide Stroke Actuator Using gear systems, two parallel motors rotate enclosed power screws. Screw nuts actuate along the power screws and hold the cleaning system. The cleaning system travels with the nuts over the solar panel, stopping on the cylindrical cleaning bar. The bar rotates, forcefully removing the cleaning system of any dust or dirt. The actuation system reverses and returns the cleaning system to its resting state above the solar panel.

Table 5. Additional Alternative Project Designs

Sketch	Description
	Vacuum Cleaner A vacuum cleaning system, spanning the width of the solar panel, is actuated up and down the face of the panel. The vacuum picks up any dust or contamination on the surface. Anything picked up by the vacuum travels through tubing to a waste bin. The vacuum sits above the panel when not cleaning.
	Wiper System Four hard edge cleaners are fixed at each corner of the solar panel. Using a motor, the cleaners rotate on pins. The four cleaners force dust off the face of the panel. The cleaners would be off the panel when not cleaning.
	Air Blower System An line of air nozzles is placed a top of the solar panel. An air compressor supplies air to the nozzles. When cleaning, the compressor is activated and the nozzles shoot air at a high velocity across the panel. This high velocity air removes dust that has accumulated on the panel.

4.4 Chosen Designs

Three design directions have been chosen as possible solutions to the problem statement. These designs incorporate the functions of the system in unique ways and will have pros and cons based on the results from testing done with the cleaning tools. In observing possible issues and risks associated with the design of a solution, a Design Hazard checklist has been included as Appendix G. The reason for choosing the design, the specific benefits of the system, and the possible issues with the system are discussed in each section.

4.4.1 Lead Screw Actuator Design

The first design the team decided to pursue was one involving linear actuation of a cleaning system directly over the ARES's solar panel. The cleaning system would be the width of the panel, functioning to collect dirt substances and or force them off the system. Moreover, the key decision that needed to be made for this design route was what linear actuation method would be used to move this cleaner. The Linear Actuation Research section of this report highlights the various methods of actuation that were considered. Through logical reasoning and a Pugh Matrix, seen in Appendix E, the team decided a lead screw actuator was best for the design. A lead screw actuator is robust, takes large force loads, and is easily available for purchase. The top alternatives were a rack and pinion, worm drive actuator and reciprocating motor actuator. The rack and pinion and worm drive actuator were too costly for the application. The reciprocating motor actuator would have to be custom built, making the product much harder to manufacture.

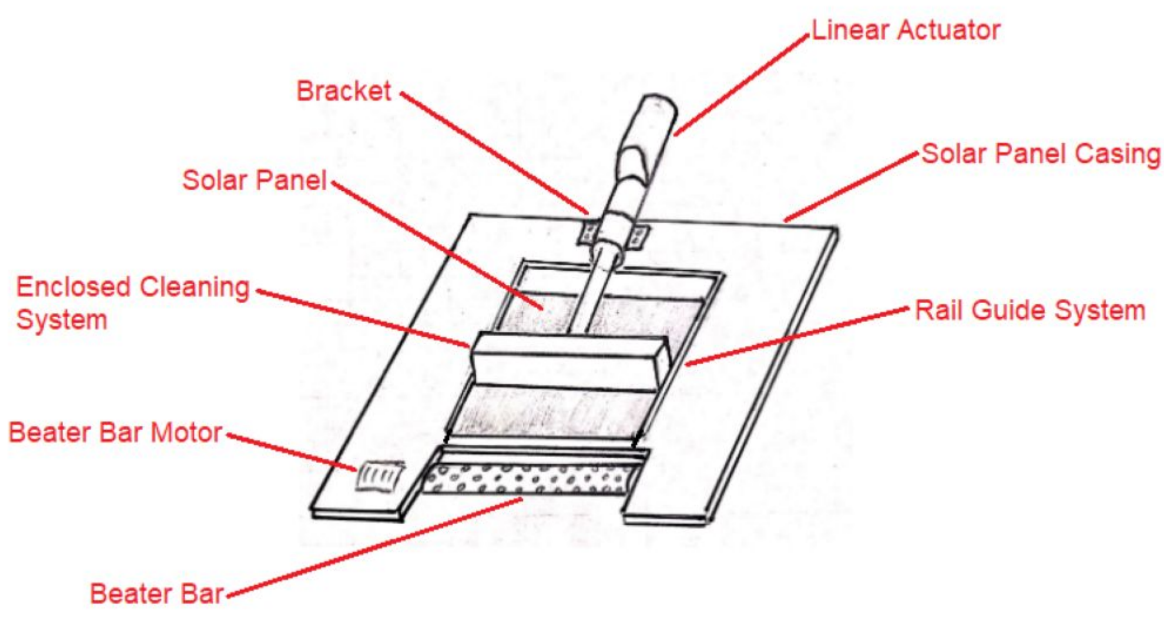


Figure 2. Lead Screw Actuator Design

Displayed in Figure 2 is the design chosen to implement a power screw linear actuation system. The actuator is fixed to the top of the panel casing. The cleaning system is attached to the actuation system thus rests above the panel when it isn't cleaning and the actuator has zero displacement. This cleaning system is completely enclosed when dormant to protect the cleaner from environmental factors. When turned on, the cleaning system is directed by the actuator across the panel. During this process the cleaner will push any dirt in front of it and pick up the remaining dirt. Guide rails will ensure the cleaner is perpendicular to the actuator and dirt is pushed forward. Once extended past the panel, the cleaner pushes the dirt over and off the panel casing. The actuator stops when the cleaning system is sitting on the beater bar. The beater bar is a cylinder with a pattern of small hemispherical extrusions. It is attached to a DC motor and pins on the panel casing. It spins for a set amount of time against the cleaning box. The extrusions on the beater bar rid the cleaning system of any dirt it has accumulated. This dirt falls below the panel. The actuator then reverses direction, traveling back over the panel to its resting position.

Because the cleaning system's method of cleaning has not been determined, specific parts have not been chosen for this design. However, a general plan has been developed. The lead screw linear actuator will be a power screw driven rod linear actuator. This is the type of actuator shown in Figure 2. In this actuation design, a DC motor and gearbox rotate a lead screw. When rotating, an encased nut holding a rod travels along the screw. The movement of the rod beyond the casing is the actuation. This power screw actuator was selected over the first two models in the Alternate Design section because it is enclosed well and the configurations of this actuator type consist of a wide array of lengths, force loads, power requirements, and control options. A 200 - 400 mm stroke would clean the 20 x 20 cm cell and permit extra movement. A 50 - 500 lbf max load, offered by actuators in our price range, would provide the cleaning force needed. The price range for the actuator is no more than half the budget, 200 dollars. The exact force range will be determined once cleaning methods are tested. The majority of actuators are offered with a 12-24 V DC input voltage, which would satisfy the ARES power specification. Most actuators are also sold with potentiometers built into their DC motors. The potentiometer would be wired to a microcontroller. This would fulfill the project's feedback requirement by tracking the position of the actuator.

As for the other components of the system, a bracket would secure the actuator on the panel casing and a lightweight plastic would enclose the cleaning system. Metal rails would be used to guide the cleaning system.

It is unknown whether the beater bar will satisfy its function of cleaning the actuators cleaning system. Once the cleaning system's cleaning method is chosen, further research will be generated. The team would then be able to make a more logical choice of what should provide the beater bar function. If the cleaning system is not completely cleaned by the beater bar component, there would be a problem reversing the actuation system back over the panel to its resting state. The remaining dirt in the cleaning system could contaminate the panel. Another unknown in this design is how the linear actuator will withstand the outdoor environment for extended periods of time. While the operating temperatures of reasonably priced actuators suit the sub-freezing temperature specification of the project, their lifetimes in these extreme environments are unknown. Our team will have to contact the actuator's manufacture to see if the product is suitable for our function.

4.4.2 Rolling Track Design

The second design under consideration is the rolling track design seen in Figure 3. In this design, the cleaning element rolls across the panel, and is stored underneath the casing where it can be protected from any environmental dust and debris when not in use. The design contains an infrared sensor in order to provide feedback as to when the panel is cleaned to Fracsun's microcontroller. A Pugh matrix analysis, found in Appendix E, was used to decide which sensors would be best for our design. Although infrared topped the list, a device with a built in potentiometer could be advantageous and will be taken under consideration. The rolling track design also features a "beater bar" that the cleaning element is able to roll against to remove any trapped dust, or debris. An exploded view showing how these elements fit together can be seen in Figure 4. An additional drawing with basic dimensions can be found in Appendix H.

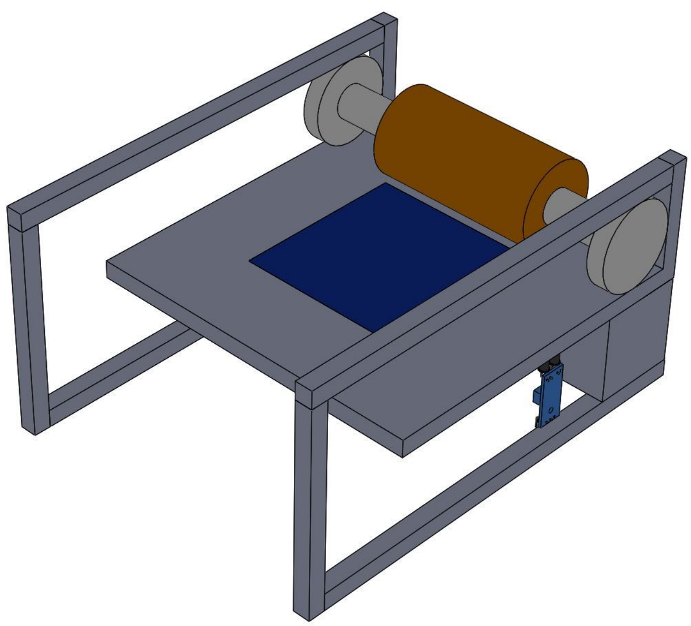


Figure 3. CAD Model of Rolling Track Design

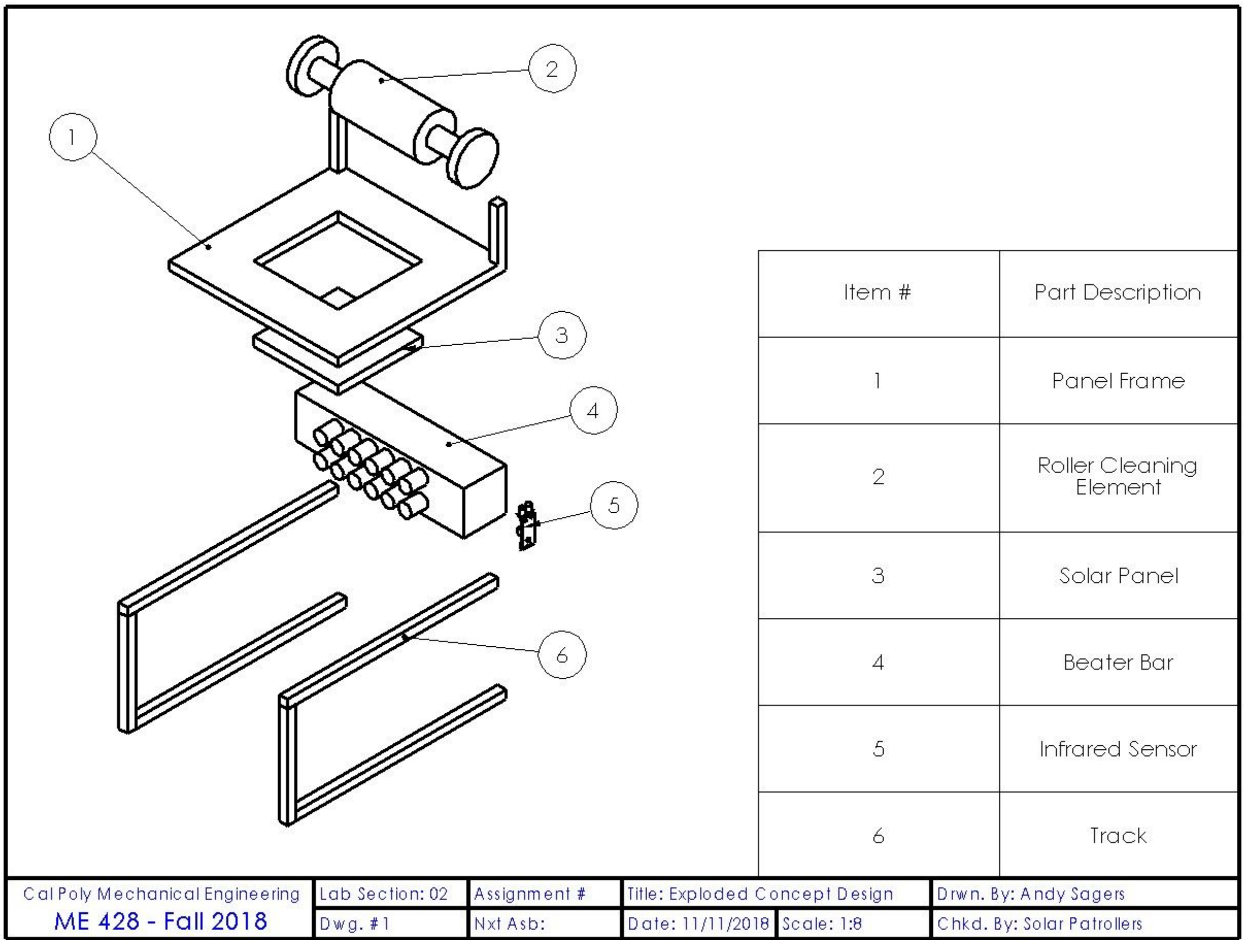


Figure 4. Exploded View of Rolling Track Design

One potential issue with the rolling track design is that the track could cast a shadow on the panel, which would impair the power readings and not provide an accurate measurement of soiling. Another potential issue is that the rolling track will require some form of non-linear actuation that could be hard to implement and costly. This rolling track will also require more power than the lead screw actuator which is critical when trying to meet our power specification. Without knowing which cleaning element is the best, how much force will need to be applied to it, or how the roller will be actuated, it is difficult to say whether or not the rolling track design will meet all the specifications listed in Table 3. With further analysis and testing, we will be able to determine if the rolling track design is the best direction to proceed with in order to satisfy all the criteria laid out in our scope.

4.4.3 Rolling Band Design

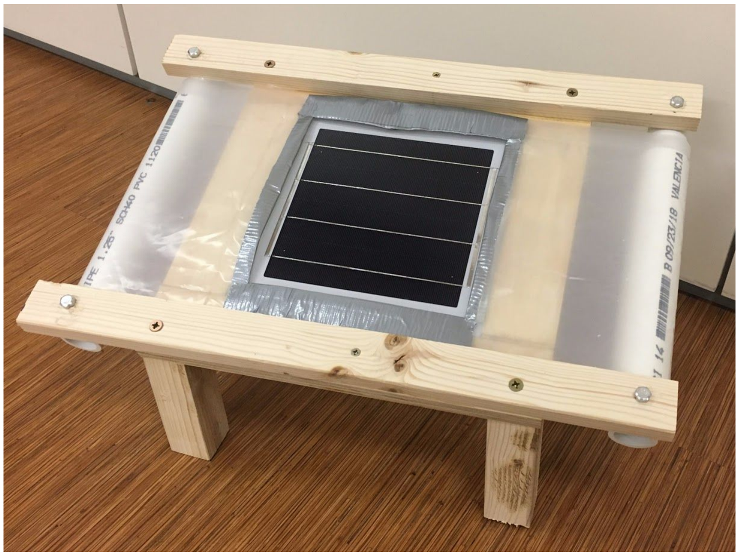


Figure 5. Concept Prototype of Rolling Band Design

The design presented in Figure 5 utilizes a rotating band that leaves the panel completely exposed during the day when the device is taking measurements. During cleaning, which will be performed at night, the band will rotate driven by a motor in one of the side axles and sweep across the panel with a cleaning method attached to the underside of the band.

The design as it stands is a housing and actuating system for the cleaner. The cleaning method has not yet been chosen yet due to need of testing. This design would allow for several different cleaning methods that we have yet to test, as well as it could accommodate multiple cleaning methods within the device. The current design would provide force against the panel only provided by tension in the band. If after testing, more force was found to be needed iteration on the design could take place to improve it. The belt could hook onto a track on the top with rigid bars attached between the tracks that would press the cleaner against the panel, shown in Figure 6.

Figure 6. Possible Modification to Rolling Band Design

This idea began during the concept model build day when a model was made that consisted of a clear cover that covered the panel at all times. The panel would protect the panel during the day when the system was taking measurements. During cleaning, the clear cover would rotate around and be cleaned on the underside of the system. When presented to Fracsun, they had mentioned that any clear covers, both plastic and glass, would affect the irradiance of the panel. This would skew any sort of measurement the device and would not be feasible. The rolling band design presented improved upon the concept model by doing away with cover but retaining the same overall idea.

Potential issues of the design would be water or dust getting underneath the band and into the cleaning area as well as an accumulation of dust after a year of cleaning. This would impair the cleaning ability of the system and instead of cleaning the panel, it would be sweeping dust across the panel surface every time it actuated. Longevity and durability of the band would also be a possible long term issue with this design, but if the band was relatively cheap and interchangeable it could be switched out on a yearly basis which would be an acceptable maintenance period for the solar industry and our sponsor.

4.5 Design Decision

With the three design directions chosen, cleaning materials were tested. The testing procedure is discussed in section 7.1. This allowed for further certainty in which system would work with the chosen cleaner. The results from testing proved the cleaners suited all the design directions. However, because results proved increasing the amount of cleaning passes was more efficient than increasing cleaning force, the roller band design was selected. Fracsun also believed this was the most fitting design. The team was able to incorporate the general ideas of the rolling band design into a more desirable final design.

5. Final Design

Figure 7. Final Design of Cleaning System

The current design shown in Figure 7 is derived from the rolling band design where belts are used to drag a cleaner across the panel. There are two belts, one above and one below the panel, that spin on four pulleys completely around the device. The pulleys are attached by set screw to steel shafts which will be supported by bearings mounted in two 3D printed brackets and aligned using spacers. A cleaner is secured between the two belts with a strap connected to the belts using a wire sew technique. The cleaner is made up of a microfiber cloth head and ostrich feather base. The shaft is be powered by a DC gear motor and pulley system mounted on the underside of the device. The system is constructed by a mixture of purchased and custom fabricated parts. It is mounted in the configuration shown in Figure 8 on the sides of the current ARES device.

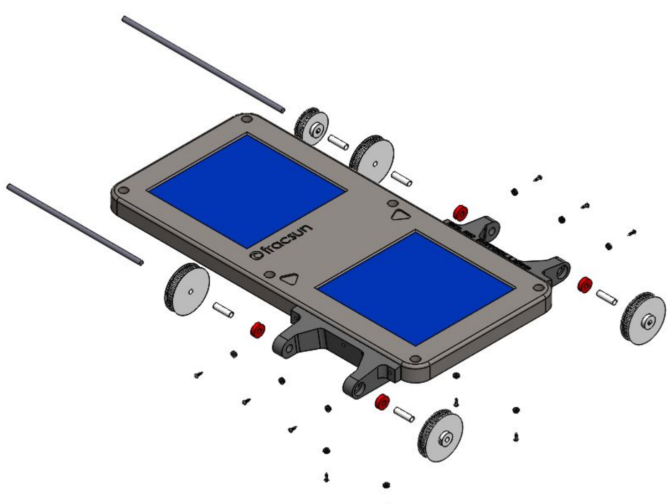


Figure 8. Assembly Exploded View

5.1 Brackets

The bracket went through a major redesign from the structural prototype. The most major change is that the brackets are fabricated instead of assembled from bought parts. The current approach is to 3D print the entire bracket as one piece seen in Figure 9. The 3D print is a black nylon to prevent UV damage. The overall design helps to eliminate major problems we encountered when assembling the structural prototype. The first being that because the structural prototype used two L-brackets with holes drilled in them to support the shaft, getting the alignment was difficult and the little misalignment in the system created a lot of friction when the belts were put on the system. Another problem that the new bracket solves is the problem of having to support the bearings between the supports. Before, we had a tube with bearings that was placed between the metal supports. The bearings were meant to support the shaft and allow it to rotate. Instead, because of the tension created by the belts, the shaft was pulled toward the middle of the device which created rubbing between the shaft and metal support. With the new design, the bearings are press fit into the bracket and they are able to fully support the shaft while also allowing it to rotate.

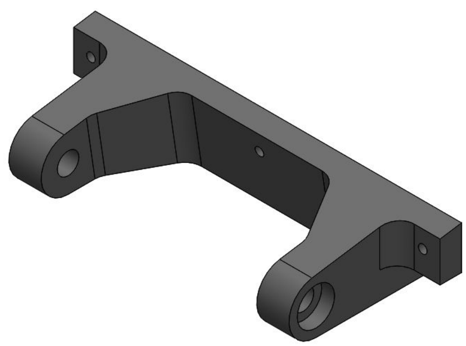


Figure 9. 3D Printed Bracket Model

Lastly, with the re-designed bracket, an angle was created that allowed for the pulleys to be offset from the top of the ARES which solved two problems, seen in Figure 10. The first being that the belts were too high above the panel which would not only make cleaning difficult, but also create a shading effect on the panel which would affect the measurement taken by the ARES. And the second problem was that the extruding panel cover on the back of the device was in the way of the belt and would have interfered with the cleaner.

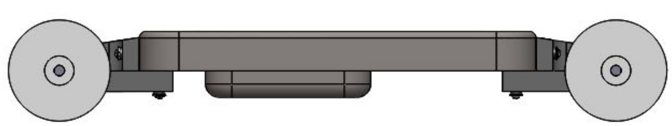


Figure 10. Offset Pulleys Bottom View

5.2 Toothed Belts

When doing preliminary testing, we determined that V-belts would introduce too much unnecessary tension. This is because the way V-belts are able to transmit power between the pulleys is that they rely on the tension in the belts. Our application does not benefit from the extra tension and instead this creates friction within the shaft and bearings. Thus a change to more flexible toothed timing belts was decided. We have decided to use urethane belts at this time in our but there are some concerns with durability of polyurethane, especially as it is exposed to the weather and UV radiation. Initial research shows that urethane would be affected by UV radiation possibly warping or loosening the belts. If more durable belts were determined to be needed, research has been done on silicone belts which have much more resistance to UV radiation, at the increase of cost. Furthermore, the urethane belts in our current design are reinforced with kevlar which give it more durability than a completely rubber belt.

5.3 Pulleys

With the change in belt type, a change also had to be made to a toothed pulley. This allows the belt tension to decrease as the force is transmitted through the teeth and does not rely on as much tension. The specific toothed pulley is shown in Figure 11. Another change with the pulleys is that their hubs are made from aluminum and have a set screw that locks the pulley to the shaft. An issue we had with the structural prototype is that the press fit between the shaft and the pulley was not able to hold and so when the shaft was rotated with a drill to rotate the belt system, the shaft rotated within the pulley instead. We made a quick fix using glue; however, a more suitable solution is to set screw the pulleys in place.

