6-8-2016

Project SPACE: Solar Panel Automated Cleaning Environment

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I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

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ENTITLED

Project SPACE: Solar Panel Automated Cleaning Environment

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Robert A. Marks — 6/7/16

Thesis Advisor — date

Drazen Fabris — June 8th, 2016

Department Chair — date

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By

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SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

Santa Clara, California

2016

SPACE:
Solar Panel Automated Cleaning Environment

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2016

Abstract

The goal of Project SPACE is to create an automated solar panel cleaner that will address the adverse impact of soiling on commercial photovoltaic cells. Specifically, we hoped to create a device that increases the maximum power output of a soiled panel by 10% (recovering the amount of power lost) while still costing under $500 and operating for up to 7.0 years. A successful design should operate without the use of water. This will help solar panel arrays achieve a production output closer to their maximum potential and save companies on costs associated energy generation.

The current apparatus utilizes a brush cleaning system that cleans on set cleaning cycles. The device uses the combination of a gear train (with 48 pitch Delrin gears) and a 12V DC motor to spin both a 5.00 foot long, 0.25 inch diameter vacuum brush shaft and drive two sets of two wheels. The power source for the drive train is a 12V deep cycle lead-acid battery.

Our light weight design eliminates water usage during cleaning and reduces the potential dangers stemming from manual labor. Our design's retail price was estimated to be around $700 with a payback period of less than 3.5 years.

To date, we have created a device that improves the efficiency of soiled solar panels by 3.5% after two runs over the solar panel. We hope that our final design will continue to expand the growth of solar energy globally.

Acknowledgements

We would like to extend a special thanks to our thesis advisor, Dr. Robert Marks, for providing great insight especially in the front end of the concept development phase. We would also like to thank Don MacCubbin for his help in the Santa Clara University Machine Shop and Dr. Tim Healy for allowing us to use the equipment within the Latimer Lab.

Financial support for this program has been provided by the Silicon Valley Student Venture Branch of ASME and Santa Clara University's Undergraduate Funding; any opinions or determinations expressed in this report are those of the stated authors above and do not necessarily reflect the views of ASME or Santa Clara University.

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Chapter 1: Introduction

1.1 Background and Motivation

Over the past ten years, the United States has seen a large increase in the reliance on solar power as a source of energy. The United States alone consumes approximately 4,146 terawatts hours per year of electrical energy. Less than 1% of this energy is from solar sources; however, solar energy represents 30% of all new energy generation capacity created every year. California was not only a leading producer of solar power over that span, but was responsible for almost 50% of the total solar power generated in the United States according to the Department of Energy [1].

Because of the increasing demand for solar energy, the efficiency of solar panels is more important than ever. However, solar panels are very inefficient; typical peak efficiency for converting solar energy to useable energy is 11% to 15% [1]. Soiling of PV panels drops the panel efficiency even farther. This accumulation of dirt on the panels is a well-documented effect that can cause a loss of efficiency as high as 27% annually [2].

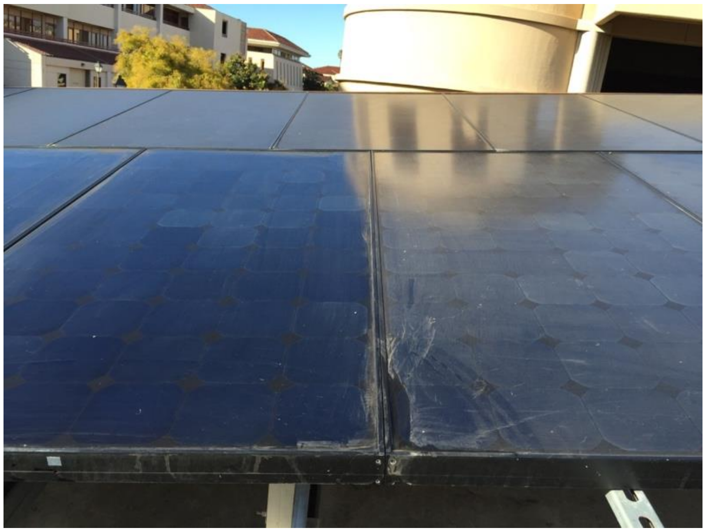

Figure 1: Cleaned panel (left) vs. Soiled panel (right) (Team Photo)

Project SPACE is an automated solar panel cleaner that aims to reduce the efficiency losses of existing solar panel arrays. The system cleans the surface of each panel to increase the energy generation. Once implemented on commercial solar panel arrays, the system aims to improve each panels' energy production by an average of 10 percent. The system is designed to be implemented on large commercial arrays, but the design is scalable to all manners of solar installations. Besides reducing maintenance costs and improving power production, this system will reduce the need for fossil fuels and reduce the nation's impact on global warming, as well as, eliminate the potential dangers for human cleaners.

1.2 Review of the Literature

The information on the effects of soiling on solar panels comes from research funded by both universities and solar