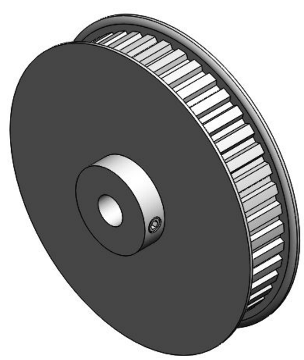


Figure 11. Toothed Pulley with Set Screw

5.4 Bearings

The bearings on the final design are press fit into the 3D printed bracket, shown in Figure 12. There are two bearings for each shaft on either side. A change made from the structural prototype is that there originally was a symmetrical design with one bracket supporting bearings and the other bracket supporting a rigid shaft on which pulleys with press fitted bearings spinned around. This introduced some manufacturing difficulty with the final design as it would be difficult to press fit bearings into an aluminum pulley. The aluminum would be much less accommodating of an interference fit than plastic. The new design is symmetrical with both brackets supporting the shaft with bearings. For durability in the weather, sealed bearings will be used.

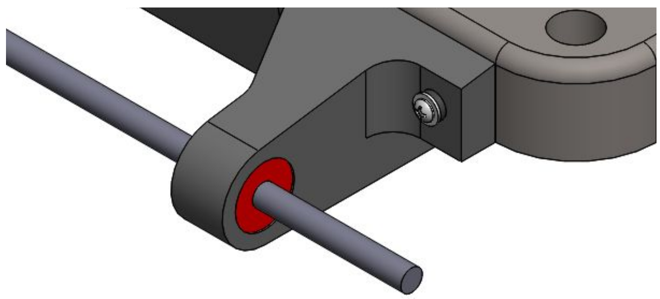


Figure 12. Press Fit Bearings Detail

5.5 Cleaner

The cleaner design is made up of three main components; the microfiber cloth head, the aluminum cleaner bar, and the ostrich feather fixture. These components are fastened together in series. This is shown in Figure 13.

Figure 13. Assembled Cleaner

They are attached to the belts via a nylon strap that runs through the slots of the cleaner bar. The cleaner bar is pictured in Figure 14. The nylon strap is sewed to the belts with galvanized wire. The strap and wire connection allows the cleaner bar to be able to rotate around the pulleys along with the belts as the strap is able to bend and stretch while the bar is rigid. In addition, the strap permits the cleaner to rotate and lead with the microfiber cloth head when the pulleys go in reverse direction. This allowed us to reverse the direction of the cleaner every day. Doing so extended the life of the cleaner greatly. Both sides of the cleaner can take on wear instead of just one side over and over. The life is also extended by storing the cleaner under the ARES fiture when not in use.

Figure 14. Metal Cleaner Bar

The microfiber cloth head is constructed from a small wooden block wrapped in microfiber cleaning material. This portion of the cleaner spans the width of the solar panel and pushes debris in front of it. Pressed against the panel when pushing, the microfiber allows little dust get by to the ostrich feathers. This component also gives the cleaner much needed height. The height allows the feathers to be higher above the solar panel, and because the nylon strap is not rigid, they come down on the panel at a steeper angle. During testing, it was clear that a steep feather angle was most effective for cleaning.

The ostrich feather portion is manufactured by gluing and wire wrapping feathers around a custom made wooden fixture piece. The feathers accumulate the dust that the microfiber cloth does not remove. During their time not cleaning the panel, the feathers are forcefully brushed against the bracket extrusions and shafts. This removes dust and debris that has previously been accumulated.

The dust accumulation and overall effectiveness on the cleaner was tested over 400 cycles. The cleaner proved effective in dry conditions and meets the yearly maintenance specification. This testing is covered further in Section 7.5. The maintenance of the cleaner would require the belt and cleaner combination to be replaced as one whole part. This replacement part would have to be provided to a solar plant operator.

5.6 Transmitting Power

The system is powered by a toothed belt linkage between the bracket shaft and a motor mounted on the rear side of the device. We determined this to be a feasible method of rotating the shaft because the belts and pulley used for the cleaner worked well and were able to transmit the required torque. The shaft pulley can be seen in Figure 15 which is placed on the end of the right shaft.

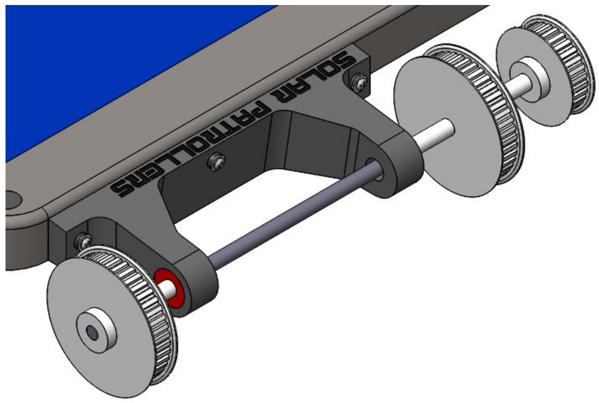


Figure 15. Gear on Shaft Detail

Seen in Figure 16, There is an approximate 1:2 gear ratio between the motor which allows for a increase in torque at the expense of speed. During testing, we determined a higher need for torque than speed as we wanted the device to be able to spin with ease. The motor is mounted securely to the rear of the device using a L bracket motor mount. For our prototype, the motor is powered by a motor driver connected to a microcontroller. For use in the field, the microcontroller code will be placed on the device computer and the power will be supplied through integration with the device.

Figure 16. Motor Shaft to Bracket Shaft Linkage

The motor chosen also came with an integrated encoder which was deemed necessary as the exact position of the cleaner was extremely important to know. If the motor simply ran for a set amount of time each day to cycle, there would be some variation which would lead to the cleaner stopping at different positions day to day. This could lead to the cleaner resting on the panel surface during the day which would skew the measurement taken by the device. With an encoder, we can be sure the cleaner will be below the device during the day during measurement.

5.7 Cost analysis

The four major subsystems as well as their cost are listed in Table 6. The majority of the cost was due to the bracket subsystem, particularly the $378.30 3D printed brackets. For higher volume manufacturing it would be recommended to find a cheaper method to make these parts. Injection molding would be a suitable option the design would allow for. If the price of the brackets were to be lowered, that would allow for more robust pulleys to be used while still staying under the $600 mark. The part by part breakdown of the cost is in Bill of Materials, Appendix I.

Table 6. Subsystem Cost Breakdown

Part #	Part Description	Total Cost
100	Existing System	-
200	Bracket Subsystem	$392.40
300	Belt/Pulley Subsystem	$79.96
400	Motor Subsystem	$70.17
500	Cleaning Subsystem	$42.05
		$584.58

6. Manufacturing Plan

The manufacturing plan for the ARES Cleaning System covers the part procurement, manufacturing operations and assembly used to construct the device. Manufacturing challenges are discussed within the section and long-term manufacturing plan is proposed.

6.1 Procurement

Parts necessary to complete these tasks were obtained from Fracsun, Home Depot, McMaster Carr and other various online retailers. The Bill Materials in Appendix I, shows specific part vendors and cost. The total expenditures for the whole project was $1,072.27. These purchases are found in Appendix J.

6.2 Modified Parts

Manufacturing the ARES Cleaning Device required the modification of the pulley shafts, shaft spacers, ARES fixture, wood block, cleaner bar, feather fixture, nylon strap and microfiber cloth. The sections below outline the process that was followed to successfully customize the parts. Drawings referenced throughout this section are found in Appendix K.

6.2.1 Pulley Shafts

The pulley shafts (5) and (6), seen in Drawing 2, were individually cut using a horizontal bandsaw in the Cal Poly Mustang 60 Machine Shop. They were cut successively from the same 5/16 inch diameter steel rod.

To perform this process, both required lengths were measured. Twelve inches for shaft (5) and 11 inches for shaft (6). The stock shaft was placed in the bandsaw vise grip and the cut was made for shaft (5). The stock shaft was realigned in the bandsaw to make the cut for shaft (6).

Once the shafts were cut to size, a file was used to deburr and smooth the ends of both shafts.

6.2.2 Shaft Spacers

The shaft spacers (8), seen in Drawing 2, were sized with the vertical bandsaw in the Cal Poly Mustang 60 Machine Shop.

Two spacers needed 4 millimeters removed from them. The vertical bandsaw was used to cut off this excess material. A deburring tool was used to smooth the edges.

These spacers needed to be sized down because the 3D Printed Bracket holes were misaligned during manufacturing, resulting in overall bracket misalignment when installed. In future manufacturing, if the brackets are perfectly aligned, four identical spacers could be used in between the pulleys and the brackets. However, because they were not aligned, the pulley's positions with four identical spacers were offset by the distance of the bracket misalignment. Thus, it was decided two spacers needed to be sized down to account for the offset and perfectly align the pulleys for belt installation. Section 6.3.2 clarifies the placement of the modified spacers.

6.2.3 ARES Fixture

The ARES fixture (1), in Drawing 2, was stripped of its water sprayers and drilled.

The provided ARES model had two water sprayers near the two upper corners of the reference panel. These are shown in Figure 17. The sprayers needed to be removed to fit the new cleaning system. To do so, the ARES fixture was fixed on a work table vise. The back end of a hammer was placed against the gold metal part of the sprayer. A downward force was provided to the hammer as if pulling out a nail. The sprayer easily popped off the fixture.

Figure 17. ARES Water Sprayers

The ARES fixture also needed to be drilled to fit fasteners required for assembly. The location and depth of these holes were determined from Drawing 2 . The holes were drilled. A challenge to note is the difficulty the team had screwing fasteners into the PVC during assembly. Initially holes were drilled conservatively assuming the fasteners would be able to penetrate any remaining PVC not drilled through. This was not the case. The PVC needed to be drilled to the full depth of the screw. Once completed, the components fixed to the ARES fixture could be secured tightly. This was the previously noted step that resulted in the brackets being misaligned. In future manufacturing, more time and precise measurements should be taken before drilling.

In order for the motor belt to rotate without rubbing on the ARES fixture, a router was used to create a 1.5” long, 0.25” deep chamfer located next to the motor driven pulley. This allowed just enough clearance for the belt without removing a noticeable or critical amount of the fixture.

6.2.4 Cleaner

The cleaner was constructed with 1/16 x 3/4 inch stock aluminum, microfiber cloth, wood block, ostrich feathers, galvanized steel wire, high strength super glue and fasteners. This subsection provides the steps used to manufacture the cleaner's parts.

Wood Block

The 1 x 2 inch wood piece was sized to 8 inches in length and drilled to proper dimensions. A vertical bandsaw was used to make the outer dimension cuts. A hand drill was used to drill the two holes.

The team initially decided to cut the wood to size, wrap it in microfiber cloth and then marked the dimensions for the drill holes. This turned out to be problematic because the microfiber cloth was easily moved around and stretched, thus the dimensions were not accurate. This problem was eliminated by marking the dimensions on the wood first. The wood was then drilled. During assembly the microfiber cloth was wrapped around the wood and a drill bit was used to find the holes under the cloth.

Feather Fixture

The wooden feather fixture was modified with a vertical bandsaw, wood sander, and drill. The feathers were glued on and wrapped with steel wire.

A vertical bandsaw was used to size the wood to 4 x 0.5 inches. The hole dimensions were sketched on the piece of wood. They were located 0.5 inches from the ends and centered. With a wood sander, the corners of the wood piece were rounded to the drawn dimensions. The two holes were drilled with a hand drill.

Next, feathers needed to be attached to the feather fixture. The feathers were obtained from a ostrich feather duster. The duster's black protector was cut off with heavy duty scissors. The wire holding the feathers on the duster was then unraveled. This process is shown in Figure 18.

Figure 18. Duster Disassembly

The feathers were individually super glued onto the feather fixture. They were placed in the orientation shown in Figure 19. They were pressed down using a wooden rod. After around five feathers were placed in series on both sides of the feather fixture, a wire wrap was performed. This was done by tieing a wire loop around the feathers and feather fixture, then wrapping the wire around them eight times. The feather placement and wire wrap was performed three more times to total four layers of feathers.

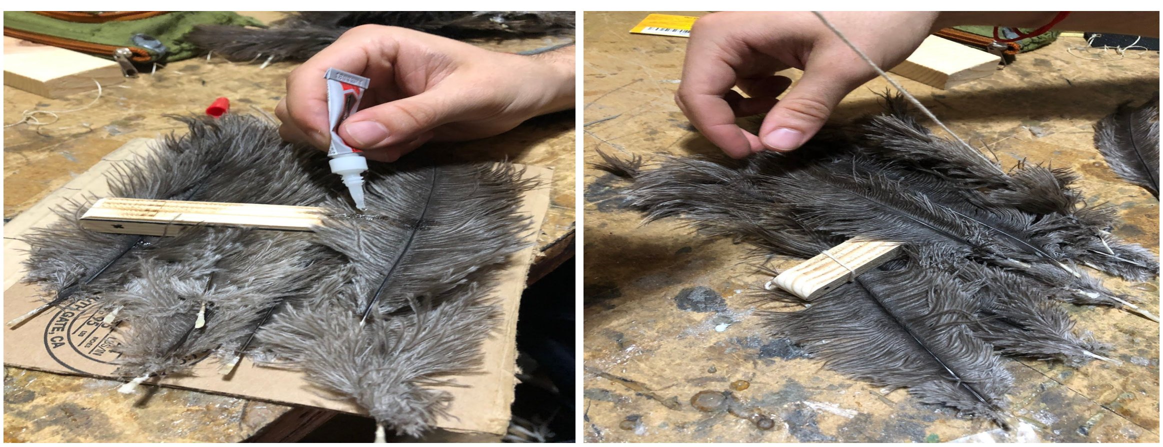


Figure 19. Cleaner Feather Placement

The feather fixture was left overnight to dry. Once dry, the base of the feathers up to the feather fixture were clipped with scissors, so that only the tips of the feathers remained. The sides of the feathers were trimmed after testing was performed with the cleaner. This was due to feather interference with the pulleys.

During this manufacturing process, the team recognized that glueing the feathers to the feather fixture was a two person job. Dealing with the gluing and feather placement posed many challenges. Specifically, when pressing the feathers down into the glue with the wooden rod, the feathers would get stuck to the rod. This often caused many of the feathers on the fixture to lose their positioning. The second person, who applied the glue, needed to quickly realign the feathers on the fixture before the glue dried. The person with the wooden rod needed to quickly readjust and begin placing the next feather.

Cleaner Bar

The cleaner bar was made from 1/16 x 3/4 inch stock aluminum. The aluminum was sized with a Beverly Shear and slotted with the Rotex Punch. This equipment was found in the Cal Poly Aero Hangar.

To size the stock aluminum, the dimension markings of Drawing 4 were made on the aluminum. The stock aluminum was cut at the identified length with the Beverly Shear. The edges were smoothed with a metal file. The Beverly Shear is shown in Figure 20.

Figure 20. Beverly Shear

Next, the aluminum was slotted. The aluminum was placed under the Rotex Punch. The 5/32 inch hole punch was used to punch holes in the shape of the slots. After each hole punch, the Y shaped tool attached to the Rotex Punch was used to part the aluminum from the punch. During this step, the team struggled to be gentle with the part as the punch would be tightly stuck into the aluminum. As a result, the part would easily bend. The Rotex Punch is shown in Figure 21.

Figure 21. Rotex Punch

Next, the punched hole slots were filed down until smooth. The team was careful not to file the outer side of the bar too thin. The photo in Figure 22 shows the extent at which the slots were filed.

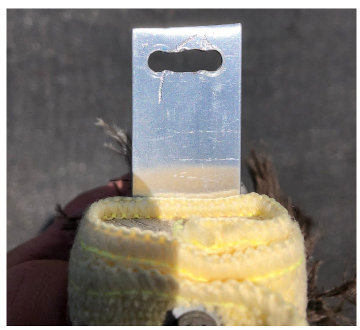


Figure 22. Filed Cleaner Slot

For the cleaner bar's two screw holes, the 1/4 inch hole punch on the was used.

Considering the struggles, the Rotex Punch still proved effective for manufacturing the cleaner bar. The slots were initially drilled using a drill press. This was extremely hard to do as the press struggled to allow drilling on top of predrilled holes. As a result, less holes were drilled for the slot and more filing needed to be done. This took much more time than using the Rotex Punch.

Nylon Strap and Microfiber Cloth

The nylon strap and microfiber cloth were cut to size with fabric cutting scissors. The strap was cut 14 inches in length. A lighter was used to mildly burn one of the strap ends. When doing so, the strap was placed in the lighter flame for two seconds. The melted material was then pressed down with fingers. This process was repeated on the other side of the strap. The singe procedure done here was to avoid fraying in the strap. The microfiber cloth was cut to be 8 x 16 inches size.

6.3 Assembly

The ARES Cleaning System was ready to assemble once all parts were obtained and the necessary parts were modified. Assembly additionally required the need of two 2 x 2 inch wooden blocks, a vise, 3/32 inch allen key, drill, galvanized steel wire and sewing needle. Section 6.2 chronologically explains the assembly of the cleaner and the overall device. Drawing 1 and 2 in Appendix K were used as a reference when building the device.

6.3.1 Cleaner Assembly

The cleaner is made up of all the parts of Section 6.2.4. This section describes the process to assemble these parts.

Step 1: Drill Cleaner head

The microfiber cloth was wrapped tightly around the wooden block. This was then placed in series with the cleaner bar and feather fixture. Using a drill, fasteners with washers were screwed through the microfiber, into the wooden block, through the cleaner bar and into the feather fixture. This setup is shown in Figure 23. Note that this figure excludes the feathers for visual purposes. Drilling through the microfiber cloth was a difficult task. Because the screw would tangle and rip the cloth's fibers, the best solution was to apply a strong and quick force to penetrate the cloth before the fibers managed to get tangled.

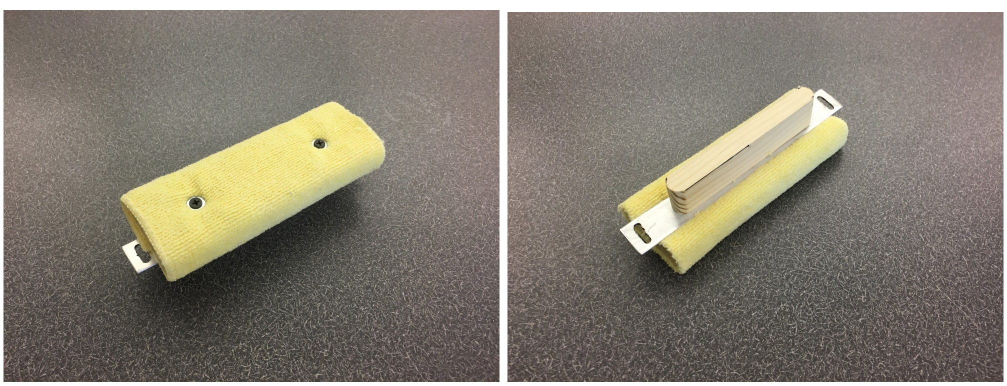


Figure 23. Cleaner Assembly Without Feathers

Step 2: Belt Sewing

The next step to assemble the cleaner was attaching the belts to the nylon strap. This was done by sewing the nylon strap onto the belt with galvanized steel wire. A sewing needle, with the wire attached, was threaded from the strap side of the belt down in between the belt teeth. If the needle could not be pulled through the strap by hand, needle nose pliers were used. The next move was made across and up to the strap within the same belt teeth. The wire was then threaded back down, but this time in between the next gap in the teeth. This sewing process can be seen in Figure 24.

Figure 24. Wire Strap Sew

Once all five teeth gaps were wired, the two wire ends were rethreaded through the sew at the top of the strap and twisted together. This can be seen in Figure 25.

Figure 25. Wire Strap Sew Detail

Step 3: Adding Cleaner Head

Lastly, the strap was inserted through the cleaner bar slots. The strap was then sewed onto the other belt using the process previously stated. The cleaner was adjusted on the strap so that the length of the strap from the edge of the belts to slot of the cleaner was 1.5 inches on both sides. The strap set up before the second sew is shown in Figure 26. The slot to strap length measurement is shown in Figure 27.

Figure 26. Nylon Strap Through Cleaner Bar

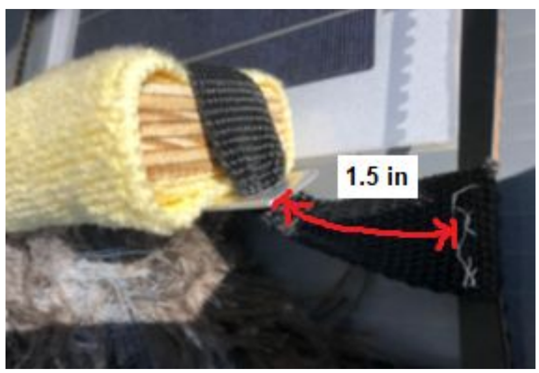


Figure 27. Slot to Strap Length

6.3.2 Device Assembly

Step 1: Press Fit Bearings

The Flip HDK Bearings, labelled (4) in Drawing 2,were press fitted into the 3D Printed Brackets. This job needed two people and the use of a vise. First, a bearing was hand placed in an outer hole of one of the brackets, only enough so it did not fall out when turned upside down. Next, in a vise grip, the bearing and bracket was sandwiched with two wooden blocks. This arrangement can be seen in Figure 28. The vise grip was tightened so that the bearing was pressed flush into the bracket. After the press, the bracket should looked like that in Figure 29. This process was repeated on the brackets for the remaining three bearings.

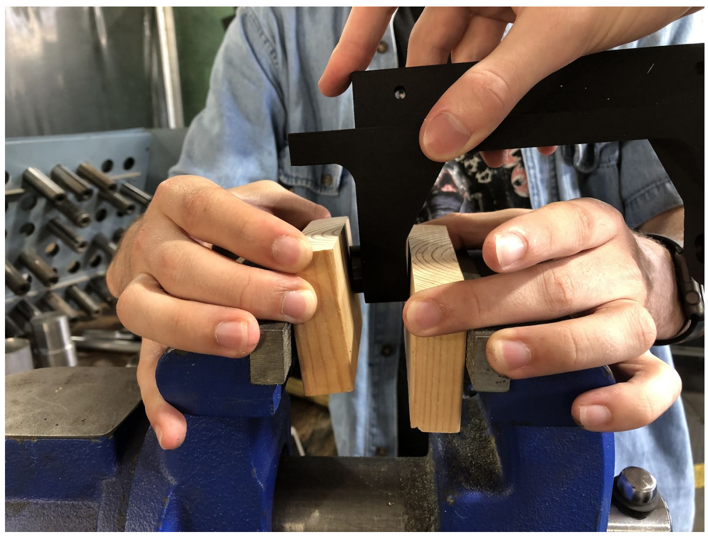


Figure 28. Bearing Before Press

Figure 29. Pressed Bearing

Step 2: Bracket Installation

The brackets, labelled (2) and (3) in Drawing 2, were installed on each side of the fixture. They were each mounted to the fixture with 5 screws and washers. To accomplish the mounting, the bracket holes were aligned with the fixture holes. The alignment is shown in Figure 30. Using the drill, the screw washer combination was tightly fastened with the bracket and fixture. This was done for both brackets.

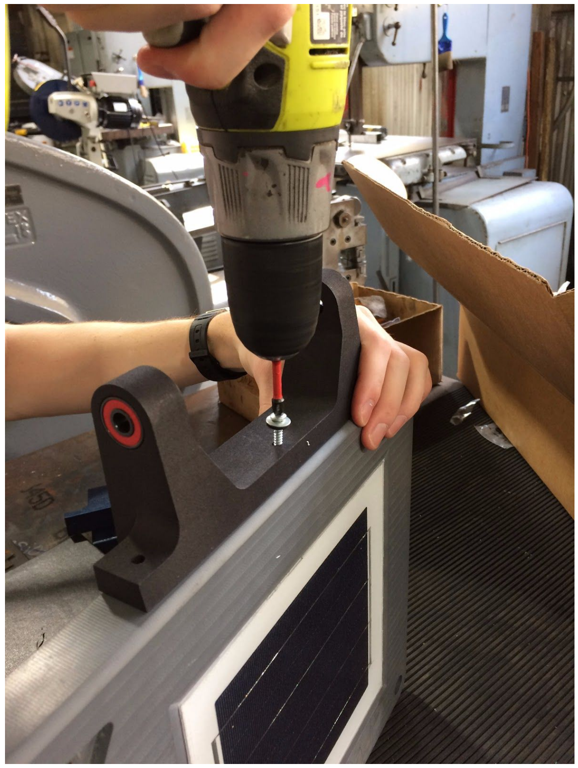


Figure 30. Aligning and Screwing Brackets

Step 3: Shaft Installation

The shafts (5) and (6) were inserted through the holes in the bearings. The long shaft (5) was put through the bearings on the motor side of the fixture and the short shaft (6) was put through the bearings on the opposite side.

Step 4: Pulley Installation

To install the pulleys, an unmodified spacer followed by a pulley was put on the shaft, with the set screw on the outside of the pulley. This was done for all four shaft ends. However, modified spacers were used on two of the shaft ends. The set screws on the pulleys were tightened with a 3/32 inch allen key. For the motor shaft, another spacer was placed after the pulley. This was followed by the placement of the 2.25 inch motor pulley. The set screw was tightened. The device's pulley placement is shown in Figure 31.

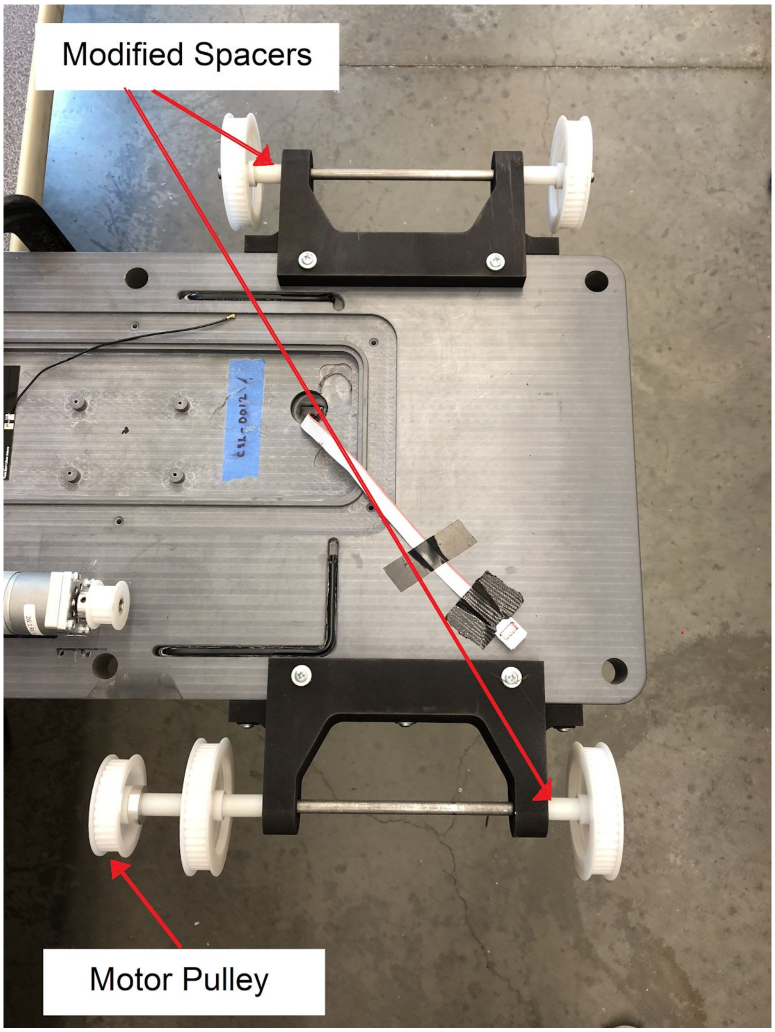


Figure 31. Pulley and Spacer Placement

Step 5: Cleaner and Belt Installation

To install the new belt and cleaner set up, the belts were placed over the device so that the cleaner laid straight across the solar panel. The innermost belt's teeth were meshed to the pulley on its side. To do so, the belt was stretched over the other pulley so that it sat on the flange. The pulley was rotated outward so that the belts teeth joined with the pulley. This process can be seen in Figure 32.

Figure 32. Belt Installation Process

For the other belt, the team performed the same process but also aligned the cleaner. The cleaner needed to be placed perfectly straight across the panel. This was done by visual inspection as the second belt was meshed with the pulleys of its side. This took multiple attempts due to cleaner misalignment. The process became easier as we gained a feel for how much the meshing of the pulley altered the alignment of the cleaner.

Step 6: Motor Installation

The first step of motor installation was assembling the motor bracket. The bracket was assembled using the ServoCity assembly photo in Figure 33. First, the 555196 Motor Mount was screwed onto the Motor. Next, the 585494 L shaped bracket was screwed onto the ARES fixture. The 555196 Motor Mount, with the motor, was then screwed into 585494 L shaped bracket.

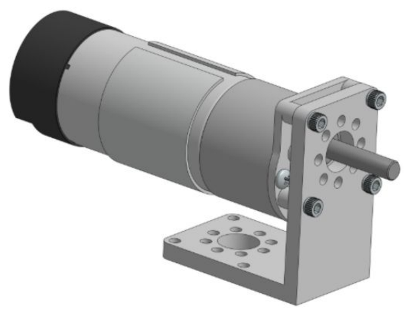


Figure 33. Servo City Motor Bracket Assembly

With the motor attached, the 1.13 inch motor pulley was then placed on the motor shaft. The set screw was tightened. Figure 34 shows this step.

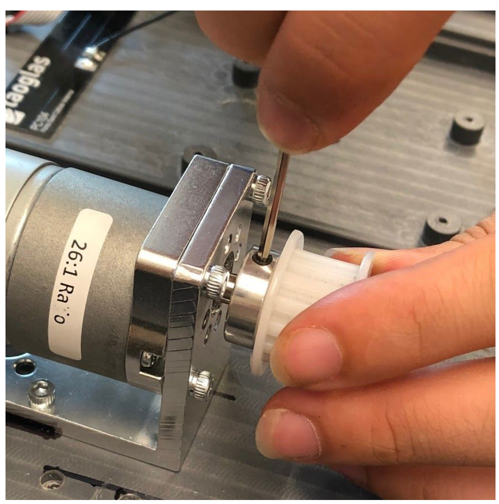


Figure 34. 1.13 inch Motor Pulley Installation

Step 7: Motor Belt Installation

The motor belt installation was done on the 1.13 and 2.25 inch motor pulleys. This process was identical to the belt installation process in Step 5. However, this installation required more strength due to the tightness of the belts.

6.4 Long-term Manufacturing Plan

The current manufacturing plan for the ARES Cleaning System is for our senior project final design. Optimally the design will be implemented by Fracsun and produced at a large scale. To produce large scale, many of the current manufacturing decisions must be changed. Large scale production will decrease the unit cost of the product.

The current pulley supports are 3D printed nylon. This is not a cost efficient manufacturing method at a large scale. For higher volume production, the pulley supports will be injection molded PVC. ARES is currently made of machined PVC. This verifies that the injection molded PVC will be cost efficient, structurally sound and UV resistant. The PVC will also allow the bearings to still be press fit.

The current procurement of the ARES Cleaning System parts is through individual part buying from stores in San Luis Obispo and online retailers. Large scale production would call for high volume buying. High volume buying decreases unit cost of parts. Specifically, this would help decrease the cost of the pulley, toothed belt, motor and bearing.

Lastly, if the production scale was high enough, the manufacturing of customized parts would be outsourced. These parts would include the pulley shafts, shaft spacers and cleaner. Outsourcing this production would save time and money.

7. Design Verification

This section addresses how the team verified that the chosen design and final prototype meet almost all the specifications listed in Chapter 3.4, Table 3. It was required that each specification is verified through at least one of four methods: Analysis (A), Testing (T), Similarity to existing designs (S), Inspection (I). This section shows describes all testing and results. The Design Verification Plan (DVP) summary of all tests completed can be found in Appendix L. When reading the DVP table, the specification numbers correspond to Table 3, and the different test stages are concept prototype (CP), structural prototype (SP) and final prototype (FP). The DVP also indicates whether a component (C), subsystem (Sub), or the full system (Sys) was tested.

7.1 Initial Testing

The specifications outlined in Table 3 that involve cleaning, require verification through testing. In order to thoroughly test that our design meet specifications such as, a maintenance schedule of once a year and a cleaning schedule of once per day, a cleaner needed to be chosen. The team conducted some initial testing of the materials seen in Figure 35 which include a screen cleaning microfiber, a microfiber cleaning cloth, a microfiber cleaning mitt, a bristled rim cleaner, and squeegee.

Figure 35. Tested Cleaning Materials

The materials were tested through through the process pictured in Figure 36. The team, along with their sponsors followed a process through which they placed a test panel inside a Shop-Vac, and vacuumed up dirt to simulate a day's worth of soiling. The panels were then cleaned with each material. The microfibers were pressed down with an aluminum plate so that the team could calculate the force required on the cleaners. This force analysis can be found in Appendix N. It was found that a pressure of 122.63 Pa is required for the panel to be cleaned. In order to determine if the panels were completely cleaned, a “white glove” test was conducted by wiping the entirety of the panel with a paper towel and examining the particulates left behind through inspection. Overall, it was concluded that all of the microfibers and ostrich feathers left no particulates behind, and that the bristled rim cleaner and squeegee were ineffective by themselves. After the initial testing was complete, the group decided to use both the microfiber cleaner and ostrich feathers in tandem.

Figure 36. Cleaning Method Testing Procedure

7.2 Motor Testing

Initial testing was done with four motors. These motors were: a DC motor provided by Fracsun, an unidentified gear motor provided by Charlie Refvem in the ME 405 Lab, and two more gear motors purchased from ServoCity.com. Motors were tested in a varying capacity. The first test the motor had to pass was whether it could spin the belt. This took the motor from the ME 405 lab out of the running because it had extreme trouble at spinning the belt at a very low speed. Another requirement we put on the chosen motor was that, through the use of an encoder, it would provide feedback that the motor spun, passing the cleaner over the panel a set number of times. The motor provided by Fracsun was used to get a baseline test for torque and speed requirements.

The measurements taken during testing, seen in Table 7, were voltage, current, and time to rotate the cleaner 10 rotations. The power supply was set to specific voltages and it automatically adjusted the current as necessary. The motor speed was calculated by first turning the time for 10 revolutions into an rpm and then turning that number, using the belt and gear ratios, into the rpm of the motor shaft itself. Motor power was calculated from voltage and current and that along with motor speed lead to the torque.

Table 7. Torque Test Results

Voltage (V)	Current (A)	Revolutions (Cleaner)	Time (s)	Cleaner Rotational Speed (rpm)	Motor Rotational Speed (rpm)	Power (W)	Torque (oz-in)	Torque Uncertainty (± oz-in)
2.500	3.9	10	16.90	35.5	337.3	9.8	38.9	1.4
3.000	3.8	10	11.01	54.5	517.7	11.5	29.8	1.2
3.500	3.9	10	8.95	67.0	636.9	13.5	28.6	1.3
4.000	4.4	10	6.98	86.0	816.6	17.6	29.0	1.4
4.500	4.8	10	6.30	95.2	904.8	21.6	32.1	1.6

The uncertainties listed in Table 8 contributed to a total torque uncertainty for each measurement. Uncertainty analysis had to be performed on each torque calculation because all the measurements taken had some sort of uncertainty.

Table 8. Torque Test Uncertainties

Voltage (V)	Current (A)	Revolutions (Cleaner)	Time (s)	Rotations Conversion Factor
0.0005	0.1	0.05	0.25	0.1

The equipment used for this test is shown in Figure 37. Although the motor was able to spin the cleaner effectively at lower voltages, it did not satisfy our 12-24VDC requirements. We concluded that we needed a motor with much twice as much torque, 80 oz-in, and slightly slower speed, 300 rpm, than the lowest voltage test. This lead us to purchase two gear motors from ServoCity.com. They were identical motors but had different gear ratios, one allowing for higher speed but at a lower torque, and the other vice versa. The chosen motors had specifications close to the determined specifications so we would be able to observe which motor worked better in our system. We found the lower torque, high speed (317rpm) motor was able to spin the belt and that the other motor was too slow (153 rpm) to what we preferred.

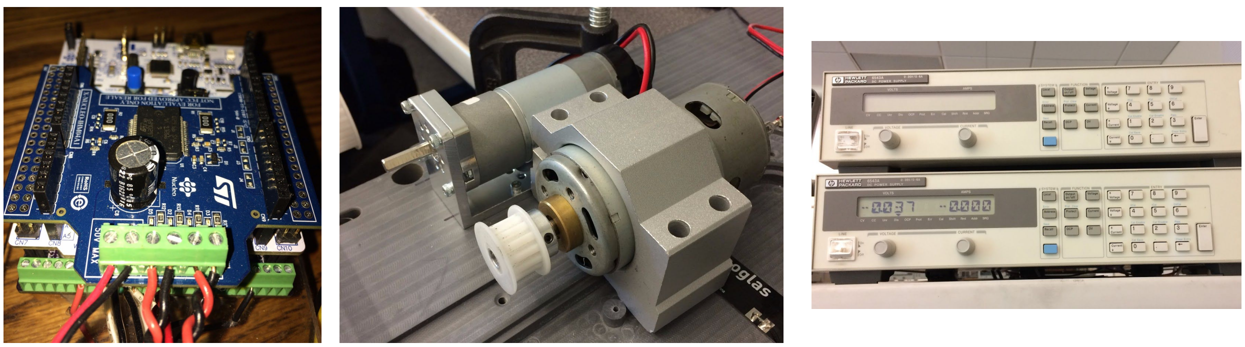


Figure 37. Motor Test Equipment: Nucleo-Microcontroller with Motor Driver Board, BDS-52-85 Motor (Right), 317 RPM Spur Gear Motor w/Encoder (Left), and Power Supply

7.3 Cleaning Testing Method

When cleaning testing was conducted, the methods used to soil the cleaner and also determine the cleanliness of the panel were kept consistent throughout our entire testing process. The method to soil the cleaner was using a shop vacuum with various types of dirt within its container set to blow mode, and a contraption that was placed over the panel surface where dust was blown into, lightly dusting the panel. Through verification from our sponsors, this accurately simulated a day of soiling in the field. For determining cleanliness, Fracsun encouraged us to employ their white-glove method of wiping a clean, white paper towel along the panel and inspecting the paper towel to see if any particulate was taken off the panel. The white-glove test was passed if the paper towel was unmarked and failed if any amount of dirt was observed.

7.4 Passes Testing

The first step in longevity testing was determining how many passes the microfiber/ostrich feather cleaner needed for daily cleaning. This was done by soiling the panel and making successive passes over the panel with the cleaner until we determined the panel was clean. Initially, the panel was being cleaned in just a single pass, but the team decided to use a factor of safety, adding two additional passes as the cleaner loses effectiveness over time.

7.5 Life Testing

After the the motor and number of passes were determined, the next step was to test if the cleaning system would be able to withstand a year of cleaning. Because of the time limitation of the project, we were not able to run our device for a year, however we were able to simulate a years worth of cleaning. We did this by running the cleaner for 400 cycles, soiling panel after every cycle.

The test took place on May 11th and 16th at John Cunningham's residence in San Luis Obispo, CA. The test was performed outdoors. The temperature was around 70 degree fahrenheit with no wind present. The soiling and white glove methods can be seen in Figure 38. The device was powered using a 12V battery. The microcontroller was powered using a usb charger. The soiling and cleaning verification methods used were those explained in Section 7.3.

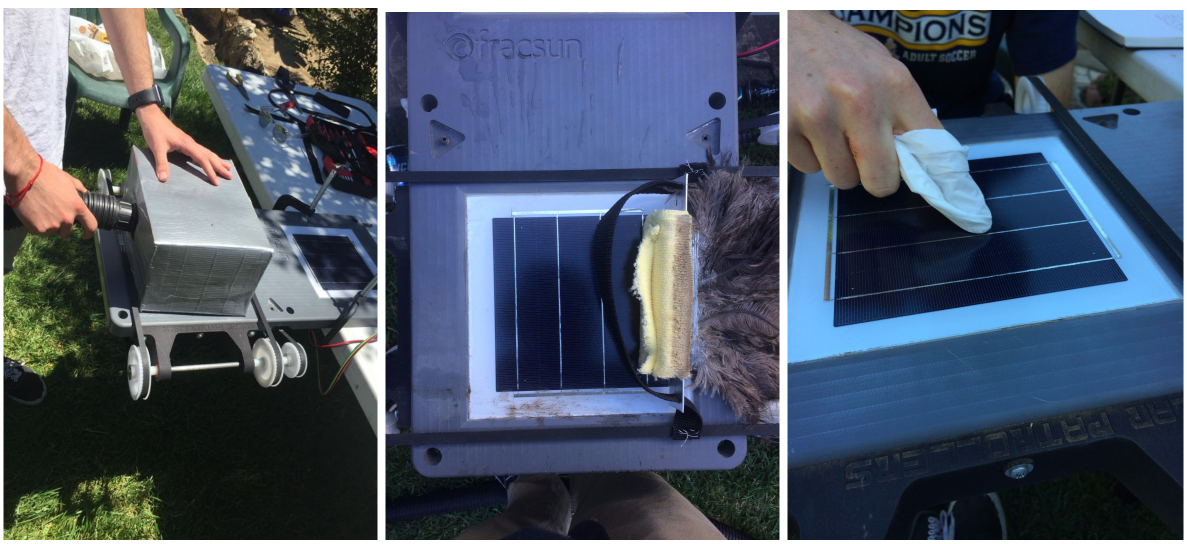


Figure 38. Soiling and White Glove Testing

The procedure consisted of the device passing the cleaner over the soiled panel three times each cycle. After each cycle, the panel was manually soiled within a 10 second time interval set on the microcontroller. Every simulated day (10s), the cleaner changed its rotational direction in order to utilize both sides of the cleaner. After every ten cycles were completed a "white glove test" was performed. After every 20 cycles, notes were recorded regarding the status of the device. At these break points the battery was manually shut off.

The first day of testing consisted of 180 total cycles. After the first 10 cycles were completed, the team noticed a small 0.5 cm strip of soiled dirt on the edge of the panel. It was apparent the microfiber head of the cleaner was not long enough in length, thus not cleaning that area of the panel. Disregarding this flaw, all white glove tests up to cycle 180 were passed. That said, the cleaner began to look noticeably dirty after cycle 20. At cycles 60 through 80, the cleaner's microfiber head ceased to rotate when the cleaner ran counterclockwise resulting in the cleaner leading with the ostrich feathers rather than the microfiber for these cycles. The middle picture in Figure 38 shows the proper orientation of the cleaner as it travels right to left. The misalignment did not affect the results of the white glove test but did prevent both sides of the cleaner from being used. The next 80 cycles, the microfiber head was inconsistent in rotating. At cycle 160, the decision was made to adjust the tension in the nylon strap of the cleaner. This was decided to potentially stop the inconsistent rotating of the microfiber head. After five test runs, the ideal nylon strap length was determined to be 1 ⅛ inch belt to slot, on both sides. At cycle 181 the battery died.

Day two of testing proved the cleaner adjustment to be effective. The microfiber head consistently rotated in both directions. The cleaner passed all white glove test up until cycle 366. At cycle 366, the cleaner was tested in wet conditions. The wet conditions were simulated by spreading one teaspoon of water evenly across the panel each cycle. The cleaner did not pass any of the three white glove test taken within these 15 cycles. Is was decided that these results were mainly due to the cleaner being relatively dirty when beginning these wet tests and the fact that the cleaner was not allowed to dry in between cycles. Further testing must be completed in different temperatures and conditions in order to accurately identify if this form of cleaner is suitable for wet conditions. For this reason, it cannot be concluded that specification 8, temperature range, has been met.

Once finished, the team noted the accumulation of dust on the devices pulleys, belts, and brackets. These accumulations were concluded to have had negligible effects on the device's function. However, the dust accumulation in the imprinted "Solar Patrollers" lettering on one of the brackets was excessive. This led the team to believe the cleaner was doing a substantial amount of dust pushing. This was surprising as our initial impressions were that the cleaner would be picking up the majority of the dust. This knowledge could be utilized in the development of a new cleaner that focuses on pushing the dust off of the panel rather than picking it up. Lastly, the team noticed an accumulation of yellow microfibers on the bracket. These fibers were ripped of the cleaner as it ran over the bracket. While this did not compromise the cleaner's functionality, this should be taken into consideration if the number of cleaner passes are increased.

7.6 Specifications

After performing all of the test procedures and making the necessary inspections, we concluded that ten out of the eleven specifications have been met.

The temperature range of the system was optimized by analysis and research of the individual parts, however, due to lack of testing in various conditions, we cannot conclude that these specifications were met entirely. The materials of the pulleys, belts, and brackets were determined carefully in order to comply with UV protection. The belts and brackets used in the final prototype are the proper material. The pulleys used are not UV stable, but can be made compliant with the addition of UV protected paint or custom-machined parts. The recommendation moving forward is to use paint to ensure UV protection over the course of a year, while allowing for easy substitution during annual maintenance. After further testing in extreme temperatures and conditions is completed, the temperature range specification will be verified.

The specifications of weight, amount H20, cost, and area cleaned were all met by inspection, testing and planning throughout the project. The solution that is presented eliminates water use completely. The weight and cost were met by careful decision making regarding parts purchased and materials used. The final cost of the system was $584.58, $15.42 under our $600 limit. The heaviest component is the bracket fixture, but after multiple iterations of CAD design, unnecessary material was removed in order to provide the same function while minimizing cost and weight. The final weight of the system is 4.38 lbf, less than the 6 lbf requirement. The area cleaned was observed through maintenance testing, and confirmed to be a 400 cm^2.

The specification for maintenance schedule, lifetime, feedback voltage, cleaning schedule, install time, and power requirement were all verified through testing, design, and analysis. Through the cycle testing described in Section 7.5, it was shown that a cleaner could potentially last more than a year in dry conditions. The entire system was designed in a way that every part can be easily replaced as needed. An operator's manual, found in Appendix O, details how the user would replace each part. Although the entire system will not last 10 years, the maintenance schedule provides time to easily replace damaged or worn parts allowing the system to last more than 10 years. The feedback and cleaning schedule were tested and confirmed during our maintenance schedule testing. The controller was able to simulate 365 days and send a signal back to a computer indicating when the panel was cleaned. The install time took 11.5 minutes, 3.5 minutes under our 15 minutes specification. The power requirement of the motor was met through the testing described in Section 7.2, and motor was selected to run on our 12-24 VDC requirement.

8. Project Management

This section addresses the design process completed by the team and the project milestones that were met for the entirety of the project. It also provides the teams thoughts on the process taken and shows recommendations for future projects based on what did or did not go well during the course of the year.

8.1 Design Process

The design process follows the ME Senior Design Project Student Success Guide's five basic steps to design success: establish a need, explicitly state the problem, generate possible solutions, evaluate the solutions, and document the work. Fracsun's soiling measurements system is in need of a waterless solar cleaning system. They presented the challenge and our team defined the problem. With a clear objective and background of the project, idea generation was completed. Here, the team brainstormed numerous conceptual ideas and refined those models to only feasible options. The team chose three of these design options based on research and the use of decision matrices. These designs were presented at Preliminary Design Review. The team then performed initial testing to determine the most effective cleaning method to incorporate into the final design. Once finished, one of the three chosen design routes was selected to utilize the best cleaning method. The design was then analyzed and prototyped for the Critical Design Review. Lastly, the final prototype was built and tested for the Senior Project Expo. The whole project was documented in our team's logbooks and class deliverables. The Gantt chart in Appendix Q provides a visual of the project plan over time. This chart was updated throughout the course of the project.

8.2 Key Milestones

The key milestones presented in Table 9 were important deadlines for not only the team, but also for our sponsor so that they knew what to expect from us. There were four major milestones in the project, along with a few other minor milestones that were used to update Fracsun. These milestones provide structure to the build process and allowed the team to have a completed product by the end of the 2019 school year.

Table 9. Important Milestone Dates and Tasks

Task	Description	Due Date
Scope of Work	This initial report was used to prove to our sponsor that we understood the scope of the project. It also allowed us to document our initial research and analysis.	October 19, 2018
Preliminary Design Review	The PDR consisted of a written report given to our sponsor, a oral presentation, and a concept model prototype.	November 16, 2018
Critical Design Review	This review entailed a presentation and report describing everything needed to complete the final design.	February 8, 2019
Final Design Review (FDR)	This final milestone showcases the results of the project and include a report, expo presentation, and working prototype.	May 31, 2019

8.3 Project Success
The process outlined in the ME Senior Design Project Student Success Guide was followed closely throughout the course of the project. The stated deliverables were met to the best of the team's ability and used as progress reports throughout the year. Along with a closely followed report process throughout the project, certain design directions were chosen that proved unique to this project.

The mechanical function of the final design was chosen fairly early on in the project. Initial brainstorming was focused on the generalities of the project, with the "what" being addressed first. By the end of the first quarter the mechanical function was narrowed down to three possibilities. When the second quarter started, the team spent significant time deciding on which idea was best. That design was then altered and built until its mechanical function met the stated goals. The final step was to decide which cleaner would then be implemented and what size motor would be used to drive this device. Although the specific cleaner materials weren't chosen until later, because we thought they may change based on the mechanical function, it is now clear that they could have been chosen earlier on.

The direction we took throughout the project was mostly successful. Testing different cleaner materials with the actual device allowed for higher certainty in the capabilities of the design. Also, sizing the motor towards the end of the project allowed for the proper torque and rotational speed to be met. This made sure that the best motor for the lowest cost was chosen. One project route that could have better helped the success of the project would have been to spend more time experimenting with the two other initial design directions. The chosen design was chosen based on analysis and research. If more time was allocated to the project or more time was spent building and testing multiple design directions, then this may have allowed for decisions to be made based off multiple built prototypes. Overall, the process was a success and allowed the team to improve their project management techniques in the future.

9. Conclusion

Our final design meets the specifications laid out at the beginning of the project, including cleaning the panel autonomously without water. Through a lengthy design process, we created a functional prototype that proved to work through various tests. The most important test to verify the success of our design was the year long cleaning effectiveness and durability. We found that, using our daily soiling process, the cleaner was still able to clean the panel surface after 365 cycles. Additionally, we did this all while staying under the set budget, under the maximum weight, and with acceptable power use. The tests that we were not able to perform are tests that determine the lifetime of the system in the field for an entire year. The test we performed on the cleaner was performed on a single day and we are unsure how the cleaner as well as entire system would last in actual use over the course of a year, with regards to weather and other conditions.

There are aspects of the project that we set out to achieve and were successful in, but also some things that we were not able to get done within the timeframe. We were able to build a robust and efficient belt and pulley system powered by a DC motor. The design went through several iterations starting with a rolling band, that changed into a V-belt, which turned into a toothed belt for the final product. The toothed belt was by far the most successful method and ran with the least amount of effort. Another component we were proud of was the bracket that we custom designed. Though there exists several different methods of supporting a spin shaft on the side of a body, there were no options that fit the specific configuration of the ARES device given the thin edges and the need for offset pulleys. The custom design is able to closely match the needs of the system. We are also very satisfied with the way the motor connects to the system and the code that runs the motor. The code we wrote is efficient in running the system and was written in a way where set parameters of the system can easily be manipulated. If there was need for the cleaner to make more passes or run at a different, the code could be very easily modified to accommodate the desired change.

We did not have sufficient time for testing for use in all climates. It would've been interesting to see how our system handled other soiling conditions such as snow, bird poop, or sprayed pesticides. If we were able to conduct these tests we could have changed the design of the cleaner as we saw necessary.

When looking back on the project, we may have made a few design decisions differently. We may have written off the linear actuation device too quickly. This design would have allowed for a more simple design that had less moving parts, but may have posed additional problems such as a worn out cleaner or shadowing. When the decision was made to move forward with the belt-and-pulley design, we rejected the linear actuation. It seems like this concept should have been built and tested alongside the belt-and-pulley design so they could be better compared.

Another choice we would have made differently was to make the cleaner more robust and immediately marketable. The general function of the cleaner is clear, but the design could have been better built and further along to be implemented into Fracsun's system right away. One final choice we should have made was to test throughout the project with the fixture at an angle. Due to ease of testing, the fixture usually sat horizontal on a table with clamps keeping it steady. The actual fixture will be mounted at an angle on a solar array. Although this would not change much, it would have allowed for better understanding of how gravity affects the design and if any additional issues surmounted.

Some next steps for Fracsun in their development of our cleaning system have mostly to do with turning this prototype design into a design that could more easily and cheaply be manufactured. For our prototype, we 3D printed the custom brackets using SLS, which while being strong and robust, was costly and the inherent properties of the sintered nylon aren't well known in regards to UV durability. The new ARES body is injection molded in polycarbonate which can take the toll of weather and the sun, and our design allows for injection molding and could be manufactured in a similar manner. The 3D printing of the brackets allowed for quick and efficient design but turned out to be the bulk of the cost of our system so that is a high priority in changing. Furthermore, the pulleys we used, sourced from McMaster-Carr, were acetal plastic and we foresee this being another weak point in our design from a weather and UV durability standpoint. The pulley choice was made because they were the exact size we need in the configuration we needed, and their were not metal or other more durable options for pulleys in the configuration we wanted.

Another design decision that needs more thought put into manufacturability is the method of attaching the cleaner to the belts. The current method of hand sewing the nylon strap to the belt using metal wire worked well, but was extremely tedious and the long term durability of the connection is unknown. We recommend further testing and analysis in sewn connections and the use of a sewing machine in aiding the manufacturing of the system. The first iteration of using staples was easier, but interfered with the teeth in the pulley as well as the connection felt weaker and more prone to failure. While we did not explicitly test any other method of connection, we believe that sewing is the correct design direction to take as opposed to glueing which would not last in both respects to the weather as well as the physical toll of constantly bending around the pulley as the cleaner turned.

In order to integrate the prototype with Fracsun's current system, the encoder, motor, and code must be set up with their system. Python code has been provided in Appendix R. It has been commented to show places where a feedback signal could be sent to their portal after the panel has been cleaned. The motor and battery should be hooked up to some sort of motor driver board/pins that can utilize pulse width modulation to control the speed of the motor. The encoder can be easily connected to any controller using a gnd, Vcc, and two output pins. The code has been commented to indicate where pin names must be changed to match the new controller.

Although Fracsun is left with a working prototype, we have some recommended directions that that they may make in further development of our system. The first is that the system we created could work in conjunction with the current water sprayer system. While this would leave the issues that come with having water, such as leaks and pump upkeep problems, the combined system could work in places where freezing can occur. By mounting a temperature sensor in addition to the weather monitoring Fracsun already does, the system could decide to spray only when there is no risk for freezing and use the cleaner when the temperature is below freezing or freezing is likely to occur. This would also lessen the wear on the cleaner as it would only be used when needed for freezing conditions and allow the field tested and proven water sprayer system to handle the majority of cleaning. Furthermore, since our cleaning system did not behave as well as we would have liked it to in wet conditions, the water sprayer could also be used when water is detected. Since the water would be on the panel in liquid form, most likely due to rain, the water would not be at risk of freezing.

If the water sprayer system would like to eliminated altogether, we also have a few recommendations on how to increase the robustness of our design. The first would be to replace the microfiber cloth, the first stage cleaner in our design, to a cleaner that would be able to either absorb the water better or just be water-resistant while still cleaning the panel however, we do recommend keeping the ostrich feathers due to their fine dust cleaning abilities. Another possible modification that may need to be added is some sort of enclosure for the cleaner while it was stationary during the day. We did not have the time or environmental conditions to emulate what could happen to the cleaner if actually left in the field for a year. The enclosure would protect the cleaner from dust blowing on it as well as weather such as rain that could soak the cleaner and negate its effectiveness.

Another recommendation is combining our cleaning method with a squeegee for cleaning in wet conditions. During testing, we found that using a squeegee in dry conditions was not at all effective but was very effective in wet conditions. The squeegee wiped away both water and any wet particulate that was on the panel. The ideal method would be only to use the squeegee when wet. Because our design allows for motion in both directions, the squeegee could be attached to only one side of the cleaner and when water was detected the cleaner rotated one way, and for dry conditions the cleaner rotated the other way.

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Appendices

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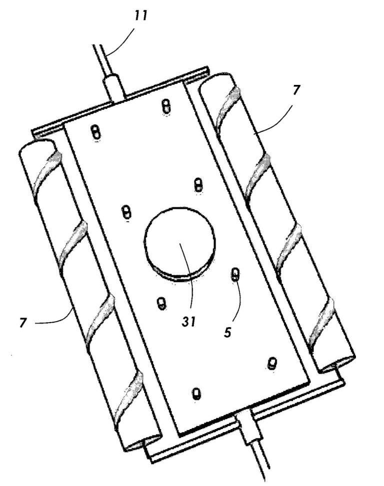
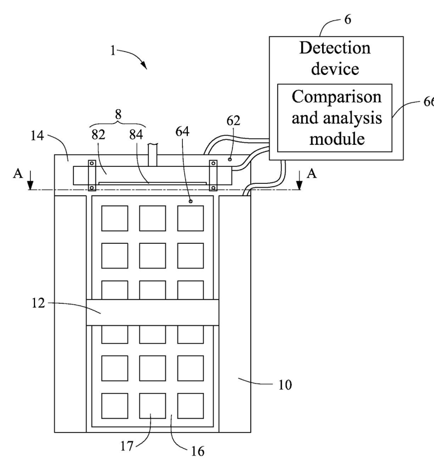
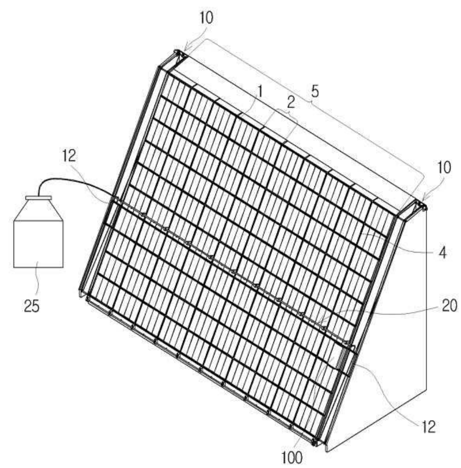
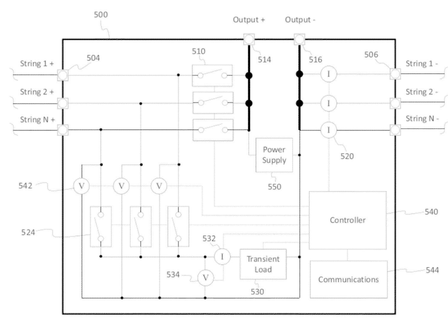
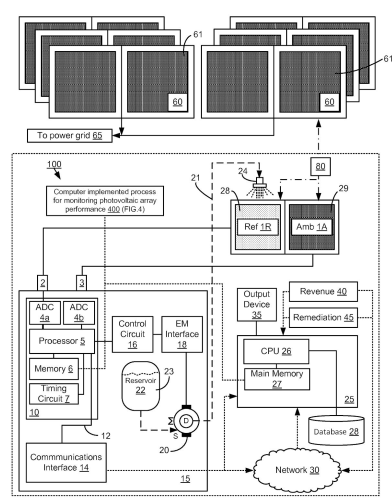
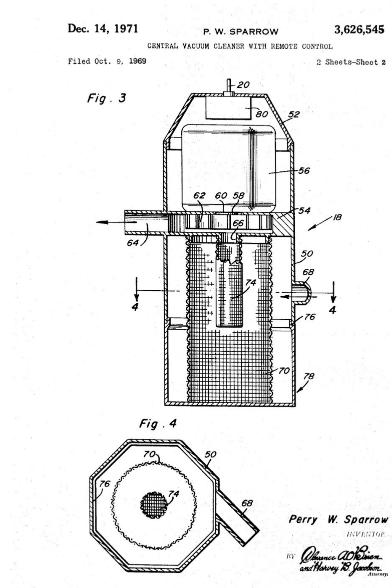
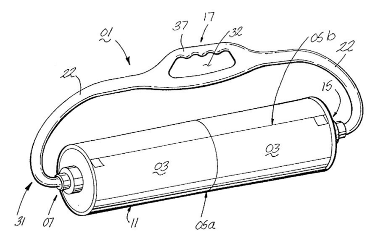
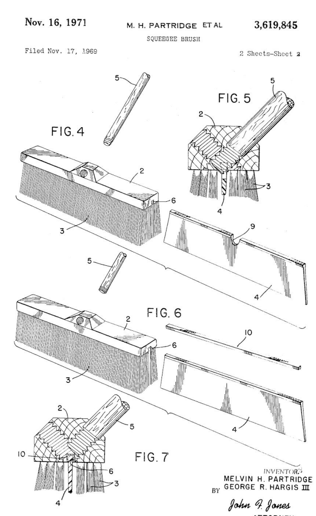
Appendix A: Patent Research Table

Patent #	Description	Image
DE201010006531	This product is listed as a device for cleaning surfaces, particularly solar panel disks. It is a robot cleaner with rails located along the x and y-axis. It’s motion is executed through the use of an electric motor. The patent describes the product as being customizable for many environmental conditions (Armut).	
US12333624	This device is described as an automatic cleaning system for solar panels with features such as a time controller, detection capabilities, perfusion integration, and a driven cleaning system (Lee).	

Patent #	Description	Image
KR20110029095A	This product is an autonomous robot device used to clean a solar panel. It integrates a battery pack, and allows adjustments in the temperature of cleaning liquid based off of external environment conditions, which optimizes the actual cleaning of the panel (히로시).	
US20120053867A1	This is Atonometric's product that measures the performance of individual strings of photovoltaic modules in a PV array. It includes a string combiner box with integrated capability for measurement of string I-V characteristics (Dunn).	
US13331904	This is Fracsun's very own photovoltaic array performance monitoring system which may include a data acquisition unit coupled with reference and ambient photovoltaic panels. The product is unique in that it supplies data management, portal access and data transmission (Fisher).	

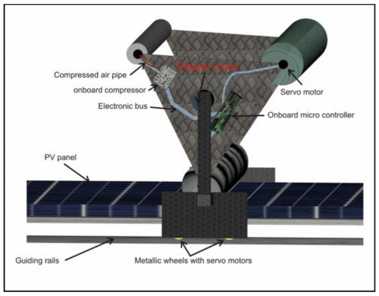
Patent #	Description	Image
US3626545A	This is a patent for a remote controlled vacuum cleaner. It includes a motor driven blower inside a dust collection chamber connected to a hose via a conduit to create the vacuum system. The system is controlled remotely through radio signals and uses a transmitter and receiver combination to relay signals from the operator to the device (Sparrow).	
US6014788A	This is a patent for a standard lint roller which is described as a large micro-debris roller with a single sided adhesive sheet facing outward which is wrapped around a rotating center. Each section has a non-adhesive perforated tab for easy disposal of each sheet (Jaffri).	 Fig. 1
US3619845A	This is a patent for a squeegee brush combination cleaning tool. The patent describes the device as push broom with a squeegee extended beyond the bottom of a set of bristles. It is useful for cleaning wet or dry surfaces (Partridge).	

Appendix B: Industry Codes and Regulations

Code/Regulation	Description
IP 68	The IP Code (International Protection Rating) is defined in international standard IEC 60529. It defines the amount of protection required against the intrusion of solid objects in electrical enclosures. In our case, the number six means that there can be no ingress of dust, and requires complete protection against contact. The number eight means that the equipment is sealed in such a way that it can handle continuous immersion in water (IP Rating Chart).
Nema 4X	4X enclosures are made for both indoor and outdoor use, and must to provide protection to all personnel against access to dangerous parts. It also must provide protection to the equipment inside the enclosure against windblown dust, water (including rain, sleet, snow, splashing water, ice, and hose directed water) as well as protection against corrosion (NEMA 4X Enclosures).
UL	UL (Underwriters Laboratories) listing means that UL has tested the product and determined that the product meets specific, defined requirements. These requirements are typically published in UL's Standards for Safety (Electrical Code).

Appendix C: Case Study Research

Case Study	Description
"A Solar Panel Cleaning System Based on a Linear Piezoelectric Actuator" (Lu)	● Driven wiper with guide ● Pressure between wiper and panel
"Wind Driven Mechanism for Solar-Power Cleaning" (Wang)	● Bi-directional reciprocating linear cam ● Rotation into linear motion ● Driven cleaning brush ● Clutch connected when cleaning required
"Ultrasonic System for Solar Panel Cleaning" (Vasiljev)	● Thin water layer ● Vacuum cavities form in water ● Ultrasonic actuator with air/water medium
"Solar Panel Cleaning Bot for Enhancement of Efficiency - An Innovative Approach" (Jawale)	● Maneuvers on surface ● Varying angles from horizontal to vertical ● Rotating nylon brushes ● Minimal water use
"Experimental Comparison of Drag-Wiper and Roller-Wiper Glass-Cleaning Robots" (Qiang)	● Drag-wiper ○ Simple ○ Can reach edge of frame ● Roller-wiper ○ Improved driving performance ○ Reduces required absorption force ○ Flexible and energy/time efficient
"Photovoltaic Glass Cleaning Methods: An Overview" (Syafiq)	● Electrostatic method ● Self-cleaning nanofilm method
"Laser Cleaning of Glass" (Ueda)	● N2 laser ● Evaporation and sputtering of stains by heat ● Need to be careful for laser effect on solar cells

<table>
<tr><th>Case Study</th><th>Description</th></tr>
<tr><td>“Novel Dry Cleaning Machine for Photovoltaic and Solar Panels”


(Aly)</td><td>

4 stage process
1st stage
Compressed air removes sand and coarse dust
Dries out any humidity
DC compressor
2nd stage
Low density flexible polyurethane foam roller
Cleans sand and dust stuck to panel
3rd stage
Compressed air clears off dust left from roller
4th stage
Polywool synthetic duster with static charge
Removes very fine dust particles
Natural ostrich feathers also effective
Operate in areas with little to no rainfall
Different method needed in case of rainfall
</td></tr>
<tr><td>“Simulation and Experimental Test of Waterless Washing Nozzles for Fresh Apricot”
(Chu)</td><td>

4 types of nozzle tested
Column cone nozzle was best performing
Apricot covered with dust or sand
High pressure water too rough
</td></tr>
<tr><td>“Cleaning of Contaminated XUV-Optics at BESSY II”
(Eggenstein)</td><td>

Waterfree oxygen/argon mixture
Contamination by carbon layers
Plasma discharge cleaning method
</td></tr>
<tr><td>“Self-Cleaning Solar Panels”
(Sumner)</td><td>

Uses electricity to statically push dust
Charge lines across panel to 1200V
Electrical field pushes away dust
3 phases in layers
Small amount of energy - “capacitive load”
</td></tr>
</table>

Appendix D: QFD House of Quality

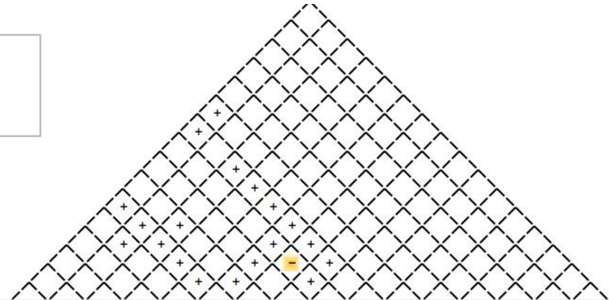
Correlations	
Positive	+
Negative	–
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: SOLAR PATROLLERS
Revision Date: 10-17-18



								Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers							Direction of Improvement	▼	▼	▼	◇	▼	▼	◇	▲	▲	▼							NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Solar Plant (Cold)	Solar Plant Military	Solar Plant (Hot)	Solar Plant (Humid)	Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Maintenance Schedule	Install Time	Power Required	Cleaning Schedule	Weight	Cost	Area Cleaned	Temperaure Range	Lifetime	Amount H2O	Feedback Voltage						Our Current Product	Competitor #1: *Atonometrics*	Competitor #2: *DustIQ*	Competitor #3: *Kintech*	Competitor #4: *NRG*	Row #
1		12%	10	10	10	10	9	Autonomous (Self-cleaning)	●		○	●		▽			▽		●						5	5	5	1	1	1
2		12%	10	10	10	10	9	Clean 20x20cm cell			▽				●			▽	○						5	2	1	1	1	2
3		9%	5	9	10	8	9	Clean nightly basis				●				○	○		○						5	5	1	1	1	3
4		12%	10	10	10	10	9	Maintenance on yearly basis minimum	●			▽					●								2	3	5	1	1	4
5		6%	10	7	1	3	9	Works in sub-freezing conditions								●		▽							1	4	2	5	5	5
6		12%	10	10	10	10	9	Accessible feedback	○		▽								●						5	3	3	3	3	6
7		10%	10	9	8	7	9	Limit water usage	○		○			○				●							1	2	5	2	2	7
8		10%	8	10	8	8	9	DC Voltage Supply			●			○	▽		○	○	○						3	2	3	5	5	8
9		8%	5	3	10	8	9	Cheap	▽		○		○	●			▽								5	1	1	1	1	9
10		9%	7	10	7	7	9	Easy Install		●			●												5	2	3	2	2	10

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	Once/Year	15 minutes	12-24 V & 30A	One/day	< 6 lbf	< $400	400 cm^2	-40-185 (Deg F)	10 Years	0 mL	0-50 mV					
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9					
	Technical Importance Rating	286.6	82.29	203	203.7	105.6	142	116.6	83.8	184.8	138.5	307.3	0	0	0	0	0
	Relative Weight	15%	4%	11%	11%	6%	8%	6%	5%	10%	7%	17%	0%	0%	0%	0%	0%
Curr. Products	Our Product	3	5	4	5	3	5	5	1	5	1	5					
	Atonometrics	3	1	3	5	1	1	2	4	4	2	5					
	DustIQ	5	4	5	1	5	1	1	2	5	5	5					
	Kintech	1	1	5	1	1	3	1	3	4	3	1					
	NRG	1	1	5	1	1	4	1	3	5	3	1					
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix E: Pugh Matrices

Motion Sense Pugh Matrix

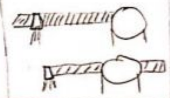
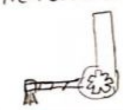
PUGH MATRIX

11/05/18

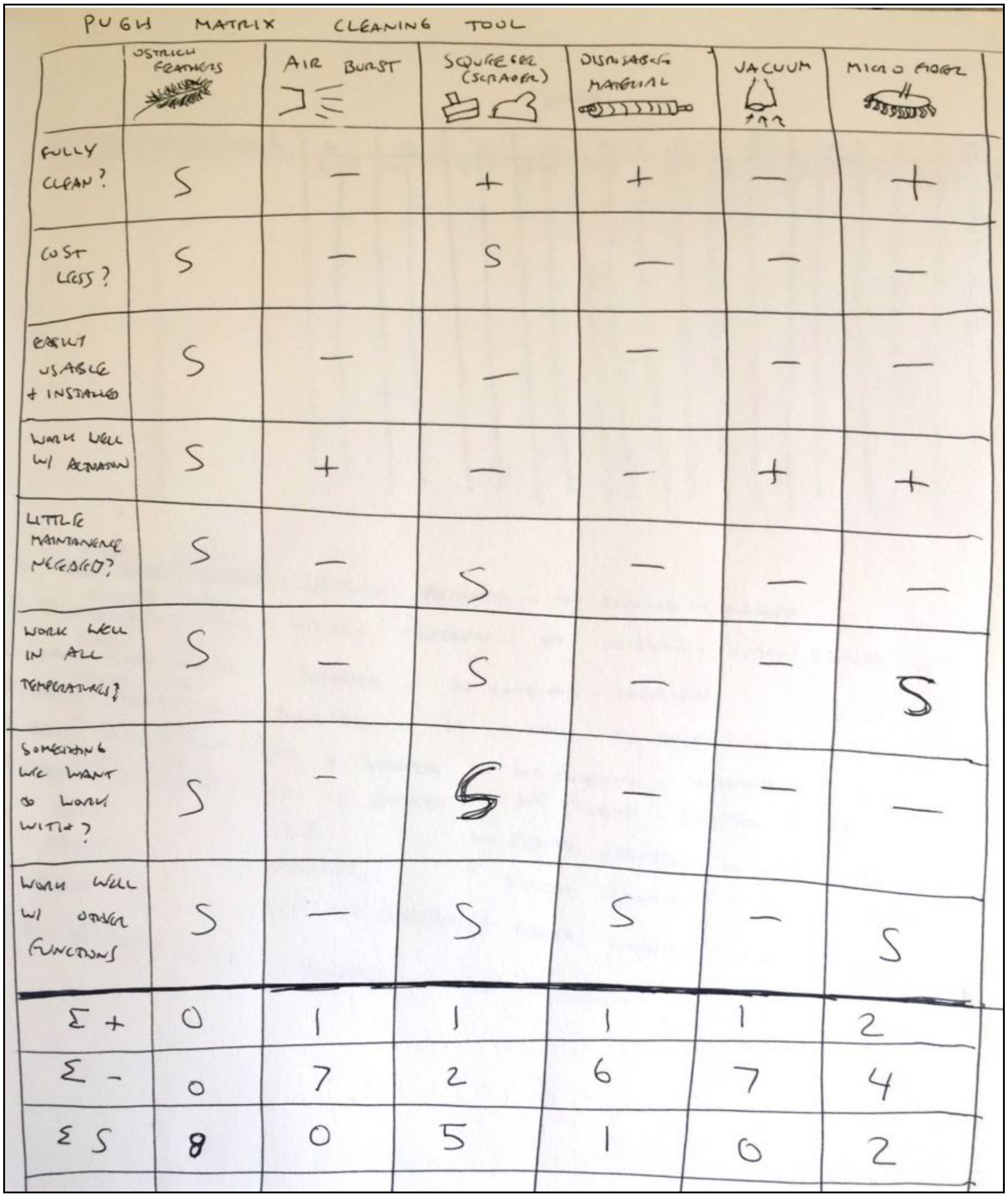
FUNCTION: MOTION SENSE

CONCEPT / CRITERIA	VIDEO	INFRARED	ULTRASONIC	MAGNETIC	CONTACT	VIBRATION	MICROWAVE
CHEAP $	S	+	−	+	−	+	+
LOW POWER	S	+	+	+	+	+	−
VOLTAGE FEEDBACK	S	S	S	S	S	S	S
EASY INSTALL	S	S	−	S	−	−	S
WORK NIGHTLY	S	+	+	+	+	+	+
LONG LIFETIME	S	S	−	+	−	−	−
WORKS WITH MICRO-CONTROLLER	S	S	S	S	S	S	S
Σ +	0	3	2	0	2	3	2
Σ -	0	0	3	4	3	2	2
Σ S	7	4	2	3	2	2	3

Moving Cleaner Pugh Matrix

FUNCTION: MOVING CLEANER	WATER PUMP SYSTEM 	POWER SCREW LINEAR ACTUATOR 	BELT SYSTEM 	RACK AND PINION 	GRAVITY AND WIRE CABLE SYSTEM 	LINEAR CHAIN ACTUATOR 
POWER REQUIRED	S	S	+	S	+	−
COST	S	S	S	+	+	−
ABILITY TO FUNCTION IN EXTREME ENVIRONMENTS	S	+	+	+	+	+
MAINTENENCE REQUIRED	S	+	+	+	+	−
OVERALL LIFETIME	S	+	S	+	S	−
ABILITY TO CLEAN CLEANER	S	S	S	S	−	S
STRENGTH REMOVING DUST	S	+	S	+	−	+

Cleaning Tool Pugh Matrix



PUGH MATRIX CLEANING TOOL

	OSTRICH FEATHERS	AIR BURST	SQUEEGEE (SCRAPER)	DISPOSABLE MATERIAL	VACUUM	MICRO FIBER
FULLY CLEAN?	S	—	+	+	—	+
COST LESS?	S	—	S	—	—	—
EASILY USABLE + INSTALLED	S	—	—	—	—	—
WORK WELL W/ ACTUATOR	S	+	—	—	+	+
LITTLE MAINTENANCE NEEDED?	S	—	S	—	—	—
WORK WELL IN ALL TEMPERATURES?	S	—	S	—	—	S
SOMETHING WE WANT TO WORK WITH?	S	—	S	—	—	—
WORK WELL W/ OTHER FUNCTIONS	S	—	S	S	—	S
Σ +	0	1	1	1	1	2
Σ −	0	7	2	6	7	4
Σ S	8	0	5	1	0	2

Appendix F: Weighted Decision Matrix

Decision Matrix – Solar Patrollers

Criteria	Weighting	Options																	
		A		B		C		D		E		F		G		H		I	
		S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T	S	T
Work with existing product?	2	5	10	5	10	5	10	5	10	5	10	5	10	3	6	3	6	3	6
Low power?	4	3	12	3	12	3	12	4	16	4	16	4	16	4	16	4	16	4	16
Low cost?	3	2	6	3	9	2	6	2	6	3	9	2	6	3	9	4	12	3	9
Clean in all environments?	5	3	15	2	10	4	20	3	15	2	10	4	20	3	15	2	10	4	20
Provide reliable feedback?	2	4	8	4	8	4	8	4	8	4	8	4	8	3	6	3	6	3	6
Simple to install and run?	2	3	6	3	6	3	6	2	4	2	4	2	4	3	6	3	6	3	6
Limited maintenance needed?	5	4	20	4	20	4	20	4	20	4	20	4	20	3	15	3	15	3	15
Total Score			77		75		82		79		77		84		73		71		78

A. Power Screw – Ostrich Feathers – No Covering – Infrared Sensor
B. Power Screw – Scraper – No Covering – Infrared Sensor
C. Power Screw – Ostrich Feathers and Scraper – No Covering – Infrared Sensor
D. Track Going Under – Ostrich Feathers – No Covering – Infrared Sensor
E. Track Going Under – Scraper – No covering – Infrared Sensor
F. Track Going Under – Ostrich Feathers and Scraper – No covering – Infrared Sensor
G. Belt – Ostrich Feathers – Rotating Plastic Covering with hole – Position sensor
H. Belt – Scraper – Rotating Plastic Covering with hole – Position sensor
I. Belt – Ostrich Feathers and Scraper – Rotating Plastic Covering with hole– Position sensor

Appendix G: Design Hazard Checklist

DESIGN HAZARD CHECKLIST

Team: 21 - Solar Patrollers Advisor: Schuster Date: 11/15

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?

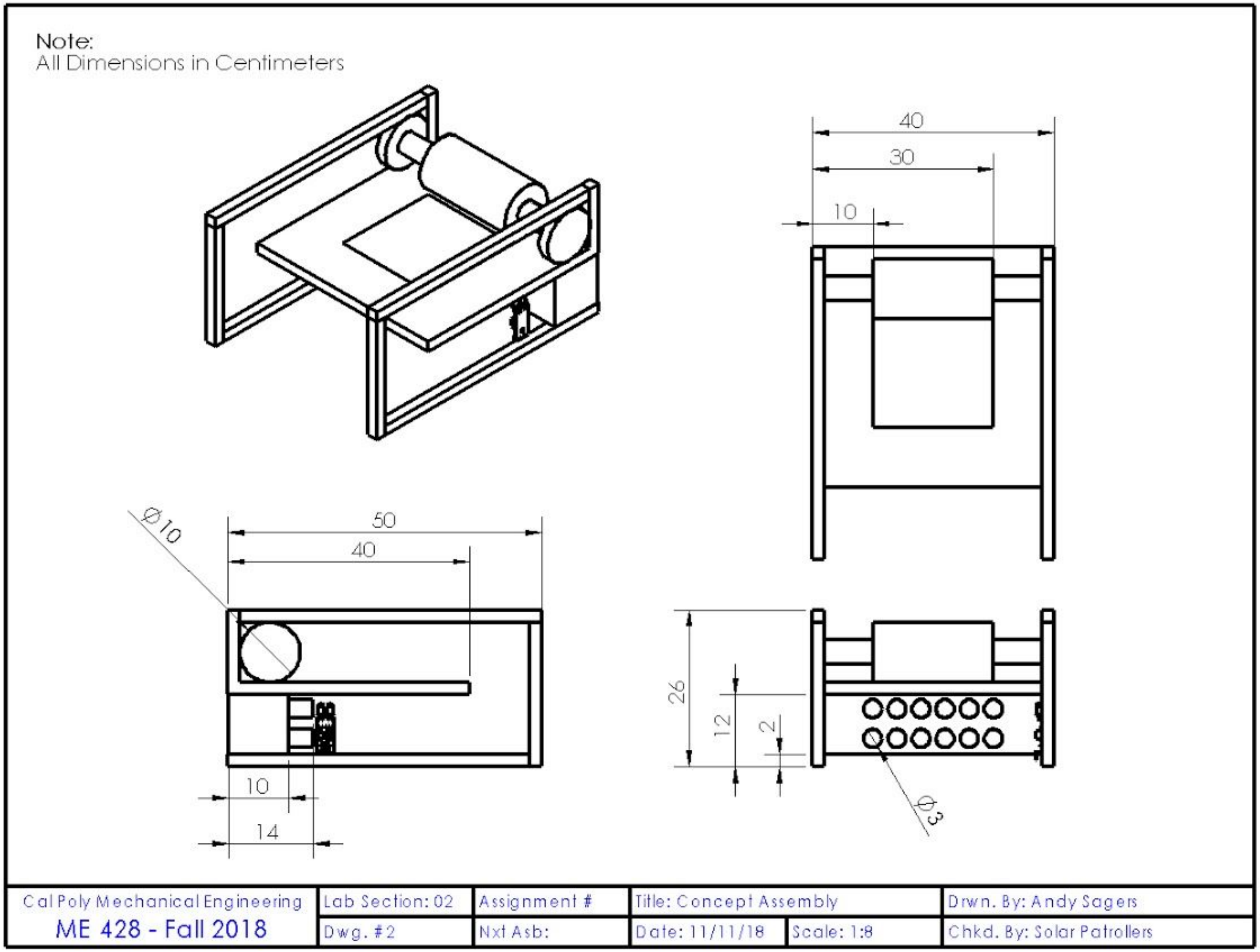
☐ ☑ 19. For powered systems, is there an emergency stop button?

☐ ☑ 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
Rolling, running hazard from cleaning actuation	Device will be operated autonomously without human intervention	1/15/19	11/15/18
High and low temperature ranges, exposure to fog and humidity	Electrical systems will be properly insulated and protected	1/15/19	11/15/18
Fall due to gravity	System will be properly mounted to the panel array	1/15/19	11/15/18

Appendix H: Dimensioned CAD Model



Appendix I: Bill Of Materials

Indent Level	Part #	Part Description	Vendor	Product Number	Material	Quantity	Unit Cost	Total Cost
0	000	Panel Cleaner Assembly	-	-	-	1	-	-
1	100	Existing System	-	-	-	1	-	-
2	110	ARES (Modified)	Fracsun	-	PVC	1	-	-
1	200	Bracket System	-	-	-	1	-	$392.40
2	210	3D Printed Bracket	Printed	Custom	ABS	2	$189.15	$378.30
2	220	Mounting Screw (10-32 1.5")	Home Depot	814741	Steel	10	$1.18	$11.80
2	230	Neoprene Washers	Home Depot	597442	Rubber	10	$0.23	$2.30
1	300	Belt/Pulley System	-	-	-	1	-	$79.96
2	310	Pulley	McMaster	57105K31	Acetal/Aluminum	4	$10.61	$42.44
2	320	Timing Belt	McMaster	1679K149	Neoprene	2	$13.60	$27.20
2	330	Long Shaft (Cut to Length) (11.81")	Home Depot	802437	Steel	1	$0.91	$0.91
2	331	Short Shaft (Cut to Length) (10.83")	Home Depot	802437	Steel	1	$0.91	$0.91
2	340	Bearing	Skate Warehouse	Flip HKD Bearings ABEC 5	-	4	$1.25	$5.00
2	350	Spacers (Modified)	Home Depot	595173	Nylon	5	$0.70	$3.50
1	400	Motor System	-	-	-	1	-	$70.17
2	410	Spur Gear Motor (317 rpm)	ServoCity	520000020026	-	1	$10.00	$10.00
2	420	Mounting Screw (7/16")	ServoCity	814741	Steel	4	$0.23	$0.92
2	421	7/8" Mounting Screw	ServoCity	632122	Steel	4	$0.32	$1.28
2	430	Motor Pulley (1.13" OD)	McMaster	57105K14	Acetal/Aluminum	1	$7.51	$7.51
2	440	Motor Pulley (2.25" OD)	McMaster	57105K26	Acetal/Aluminum	1	$8.91	$8.91
2	450	Timing Belt	McMaster	6484K225	Neoprene	1	$6.14	$6.14
2	460	Pattern Mount	ServoCity	585494	Steel	1	$5.99	$5.99
2	470	Motor Mount	ServoCity	555196	Steel	1	$5.99	$5.99
2	480	Encoder Cable	ServoCity	AM-2992	Wire	1	$0.99	$0.99
2	490	Wire Disconnects	ACE	34519	Steel	2	$0.36	$0.72
2	491	Battery	Amazon	NP2.3-12FR	-	1	$29.00	$29.00
1	500	Cleaning System	-	-	-	1	-	$42.05
2	510	Microfiber (Modified)	Amazon	97246852	Microfiber	1	$2.99	$2.99
2	520	Cleaner Bar (Modified)	McMaster	8975K196	Aluminum	1	$0.89	$0.89
2	530	Strap (Modified)	Amazon	B07JJ6HFY2	Nylon	1	$7.80	$7.80
2	550	Staples	Amazon	55012	Stainless Steel	2	-	$3.99
2	560	16 " Ostrich Feathers	Amazon	ST-M1	Bird Feathers	1	$14.00	$14.00
2	570	Wrapping Wire	Ace Hardware	5337431	Steel	1	$3.59	$3.59
2	580	Wood	Home Depot	161640	Wood	1	$2.82	$2.82
2	590	Super Glue	Home Depot	7700103	Adhesive	1	$5.97	$5.97
							Total Cost	**$584.58**

Appendix J: Budget

BOM Part #	Part Literature	Vendor	Product Number	Quantity	Unit Cost	Total Cost (Including Tax and Shipping)	Product link
210	3D Printed Bracket	Printed	Custom	2	$189.15	$378.30	-
220	Mounting Screw (10-32 1.5")	Home Depot	814741	10	$0.25	$2.50	https://www.homedepot.com/p/Everbilt-10-32-x-1-1-2-in-Phillips-Slotted-Round-Head-Machine-Screws-3-Pack-33171/202706431
230	Neoprene Washers	Home Depot	597442	10	$0.23	$2.30	https://www.homedepot.com/p/3-16-in-x-1-2-in-Black-Neoprene-Washer-4-Piece-815728/204276433?keyword=597442&semanticToken=20330000011_410437839253033_21zz+20330000011+%3E++st%3A%7B597442%7D%3Ast+cnn%3A%7B0%3A0%7D+cnr%3A%7B8%3A0%7D+cn1%3A%7B5%3A0%7D+cnd%3A%7B6%3A0%7D+f%3A%7Bb%7D+cnv%3A%7B1%3A1%7D+oos%3A%7B0%3A1%7D+dln%3A%7B562916%7D+qu%3A%7B597442%7D%3Aqu
310	Pulley	McMaster	57105K31	6	$10.61	$84.29	https://www.mcmaster.com/catalog/125/1153
320	Timing Belt (15" OD)	McMaster	1679K149	2	$13.60	$27.20	https://www.mcmaster.com/catalog/125/1152
330	Long Shaft (Cut to Length) (11.81")	Home Depot	802437	1	$0.91	$0.91	https://www.homedepot.com/p/5-16-in-x-36-in-Plain-Steel-Round-Rod-802437/204273958?keyword=802437&semanticToken=20330000011_428810828774822_6xz5+20330000011+%3E++st%3A%7B802437%7D%3Ast+cnn%3A%7B0%3A0%7D+cnr%3A%7B8%3A0%7D+cn1%3A%7B5%3A0%7D+cnd%3A%7B6%3A0%7D+f%3A%7Bb%7D+cnv%3A%7B1%3A1%7D+oos%3A%7B0%3A1%7D+dln%3A%7B563052%7D+qu%3A%7B802437%7D%3Aqu

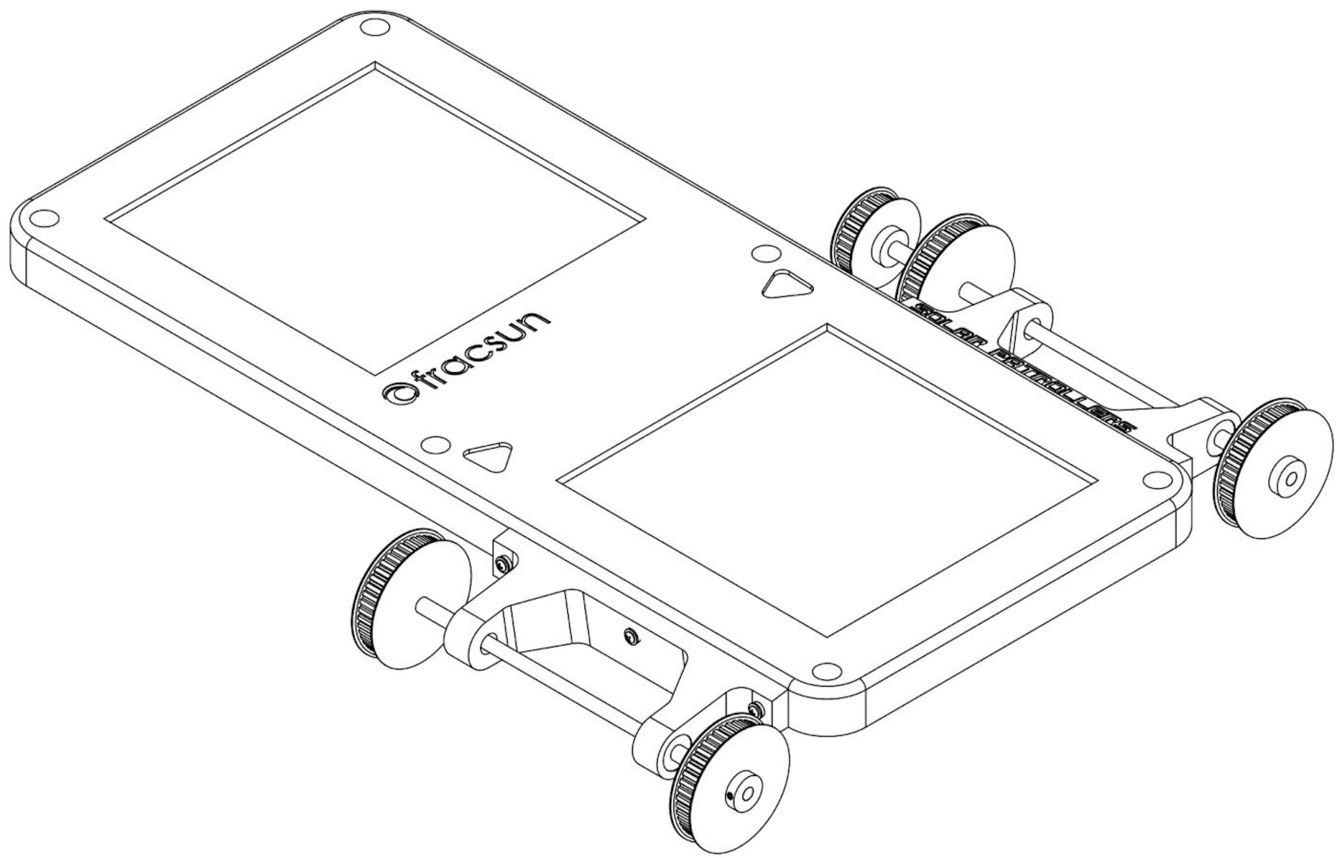
331	Short Shaft (Cut to Length) (10.83")	Home Depot	802437	1	$0.91	$0.91	https://www.homedepot.com/p/5-16-in-x-36-in-Plain-Steel-Round-Rod-802437/204273958?keyword=802437&semanticToken=20330000011_428810828774822_6xz5+20330000011+%3E++st%3A%7B802437%7D%3Ast+cnn%3A%7B0%3A0%7D+cnr%3A%7B8%3A0%7D+cn1%3A%7B5%3A0%7D+cnd%3A%7B6%3A0%7D+f%3A%7Bb%7D+cnv%3A%7B1%3A1%7D+oos%3A%7B0%3A1%7D+dln%3A%7B563052%7D+qu%3A%7B802437%7D%3Aqu
340	Bearing	Skate Warehouse	Flip HKD Bearings ABEC 5	4	$1.00	$9.99	https://www.skatewarehouse.com/Flip_HKD_Bearings_ABEC_7/descpage-FLHKD7BR.html
350	Spacers (Modified)	Home Depot	595173	5	$0.70	$3.50	https://www.homedepot.com/p/1-2-in-x-1-4-in-Nylon-Spacers-2-Pieces-814918/204225907
410	317 rpm Spur Gear Motor	ServoCity	520000020026	1	$9.99	$9.99	https://www.servocity.com/317-rpm-spur-gear-motor-w-encoder
420	7/16" Mounting Screw	ServoCity	632112	1	$2.29	$2.29	https://www.servocity.com/6-32-zinc-plated-socket-head-machine-screws
421	7/8" Mounting Screw	ServoCity	632122	1	$3.19	$3.19	https://www.servocity.com/6-32-zinc-plated-socket-head-machine-screws
430	Motor Pulley (1.13" OD)	McMaster	57105K14	1	$7.51	$7.51	https://www.mcmaster.com/catalog/125/1153
440	Motor Pulley (2.25" OD)	McMaster	57105K26	1	$8.91	$8.91	https://www.mcmaster.com/catalog/125/1153
450	Timing Belt	McMaster	6484K225	1	$6.14	$6.14	https://www.mcmaster.com/catalog/125/1152
460	Pattern Mount	ServoCity	585494	1	$5.99	$5.99	https://www.servocity.com/90-hub-mount-bracket-a
470	Motor Mount	ServoCity	555196	1	$5.99	$5.99	https://www.servocity.com/spur-gear-motor-mount-g
480	Encoder Cable	ServoCity	AM-2992	1	$0.99	$0.99	https://www.servocity.com/encoder-cable-female-jst-xh-to-female-header-row

490	Wire Disconnects	ACE	34519	1	$3.59	$3.59	https://www.acehardware.com/departments/lighting-and-electrical/boxes-fittings-and-conduit/lugs/34519
510	Microfiber (Modified)	Amazon	97246852	1	$5.87	$5.87	https://www.amazon.com/gp/product/B073HLZLK9/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
520	Cleaner Bar (Modified)	McMaster	8975K196	1	$0.89	$0.89	https://www.mcmaster.com/catalog/125/3799
530	Strap (Modified)	Amazon	B07JJ6HFY2	1	$7.80	$7.80	https://www.amazon.com/gp/product/B01KTVG0KI/ref=ppx_yo_dt_b_asin_title_o07_s00?ie=UTF8&psc=1
560	16 " Ostrich Feathers	Amazon	ST-M1	2	$14.00	$28.00	https://www.amazon.com/gp/product/B06WGNK49K/ref=ppx_od_dt_b_asin_title_s00?ie=UTF8&th=2
570	Wrapping Wire	ACE	5337431	1	$3.59	$3.59	https://www.acehardware.com/departments/hardware/chain-and-rope/wire/5337431
580	Wood	Home Depot	161640	5	$2.82	$14.10	https://www.homedepot.com/p/2-in-x-4-in-x-96-in-Premium-Kiln-Dried-Whitewood-Stud-161640/202091220
-	44" V-Belts	Home Depot	583529	2	$4.61	$9.22	https://www.homedepot.com/p/44-in-Evaporative-Cooler-V-Belt-65445/100346001
-	Wood Glue	Home Depot	638489	1	$3.97	$3.97	https://www.homedepot.com/p/Gorilla-8-oz-Wood-Glue-62000/100672167
-	Metal Brackets	Home Depot	243078	4	$2.77	$11.08	https://www.homedepot.com/p/Crown-Bolt-5-in-Zinc-Plated-Corner-Brace-15212/202585414
-	PVC Pipe	Home Depot	254977	2	$2.13	$4.26	https://www.homedepot.com/p/VPC-1-in-x-24-in-PVC-Sch-40-Pipe-2201/202300506
-	45" V-Belts	Amazon	B009HEGD1K	2	$8.87	$17.74	https://www.amazon.com/gp/product/B009HEGD1K/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1

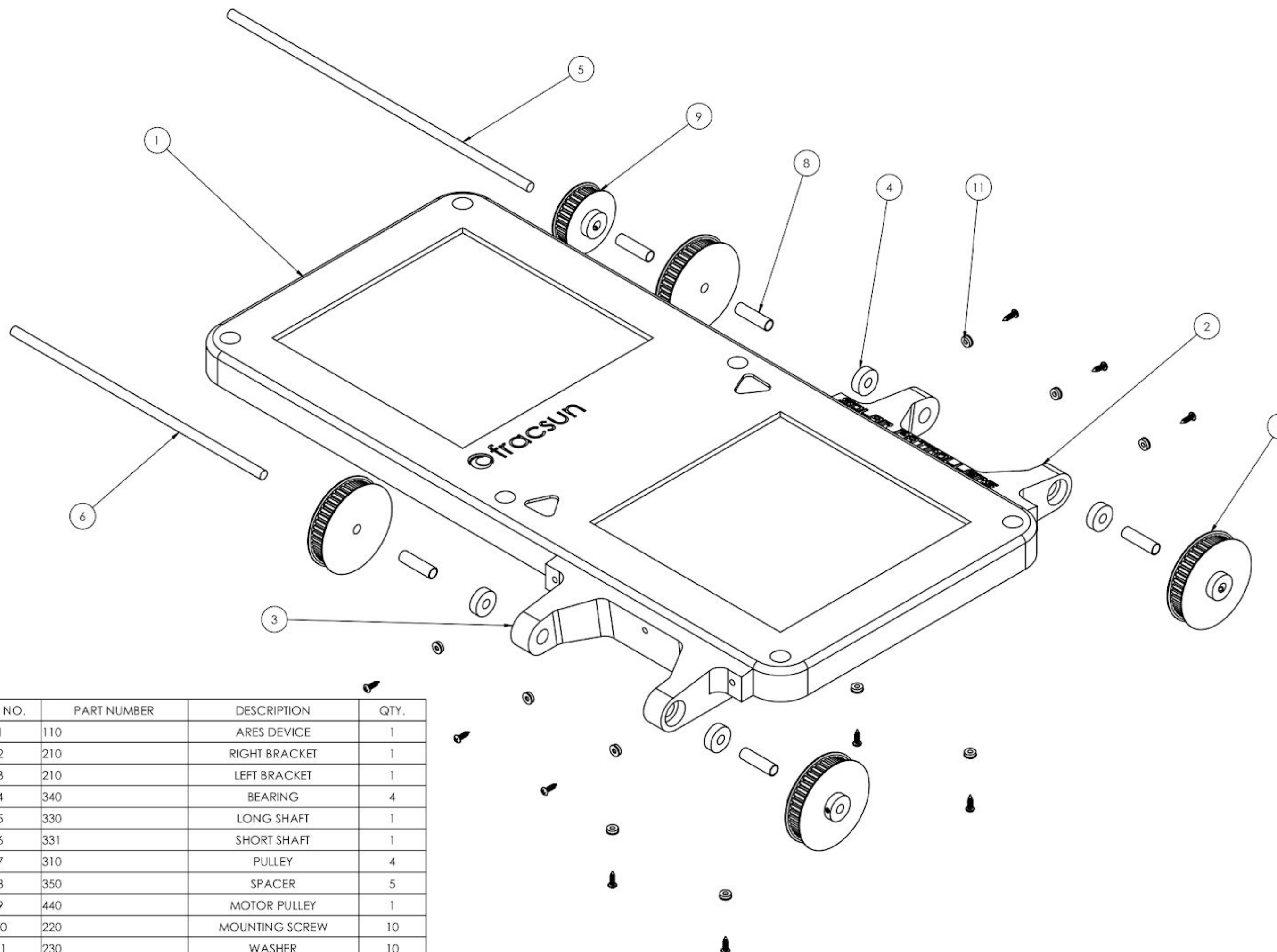
-	Squeegee	Amazon	B000CCDBRK	1	$6.99	$6.99	https://www.amazon.com/gp/product/B000CCDBRK/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
-	Bristle Rim Cleaner	Amazon	5823901329	1	$15.87	$15.87	https://www.amazon.com/gp/product/B071VRJRKK/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
-	MagicFiber	Amazon	B0043XZEEC	1	$5.99	$5.99	https://www.amazon.com/gp/product/B0043XZEEC/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1
-	Microfiber Mitt	Amazon	MIT_BLU	2	$4.99	$9.98	https://www.amazon.com/gp/product/B07H2KS12T/ref=ppx_yo_dt_b_asin_title_o07_s00?ie=UTF8&psc=1
	Small Motor Bracket	Amazon	ST-M1	1	$6.50	$6.50	https://www.amazon.com/gp/product/B00Q6F51C0/ref=ppx_yo_dt_b_asin_title_o02_s00?ie=UTF8&psc=1
-	Aluminum 8mm Round Stock	McMaster	4634T34	1	$5.47	$5.47	https://www.mcmaster.com/catalog/125/3808
-	Aluminum 1/16" Stock	McMaster	8975K196	1	$5.31	$5.31	https://www.mcmaster.com/catalog/125/3799
-	V Belt 1/4" Pulley (2.05"OD)	Mcmaster	6274K12	4	$11.00	$96.04	https://www.mcmaster.com/catalog/125/1146
-	V Belt 1/4" Pulley (3.05"OD)	McMaster	6274K21	4	$14.44	$69.27	https://www.mcmaster.com/catalog/125/1146
-	V-Belt	McMaster	6191K31	2	$8.28	$26.56	https://www.mcmaster.com/catalog/125/1140
-	XL Series Timing Belt (42" OD)	Mcmaster	6484K446	6	$10.63	$63.78	https://www.mcmaster.com/catalog/125/1152
-	XL Series Timing Belt (10" OD)	McMaster	6484K22	1	$5.38	$14.59	https://www.mcmaster.com/catalog/125/1152
-	Timing Pulley (2.13" OD)	McMaster	57105K25	1	$8.88	$8.88	https://www.mcmaster.com/catalog/125/1152
-	Timing Pulley (2" OD)	McMaster	57105K24	1	$8.75	$8.75	https://www.mcmaster.com/catalog/125/1153
-	Timing Belt (14" OD)	McMaster	6484K224	1	$6.01	$6.01	https://www.mcmaster.com/catalog/125/1152
-	Timing Belt (13" OD)	McMaster	6484K22	1	$5.77	$27.39	https://www.mcmaster.com/catalog/125/1152
-	Spur Gear Motor (153 rpm)	ServoCity	5200-0002-0053	1	$9.99	$9.99	https://www.servocity.com/153-rpm-spur-gear-motor-w-encoder

-	Large Mounting Bracket	Banggood	1051488	1	$13.89	$13.89	https://www.banggood.com/52mm-Mount-Clamp-Holder-Spindle-Motor-Mount-Bracket-p-1051488.html?utm_design=41&utm_source=emarsys&utm_medium=Shipoutinform171129&utm_campaign=trigger-emarsys&utm_content=Winna&sc_src=email_2671705&sc_eh=7615cfbdcb6c76161&sc_llid=12128690&sc_lid=104858042&sc_uid=NGkXCqDIT3&cur_warehouse=CN
						$1,072.27	

Appendix K: Drawing Package

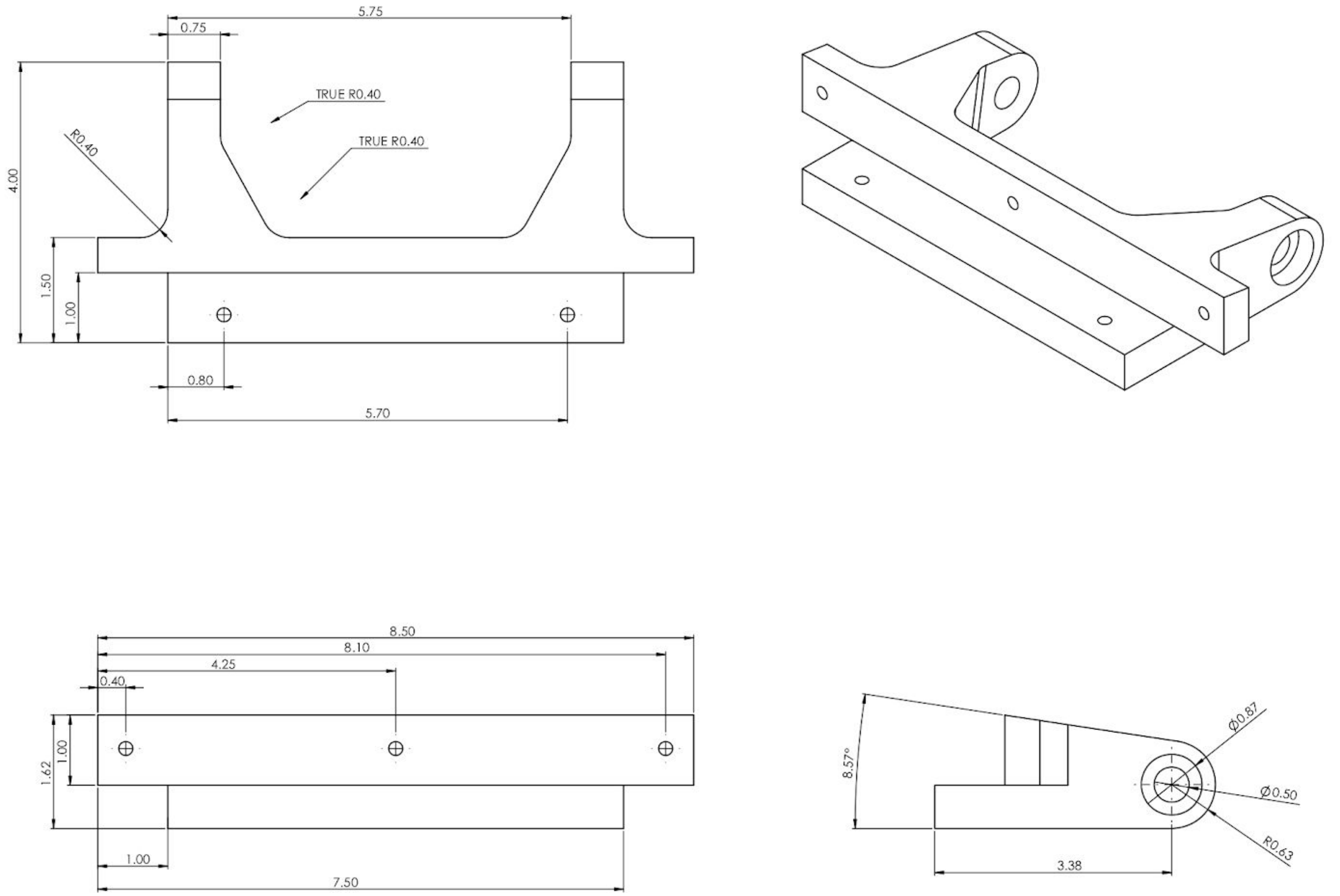


Cal Poly Mechanical Engineering	ISOMETRIC VIEW		Drwn. By: JACK GLYNN
ARES Cleaning Device	Date: 5/30/19	Scale: 2:3	Chkd. By: SOLAR PATROLLERS

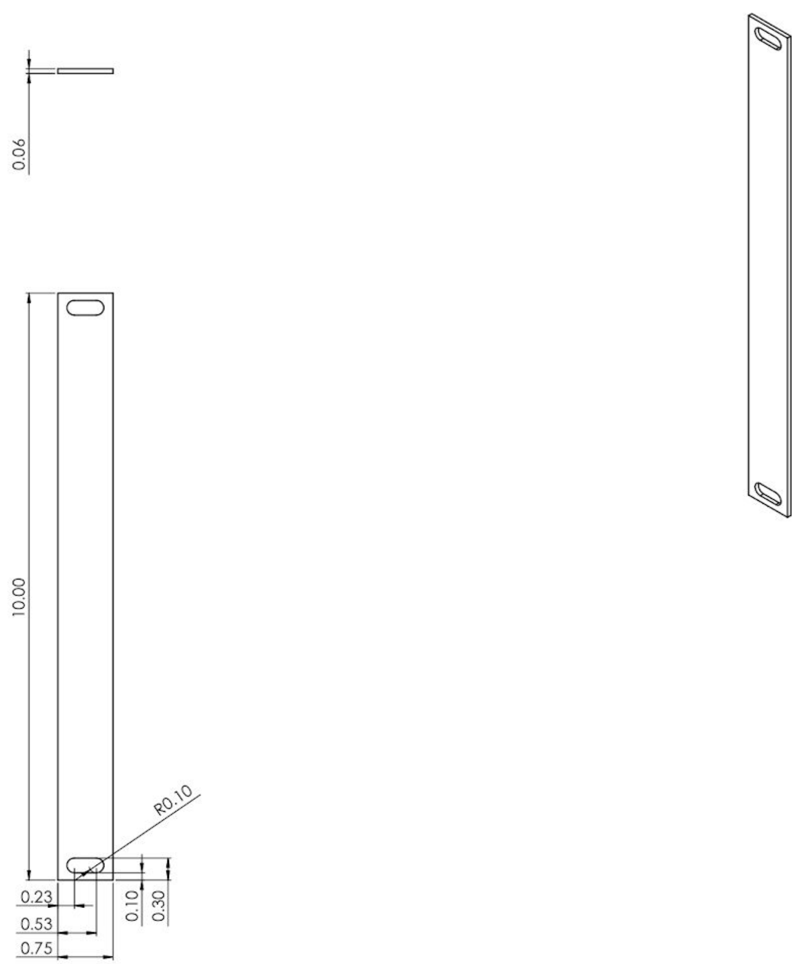


ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	110	ARES DEVICE	1
2	210	RIGHT BRACKET	1
3	210	LEFT BRACKET	1
4	340	BEARING	4
5	330	LONG SHAFT	1
6	331	SHORT SHAFT	1
7	310	PULLEY	4
8	350	SPACER	5
9	440	MOTOR PULLEY	1
10	220	MOUNTING SCREW	10
11	230	WASHER	10

Cal Poly Mechanical Engineering	ISOMETRIC EXPLODED VIEW		Drwn. By: JACK GLYNN
ARES Cleaning Device	Date: 5/30/19	Scale: 1:2	Chkd. By: SOLAR PATROLLERS



Cal Poly Mechanical Engineering	BRACKET	Drwn. By: JACK GLYNN
ARES Cleaning Device	Date: 5/30/19 — Scale: 1:1	Chkd. By: SOLAR PATROLLERS



Cal Poly Mechanical Engineering	CLEANER BAR	MATERIAL: ALUMINUM	Drwn. By: JACK GLYNN
ARES Cleaning Device	Date: 5/30/19	Scale: 1:1	Chkd. By: SOLAR PATROLLERS

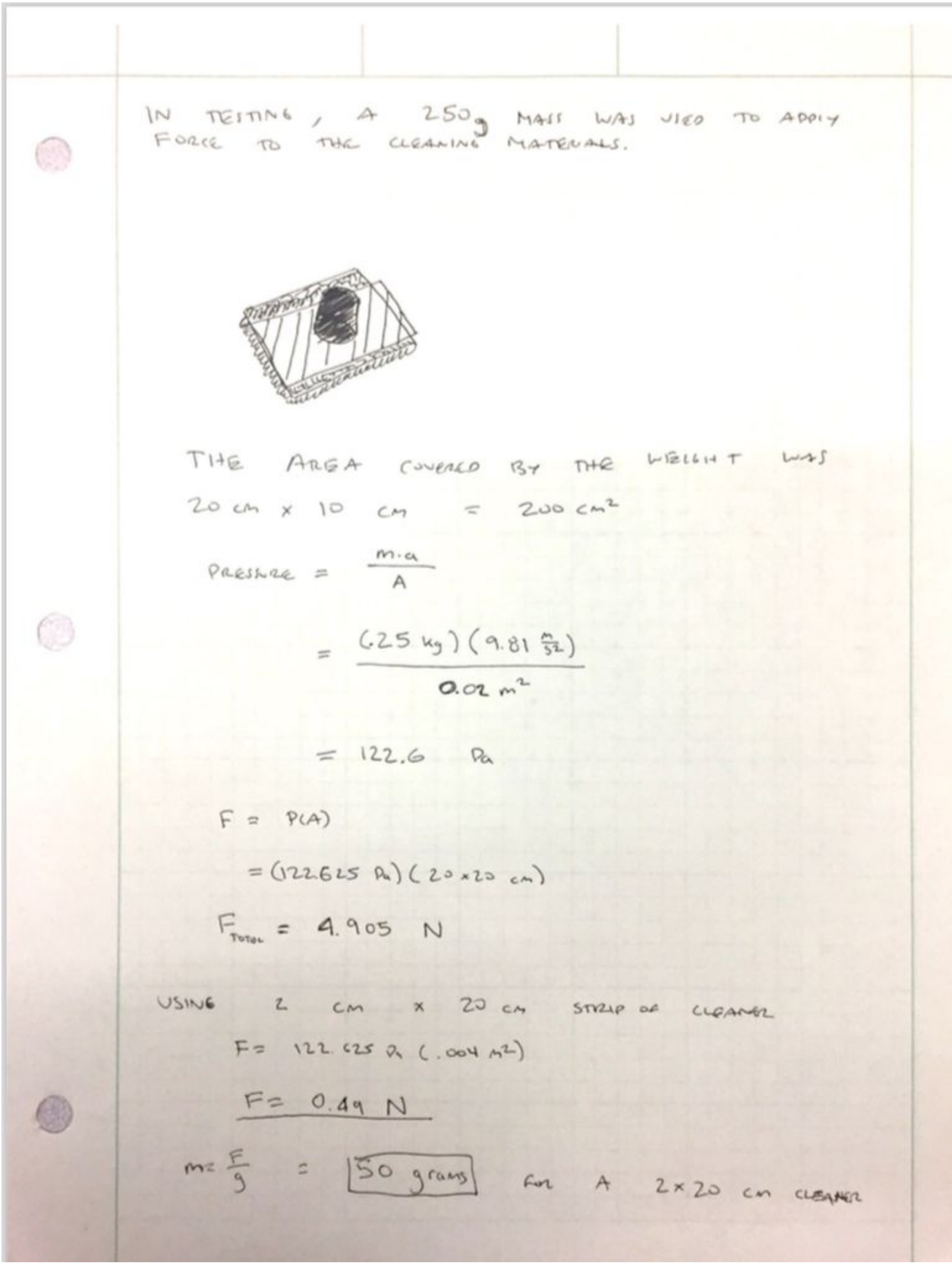
Appendix L: Design Verification Plan

Senior Project DVP&R													
Date: 2/13/19		Team: Solar Patrollers	Sponsor: Fracsun			Description of System: Cleaning method for Fracsun's soiling measurement device					DVP&R Engineer:		
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	2	How long it takes to install cleaning system to apparatus (without cleaner).Test done in Bonderson.	15 minutes	Andy	SP	1	Sub	2/3/2019	2/3/2019	5 minutes	1	0	This does not include manufacturing time
2	7	Ability of microfiber cloth to clean panel (daily amount of dirt) completely, verified with white glove test. Test done at Fracsun HQ.	0 Particulates On 20x20 cm Cell	Peter	CP	2	C	1/15/2019	1/15/2019	0 Particulates On 20x20 cm Cell	2	0	Easy to cut and shape
3	7	Ability of Ostrich Feathers to clean panel completely, verified with white glove test. Test done at John's house.	0 Particulates On 20x20 cm Cell	Andy	CP	2	C	2/16/2019	2/16/2019	0 Particulates On 20x20 cm Cell	2	0	Works well, also thinking about fine bristles.
4	7	Ability of Ostrich Feathers to clean panel (daily amount of dirt) completely with attachment to final prototype, and three different dirty conditions (wet, dry, with different soils) verified with white glove test. Test done at John's house.	0 Particulates On 20x20 cm Cell	Andy	FP	3	Sys	4/23/2019	4/30/2019	0 Particulates On 20x20 cm Cell	2	1	This also serves as a test for our attachment method with nylon straps, glue and metal plate
5	7	Ability of microfiber cloth to clean panel (daily amount of dirt) completely with attachment to structural prototype, and three different dirty conditions (wet, dry, with different soils) verified with white glove test. Test done at John's house.	0 Particulates On 20x20 cm Cell	Andy	FP	3	Sys	4/23/2019	4/30/2019	0 Particulates On 20x20 cm Cell	3	0	Made Decision at this point to use microfiber and ostrich feathers and microfibers in unison.
6		How many passes does it take to clean the panel each day	0 Particulates On 20x20 cm Cell	Peter	FP	1	Sys	5/11/2019	5/11/2019	3 passes	1	0	2 passes worked okay, but the additional pass allows for confidence in long term cleaning
7	1	Maintenance Schedule Test with chosen cleaner, running through multiple cycles until no longer cleans. Test done at John's house.	365 Cycles	John	FP	1	Sys	5/11/2019	5/16/2019	400 Cycles	1	0	Completed 400 cycles to provide a factor of safety. This test allowed for confidence in multiple specifications
8	2	How long it takes to install cleaning system to apparatus. Test done anywhere.	15 minutes	Jack	FP	1	Sys	4/22/2019	4/22/2019	11.5 minutes	1	0	Not include drilled holes in ARES system
9	5	Weigh Components of final prototype. Test done in building 42, room D13.	6 lbf	John	FP	1	Sys	4/22/2019	4/22/2019	4.38 lbf	1	0	Does not include weight of ARES system or battery
10	3	Determine Speed and Torque of Motor Needed by varying voltage on existing motor and cleaning panel. Conduct uncertainty propagation and data analysis using motor specs and monitoring current draw with DVM. Test done in ME 405 lab.	Must run on 12-24 VDC	Jack	FP	1	Sys	4/23/2019	4/30/2019	Allowed us to narrow down motor size and choose two additional motors to try, one of which was incorporated into the final design.	1	0	Helped determine which motor should be purchased as well as gear ratios needed.
11	11	Connect motor to microcontroller, and test encoder feedback using ME 405 Code. Test done in ME 405 lab.	Provides cleaning feedback (0-50mV)	Andy	FP	1	Sys	4/22/2019	4/29/2019	Working Code	1	0	Feedback will most likely go beyond just voltage and will provide notification of completed cycle when implemented with exisiting system
12	4	Connect motor to microcontroller, and test timing code for cleaning once a day. Test done in ME 405 lab.	Runs Once/24hrs	Jack	FP	1	Sys	4/30/2019	5/9/2019	Working Code	1	0	Code written in Python

Appendix M: Failure Modes Effects and Analysis

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	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality	RPN
Cleaning	Cleaning system not clean	Makes panel dirty	7	1) Long term environmental exposure. 2) Cleaning system encasement compromised	1) Encase the cleaning method under the panel 2) Use reliable materials	6	ARES System	6	252	Conduct preliminary tests to rate effectiveness of cleaner under fixture that brushes up against cleaner	Team 1/31/2019	Tested cleaners, and chosen proper cleaning material that lasts	5	3	4	60
	Cleaner wears out	Loses cleaning ability	5	1) Fatigue and Wear	1) Encase the cleaning method under the panel. 2) Have replacements annualy	7	ARES System	5	175	Do fatigue analysis and research into the life of the chosen cleaning method	Team 3/15/2019	n/a	4	2	4	32
	Cleaner detaches	Panel not being cleaned	9	1) Fatigue and wear	1) Design for support 2) Feedback shows how clean panel is	3	ARES System	1	27							0
Actuation	Doesn't move	Panel not being cleaned	9	1) Battery failure 2) Pulley failure 3) Debris jamming motion	1) Test to confirm working mtor and pulleys after installation	6	Sensor	1	54							0
	Moves then gets stuck	Panel not being cleaned or only partially cleaned	7	1) Pulley failure 2) Debris jamming motion	1) Use metal pulleys and long life belts	6	Sensor	1	42							0
	Belt wears out	Belt snapping, resulting in an unclean panel	7	1) Poor belt choice 2) Weather causing wear on the belt	1) Use a belt that we have proven can have long lasting life 2) Calling the belt provider and asking about life of belt in high temperatures	3	Sensor	3	63							0
Feedback	Feedback system damaged	1) Doesn't provide feedback 2) Provides false feedback	9	1) Water damage to microcontroller 2) Dirty or debris accumulation in system	1) Enclose feedback system	4	Enclosure	2	72	Ensure system is properly enclosed according to IP industry standards	Team 3/12/2019	n/a	3	3	3	27
	Internal failure of stock potentiometer	1) Doesn't provide feedback	6	1) Potentiometer manufactured incorrectly	1) Test linear actuator's potentiometer preinstallation	2	Testing	4	48							0
	Wires disconnected from microcontroller	1) Doesn't provide feedback	6	1) Force from weather or natural disaster 2) Performing maintenece on ARES system	1) Solder wires in place	3	Testing forces and maintence routine	1	18							0

Appendix N: Hand Calculation



IN TESTING, A 250g MASS WAS USED TO APPLY FORCE TO THE CLEANING MATERIALS.

THE AREA COVERED BY THE WEIGHT WAS

20 cm x 10 cm = 200 cm^2

$$\text{PRESSURE} = \frac{m \cdot a}{A}$$

$$= \frac{(.25\ kg)(9.81\ \frac{m}{s^2})}{0.02\ m^2}$$

$$= 122.6\ Pa$$

$$F = P(A)$$

$$= (122.625\ Pa)(20 \times 20\ cm)$$

$$F_{Total} = 4.905\ N$$

USING 2 cm x 20 cm STRIP OF CLEANER

$$F = 122.625\ Pa\ (.004\ m^2)$$

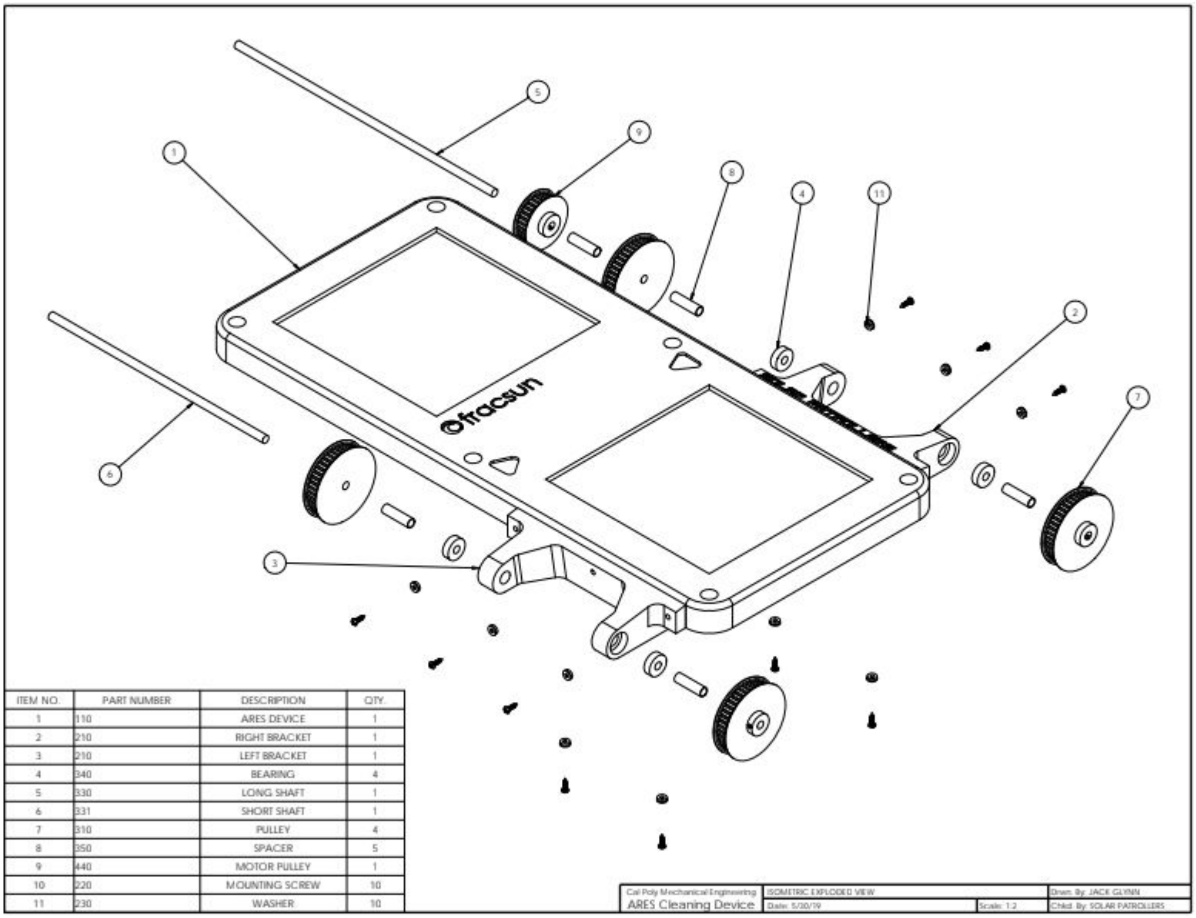
$$F = 0.49\ N$$

$$m = \frac{F}{g} = \boxed{50\ grams}$$ FOR A 2 x 20 cm CLEANER

The above is a calculation showing that the cleaner and cleaner bar combined must weight 50 grams in order to exert the same force that was applied during testing. In addition, if the mass is less than 50 grams, the guide rails will apply additional downward force.

Appendix O: Operators' Manual

The ARES Cleaning System Operators' Manual explains a solar plant operator's maintenance duties involving the the ARES Cleaning System. It describes the replacement and upkeep process for any components susceptible to wear or failure. Figure 1 may be used as reference while performing these operations. All safety recommendations should be followed as stated.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	110	ARES DEVICE	1
2	210	RIGHT BRACKET	1
3	210	LEFT BRACKET	1
4	340	BEARING	4
5	330	LONG SHAFT	1
6	331	SHORT SHAFT	1
7	310	PULLEY	4
8	350	SPACER	5
9	440	MOTOR PULLEY	1
10	220	MOUNTING SCREW	10
11	230	WASHER	10

Figure 1. Assembly of ARES Cleaning System

1. Belts and Cleaner Installation and Replacement

It is required that the belts and cleaner components of the ARES Cleaning System are to be replaced on an annual schedule. Because these parts are linked through a sewn wire connection, they must be replaced together. Operators must obtain a new belt and cleaner set up from Fracsun if not already provided. To install, one must first remove the old belts and cleaner. This is done by stretching one of the cleaner belts over the outermost flange of a pulley and rotating the pulley outwards. The belt should slip off the pulley. Be careful to avoid the pinch point between the flange and the belt. Perform this same process with the other belt.

To install the new belt and cleaner set up, a reverse process is performed. Place the belts over the device so that the cleaner lays across the solar panel. Take the innermost belt and mesh the teeth with the one of the pulleys on its side. Stretch the belt over the other pulley so that it lies on the flange. Rotate the pulley outward so that the belts teeth join with the pulley. This process can be seen in Figure 2 and 3. For the other belt, one must perform the same process but also align the cleaner. The cleaner is to be placed perfectly straight across the panel. This is done by visual inspection as one aligns the second belt. This may take multiple attempts. The process becomes easier as one gains a feel for how much the meshing of the pulley alters the alignment of the cleaner.

Figure 2. Cleaner Belt Installation on Flange

Figure 3. Rotating for Cleaner Belt Installation

2. Motor Belt Installation and Replacement

The motor belt should be replaced annually along with the cleaner. To begin, remove the old motor timing belt. Loosen all other pulley set screws on the long shaft. Remove the pulley by sliding it off the shaft outward. To make this process smoother, also pull the shaft outward in the opposite direction. The removal process can be seen in Figure 3. To place the new motor belt over the motor pulley, mesh the motor belt with the small motor pulley. Perform the same belt installation process explained in Section 1, rotating the pulley outward with the belt until it meshes.

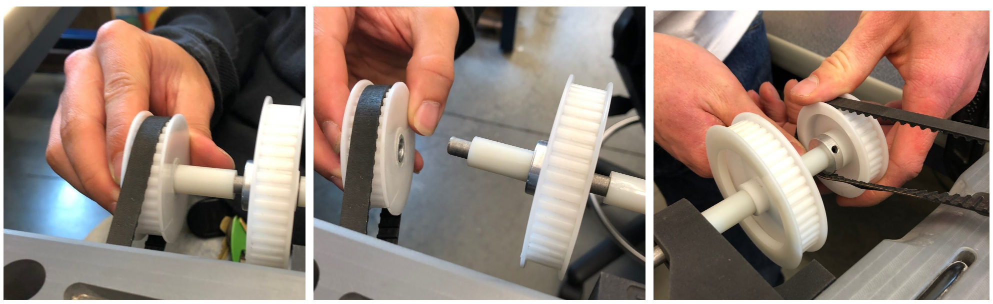


Figure 3. Motor Belt Installation

3. Pulley Installation and Replacement

Refer to sections 1 and 2 to remove the cleaner or motor belt before removing the pulley(s). Once the cleaner, spacers, and or motor belt have been removed, take the 3/32 inch (5/64 for motor pulley) allen key and loosen the set screw located on the center of the pulley shown in Figure 4. Once the pulley is loose, it can be moved along the shaft for adjustment or easily replaced with a new pulley. Make sure the set screw is loose and the spacers on the main shaft are in place before sliding the new pulley on the shaft. Once the pulley is in the desired position, tighten down the set screw with the allen key. Refer to sections 1 and 2 to properly place the cleaner and motor belt back onto the device.

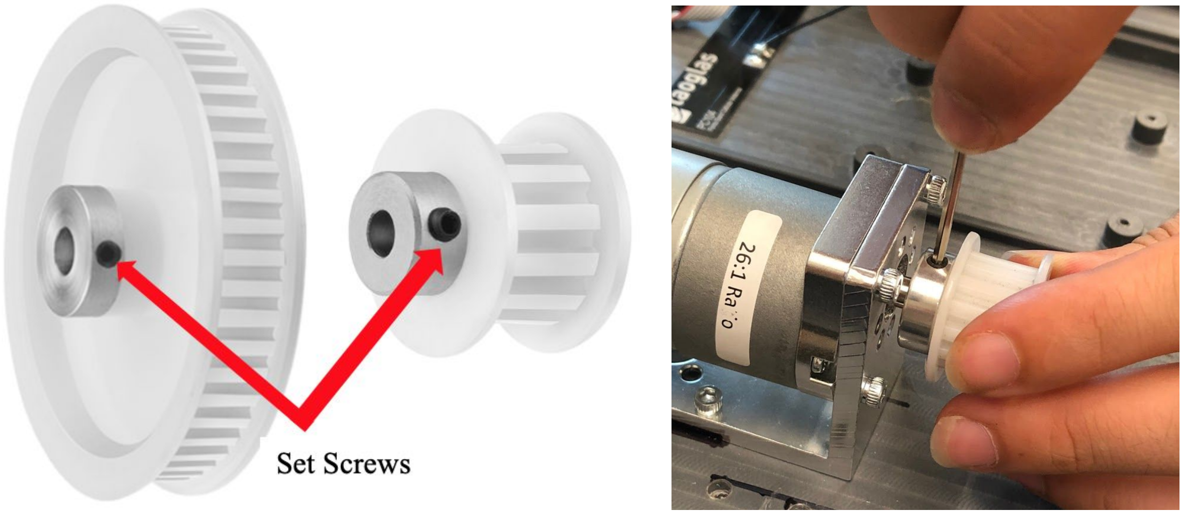


Figure 4. Set Screw Location

4. Shaft Installation and Replacement

Refer to sections 1 and 3 to properly remove the cleaner, and pulleys before removing the shaft(s). Once the pulleys are removed, the shaft will easily slide out of the bracket and can be easily be replaced as shown in Figure 5. Refer to sections 1 and 3 to properly place the cleaner, belts and pulleys back on the device.

Figure 5. Shaft Removal

5. Motor Installation and Replacement

Refer to section 2 and 3 to properly remove motor driven belt and timing pulley. When handling the motor, never short any wire leads. Avoid any water exposure to the electronics and never handle the connections while the system is powered. Following the photos in Figure 6, disconnect the battery from the microcontroller by disconnecting the positive lead on the battery followed by the negative lead. Next, unscrew the motor connection terminals on the motor driver board of the microcontroller. Remove the wires from the terminals. Remove the encoder wire connection from the motor. Unscrew the 4 bolts holding the motor to the mount with a 7/64 size allen wrench. Remove the motor and mounting plate. Place the new motor in the mounting plate and replace the bolts. Recconnect the encoder connection, and motor wires to the board. Tighten down all terminals before reconnecting the battery, ground first.

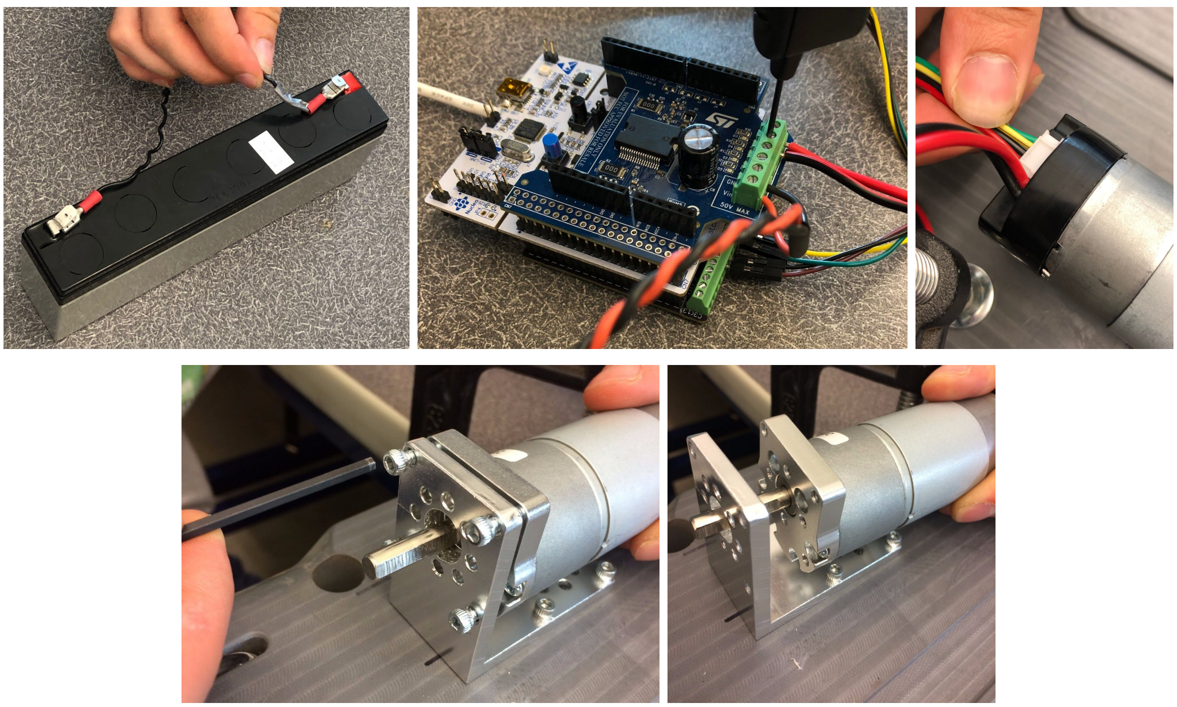


Figure 6. Motor Replacement Steps

Appendix P: Risk Assessment

designsafe Report

Application:	ARES Solar Cleaner	Analyst Name(s):	John, Andy, Jack, Peter
Description:	Risk assessment analysis of ARES Solar Cleaner Senior Project	Company:	The Solar Patrollers
Product Identifier:		Facility Location:	Cal Poly San Luis Obispo
Assessment Type:	Detailed		
Limits:	Risk analysis of product design as of 2/13/19		
Sources:			
Risk Scoring System:	ANSI AIHA Z10 2005		

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

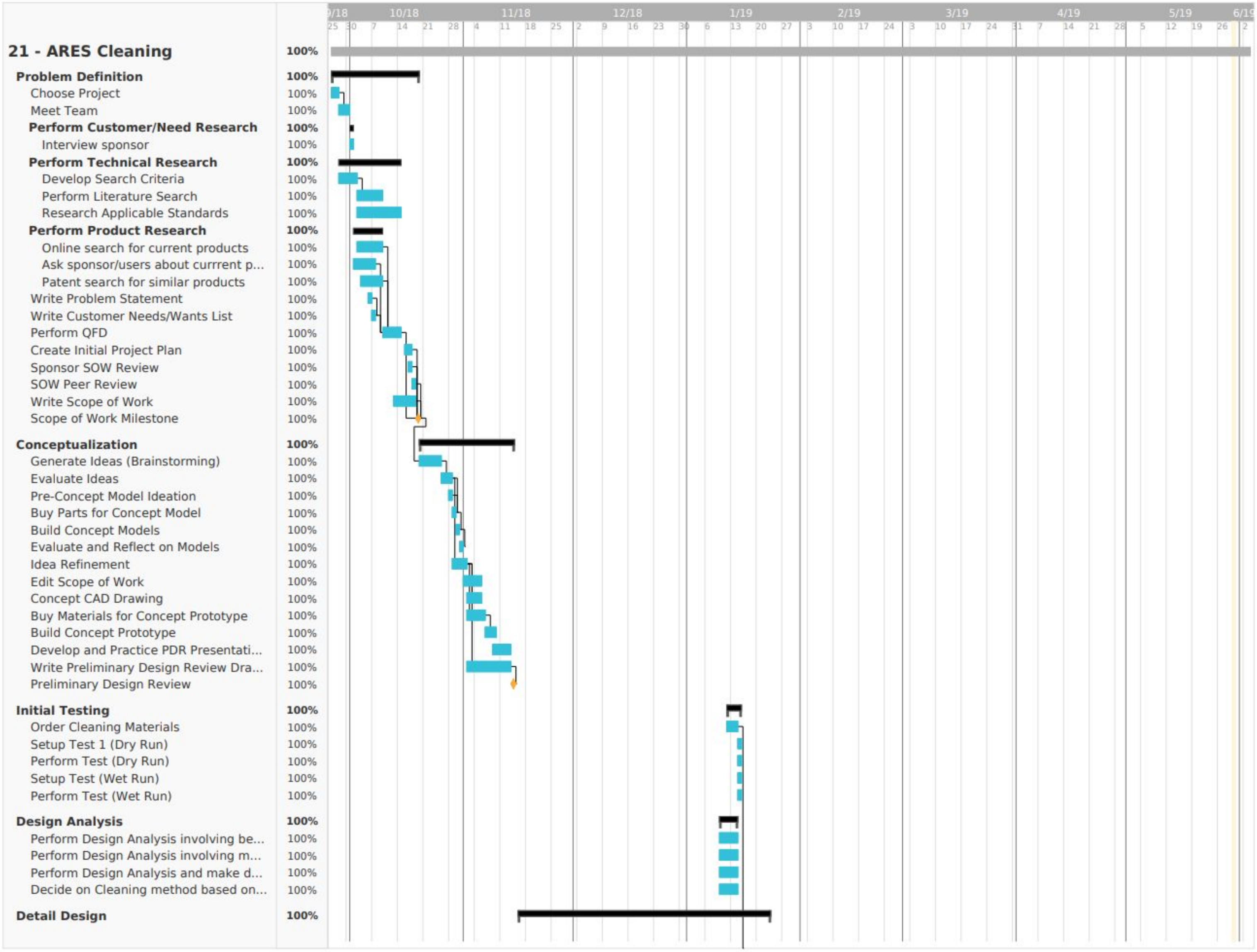
Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Likelihood of Oc	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Likelihood of Oc	Risk Level	Status / Responsible /Comments /Reference
1-1-1	maintenance technician set up or parts replacement	heat / temperature : severe heat extremely hot day	Marginal Occasional	Medium	avoid touching solar panel when doing maintenance	Marginal Remote	Medium	On-going [Daily] John
1-1-2	maintenance technician set up or parts replacement	material handling : excessive weight lifting panel fixture	Critical Occasional	Serious	maintenance worker must be fit to easily lift fixture	Critical Remote	Medium	On-going [Daily] John
1-1-3	maintenance technician set up or parts replacement	mechanical : pinch point assembly or disassembly	Negligible Probable	Medium	add warnings in assembly instructions	Negligible Remote	Low	Action Item [2/15/2019] John
1-1-4	maintenance technician set up or parts replacement	mechanical : drilling assembly or disassembly	Marginal Remote	Medium	maintenance worker must be fit to properly use drill	Marginal Remote	Medium	Action Item John
1-1-5	maintenance technician set up or parts replacement	electrical / electronic : water / wet locations weather conditions	Marginal Remote	Medium	electrical parts must be completely enclosed and electrical maintenance must not be done in wet conditions	Marginal Improbable	Low	Action Item Peter
1-1-6	maintenance technician set up or parts replacement	electrical / electronic : unexpected start up / motion performing maintence when device is cleaning	Negligible Remote	Low	device only cleans at night	Negligible Improbable	Low	Complete [2/13/2019] All

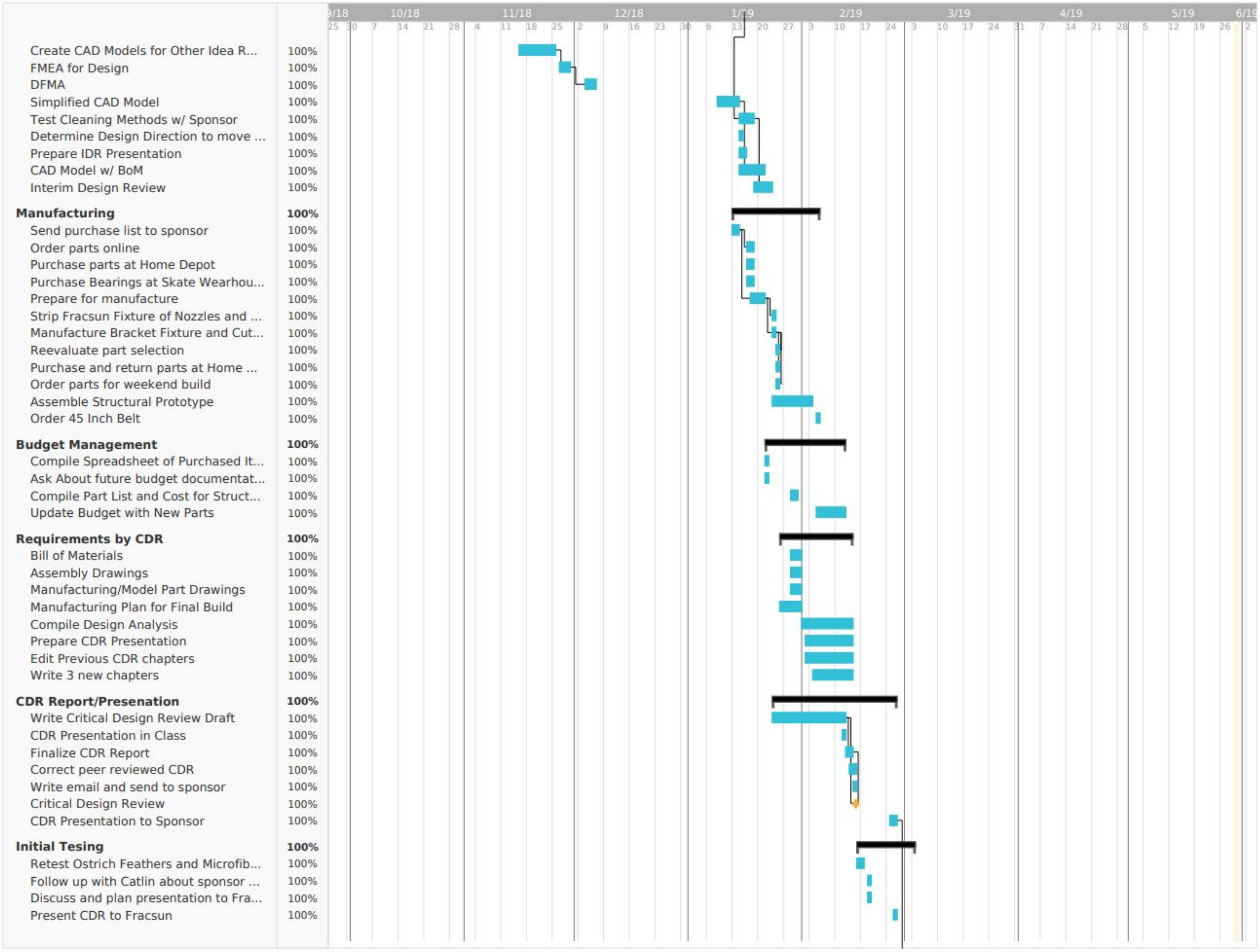
Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Llkelihood of O	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Llkelihood of O	Risk Level	Status / Responsible /Comments /Reference
1-1-7	maintenance technician set up or parts replacement	electrical / electronic : improper wiring wires not connected correctly	Marginal Remote	Medium	wiring instructions	Marginal Remote	Medium	Action Item Peter
1-2-1	maintenance technician trouble-shooting / problem solving	heat / temperature : severe heat extremely hot day	Marginal Occasional	Medium	avoid touching solar panel when troubleshooting	Marginal Remote	Medium	Action Item John
1-2-2	maintenance technician trouble-shooting / problem solving	mechanical : pinch point assembly or disassembly	Negligible Probable	Medium	add warnings in assembly instructions	Negligible Occasional	Low	Action Item [2/15/2019] John
1-2-3	maintenance technician trouble-shooting / problem solving	electrical / electronic : water / wet locations weather conditions	Marginal Remote	Medium	electrical parts must be completely enclosed and electrical maintenance must not be done in wet conditions	Marginal Improbable	Low	Action Item Peter
2-1-1	Solar Plant Cleaner (Manual) cleaning panel	electrical / electronic : water / wet locations cleaning with liquid	Marginal Occasional	Medium	do not directly touch device when cleaning	Marginal Remote	Medium	Action Item John
2-1-2	Solar Plant Cleaner (Manual) cleaning panel	electrical / electronic : unexpected start up / motion cleaning when device is planned to clean	Negligible Occasional	Low	device only cleans at night	Negligible Improbable	Low	Complete [2/13/2019] All
3-1-1	Manufacturer using hack saw	mechanical : pinch point vise grip adjusting	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John
3-1-2	Manufacturer using hack saw	mechanical : cutting / severing misuse of saw	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John
3-2-1	Manufacturer using mill	mechanical : pinch point vise grip adjusting	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Likelihood of O	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Likelihood of O	Risk Level	Status / Responsible /Comments /Reference
3-2-2	Manufacturer using mill	mechanical : cutting / severing misuse of mill	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John
3-3-1	Manufacturer using scissors	mechanical : cutting / severing misuse of scissors	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John
3-4-1	Manufacturer using drill	mechanical : drilling misuse of drill	Negligible Remote	Low	careful machine processes	Negligible Remote	Low	Action Item John
3-5-1	Manufacturer press fiting	ergonomics / human factors : excessive force / exertion press fitting bearings	Negligible Probable	Medium	add warnings in assembly instructions	Negligible Remote	Low	Action Item [2/15/2019] John
3-5-2	Manufacturer press fiting	mechanical : pinch point press fitting bearings	Negligible Probable	Medium	add warnings in assembly instructions	Negligible Remote	Low	Action Item [2/15/2019] John
3-6-1	Manufacturer wiring	electrical / electronic : improper wiring incorrect wiring	Marginal Remote	Medium	wiring instructions	Marginal Remote	Medium	Action Item Peter
3-7-1	Manufacturer other assembly	mechanical : drilling assembly and manufacturing	Marginal Remote	Medium	careful machine processes	Marginal Remote	Medium	Action Item John
4-1-1	Senior Project Expo Attendees touching parts	mechanical : pinch point touching parts at expo booth	Negligible Remote	Low	warning labels that only allow touch when device is powered off	Negligible Improbable	Low	Action Item [5/13/2019] John
4-1-2	Senior Project Expo Attendees touching parts	mechanical : moving parts putting hands on device during cleaning	Negligible Remote	Low	warning labels that only allow touch when device is powered off	Negligible Remote	Low	Action Item [5/13/2019] John

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Likelihood of O	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Likelihood of O	Risk Level	Status / Responsible /Comments /Reference
5-1-1	Installer mounting product	ergonomics / human factors : lifting / bending / twisting lifting panel fixture	Critical Occasional	Serious	installer must be fit to easily lift fixture	Critical Remote	Medium	Action Item John
5-1-2	Installer mounting product	mechanical : drilling using drill to mount fixture	Marginal Remote	Medium	installer must be fit to drill	Marginal Remote	Medium	Action Item John

Appendix Q: Gantt Chart




10/18
11/18
12/18
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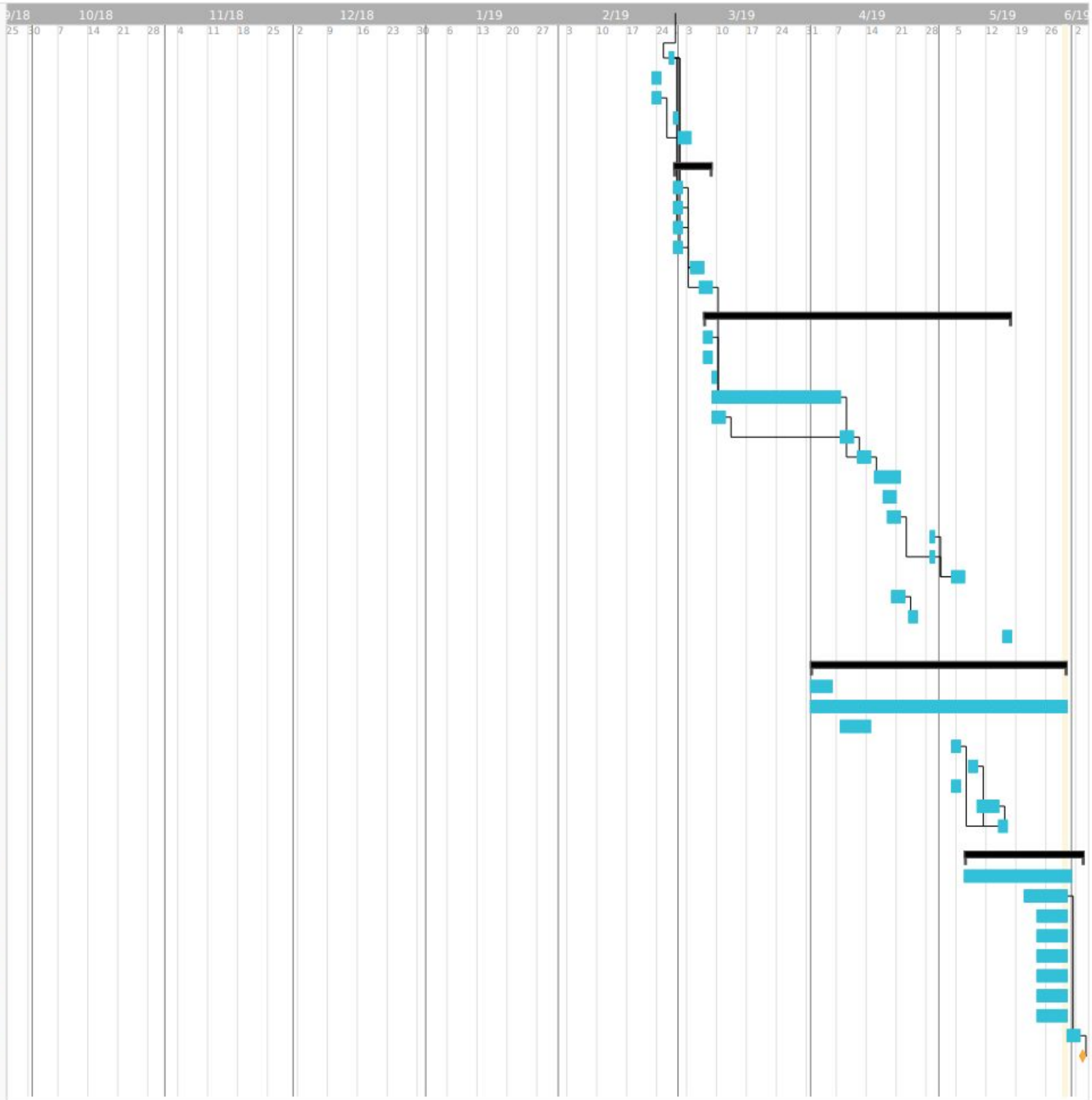
Create CAD Models for Other Idea R... 100%
FMEA for Design 100%
DFMA 100%
Simplified CAD Model 100%
Test Cleaning Methods w/ Sponsor 100%
Determine Design Direction to move ... 100%
Prepare IDR Presentation 100%
CAD Model w/ BoM 100%
Interim Design Review 100%
Manufacturing 100%
Send purchase list to sponsor 100%
Order parts online 100%
Purchase parts at Home Depot 100%
Purchase Bearings at Skate Wearhou... 100%
Prepare for manufacture 100%
Strip Fracsun Fixture of Nozzles and ... 100%
Manufacture Bracket Fixture and Cut... 100%
Reevaluate part selection 100%
Purchase and return parts at Home ... 100%
Order parts for weekend build 100%
Assemble Structural Prototype 100%
Order 45 Inch Belt 100%
Budget Management 100%
Compile Spreadsheet of Purchased It... 100%
Ask About future budget documentat... 100%
Compile Part List and Cost for Struct... 100%
Update Budget with New Parts 100%
Requirements by CDR 100%
Bill of Materials 100%
Assembly Drawings 100%
Manufacturing/Model Part Drawings 100%
Manufacturing Plan for Final Build 100%
Compile Design Analysis 100%
Prepare CDR Presentation 100%
Edit Previous CDR chapters 100%
Write 3 new chapters 100%
CDR Report/Presenation 100%
Write Critical Design Review Draft 100%
CDR Presentation in Class 100%
Finalize CDR Report 100%
Correct peer reviewed CDR 100%
Write email and send to sponsor 100%
Critical Design Review 100%
CDR Presentation to Sponsor 100%
Initial Tesing 100%
Retest Ostrich Feathers and Microfib... 100%
Follow up with Catlin about sponsor ... 100%
Discuss and plan presentation to Fra... 100%
Present CDR to Fracsun 100%

Task	% Complete
Make changes based on sponsor fee...	100%
Integrate Cleaner into Structural Prot...	100%
Test Cleaners w/ Drill and Shopvac	100%
Create Project Budget Table	100%
Make final decision on cleaner direct...	100%
Order Materials	**100%**
Design 3D Printed Bracket	100%
Order Parts from McMasterCarr	100%
Order non-McMasterCarr parts	100%
Buy parts from Home Depot	100%
Meet to get all purchased parts toge...	100%
Get 3D printed brackets	100%
Build	**100%**
Machine cleaner bar	100%
Implement nylon strap	100%
Size Timing Belts	100%
Build Prototype with everything exce...	100%
Order nylon 3D printed bracket	100%
Implement New Bracket	100%
Retest cleaner on final prototype w/ ...	100%
Add in cleaner to final prototype	100%
Determine solution for slipping probl...	100%
Test motor speeds and size motor	100%
Order Motor Attachments	100%
Order motor (with sensor)	100%
Add motor to final prototype (With b...	100%
Manufacture new cleaner bar	100%
Install new cleaner bar/belts/	100%
Integrate with Fracsun electrical syst...	100%
Final Testing/Deliverables	**100%**
Write Testing Procedures	100%
Write Operator's Manual	100%
Take Pictures for Operator Manual	100%
Test Encoder Feedback	100%
Test timing of cleaner once per day	100%
Speed and Torque Test	100%
Test Cleaner Life	100%
Test Results Review	100%
Final Report	**100%**
Revise Manufacturing Plan	100%
Write Final Design Review Draft	100%
Revise CDR chapters for FDR	100%
Revise Appendices for Final Prototype	100%
Write Design Verification Chapter	100%
Revise Final Design Chapter	100%
Write Conclusion	100%
Create CAD package	100%
Create Expo Poster	100%
Project Expo	100%



Appendix R: Python Code for Motor Operation

Motor Class

```
## @file motor.py
# this source file contains a motor driver class which initializes and allows
# variable duty cycle
## This class implements a motor driver for the ME405 board.  It does this
# by initializing certain pins and taking user input to control both
# direction and speed.
class MotorDriver:
    ## Creates a motor driver by initializing GPIO pins and turning the motor
    # off for safety.
    def __init__ (self,MotorPort):
        import pyb
        if MotorPort == 1:
            pinA10 = pyb.Pin (pyb.Pin.board.PA10, pyb.Pin.OUT_PP)
            pinA10.high ()
            tim3 = pyb.Timer (3, freq=20000)
            pinB4 = pyb.Pin (pyb.Pin.board.PB4, pyb.Pin.OUT_PP)
            ## ch1 provides power in the clockwise direction
            self.ch1 = tim3.channel (1, pyb.Timer.PWM, pin=pinB4)
            pinB5 = pyb.Pin (pyb.Pin.board.PB5, pyb.Pin.OUT_PP)
            ## ch2 provides power in the counter-clockwise direction
            self.ch2 = tim3.channel (2, pyb.Timer.PWM, pin=pinB5)
        elif MotorPort == 2:
            pinC1 = pyb.Pin (pyb.Pin.board.PC1, pyb.Pin.OUT_PP)
            pinC1.high ()
            tim5 = pyb.Timer (5, freq=20000)
            pinA0 = pyb.Pin (pyb.Pin.board.PA0, pyb.Pin.OUT_PP)
            ## ch1 provides power in the clockwise direction
            self.ch1 = tim5.channel (1, pyb.Timer.PWM, pin=pinA0)
            pinA1 = pyb.Pin (pyb.Pin.board.PA1, pyb.Pin.OUT_PP)
            ## ch2 provides power in the counter-clockwise direction
            self.ch2 = tim5.channel (2, pyb.Timer.PWM, pin=pinA1)
        else:
            print('Invalid Input, Select Port A or B as a String')

    def set_duty_cycle (self, level):
        ## This if statement accounts for a duty cycle that will spin
```

```
        # the motor counter-clockwise.
        if level <0:
            level = abs(level)
            self.ch2.pulse_width_percent (level)
            self.ch1.pulse_width_percent (0)
        ## This else statement accounts for a duty cycle that will spin
        # the motor clockwise
        else:
            self.ch2.pulse_width_percent (0)
            self.ch1.pulse_width_percent (level)
        ## This prints user feedback for the duty cycle entered.
        #   print ('Setting duty cycle to ' + str (level))
```

Encoder Class

```
## @file encoder.py
## This class measures the position of a motor. It does this by reading an
#  optical encoder. The inputs are pinlabel, chan, and TIM. The pin label is
#  inputted as a string of the characters of the desired pin. Chan is an
#  integer number for the proper channel. TIM is an integer for corresponding
#  timer. The init constructor initializes the encoder, and sets the position
#  of the motor to zero. The read method returns the postion of the motor.
#  The zero method resets the position of the motor. The class will be called
#  twice to properly read the encoder in lab via a test file or in putty
#  directly.
import pyb
class MotorEncoder:
    ## The init constructor intializes the encoder pin selected by using the
    #  inputted string for pinlabel to specify the input signal. Init
    #  selects the iputted timer and sets a prescaler of 0 with a period of
    #  ffff (hex). The inputed channel is configured with the inputted timer and
    #  the intial position  and encoder count are reset.
    def __init__ (self):
        ## tim is the desired timer to use with the encoder.
        self.tim = pyb.Timer (8, prescaler=0, period = 65535)
        ## self.pos is the position of the motor that is read using the read
        #  method. It is the calculated by adding the previous position to
        #  to the current change in position. It is reset using the zero
        #  method.
        self.pos = 0
```

```
        ## self.encoder_old is the previous encoder count used to calculate the
        #  change in position, delta, of the motor in the read method.
        self.encoder_old = 0
        ## pinch is the configured input pin corresponding to the inputted pin
        #  label. It is used to configure the proper channel.
        pinch1 = pyb.Pin('PC6',pyb.Pin.IN)
        pinch2 = pyb.Pin('PC7',pyb.Pin.IN)
        ## self.tim is the configured timer that is assigned to the inputted
        #  channel. It has a period of 65535, and a prescaler equal to zero.
        self.tim = pyb.Timer (TIM, prescaler=0, period = 65535)
        ## ch is an object configured in encoder moded and is triggers the
        #  counter when either Channel 1 or Channel 2 changes. It uses the
        #  inputted timer, encoder pin, and channel number for setup.
        self.ch1 = self.tim.channel(1,pyb.Timer.ENC_A,pin=pinch1)
        self.ch2 = self.tim.channel(2,pyb.Timer.ENC_B,pin=pinch2)
    ## The read method returns the current encoder reading by subtracting off
    #  the previous encoder reading. It checks for overflow in the positive
    #  and negative directions by comparing the change in counnts to half of
    #  the period and adjusts accordingly. It sets the next encoder reading,
    #  and returns the new position.
    def read(self):
        ## encoder_new is current encoder count kept track of by the timer.
        #  it it used to calculate the change of position of the motor, delta,
        #  which is the difference in encoder counts which is then added to the
        #  previous position to get an accurate position of the motor.
        encoder_new = self.tim.counter()
        ## delta is the difference in encoder counts added to the previous
        #  position of the motor to gain an updated postion which is then
        #  returned.
        delta = encoder_new - self.encoder_old
        if delta > (65536/2):
            delta = delta-65536
        elif delta < (-65536/2):
            delta = delta + 65536
        else:
            delta = delta
        self.pos = self.pos + delta
        self.encoder_old = encoder_new
```

```
        return self.pos
    ## The zero method resets the position and timer back to zero.
    def zero(self)
        self.pos = 0
        self.encoder_old = 0
    self.tim.counter(0)
```

Main File

```
## @main
# This is the main file that utilizes the motor driver, and encoder to run the cleaning cycle on the
#ARES device
import encoder
import motor
import utime
## Setting up motor and encoder
A = motor.Motor(1)
B = encoder.Encoder()
## Defining cycle parameters (Passes, Number of days, Pulse-Width Modulation, and time
#between cycles)
Passes = 3
Cycles = 398
PWM = 75
Pause = 60 ## Time in seconds
## Defining constants used in loop (J is used to switch direction of the cleaner)
C = 0
i = 0
t = 0
j = 1
## While loop reading position of cleaner, cycle number, and pass number switching directions
#each day
while t < Cycles:
  A.mset(0)
```

```
  utime.sleep(Pause)
  j = j*-1
  i = 0
  while i<Passes:
     while abs(C) < 3932:
        A.mset(j*PWM)
        C = B.read()
  ## Feedback could easily be placed here for pass number
   print('Pass')
   B.zero()
     C = 0
     i = i+1
  t = t + 1
  ## Feedback could easily be placed here for cycle number
  print('Cycle')
A.mset(0)
## Feedback could be placed here for when maintenance is required.
print('Done')
```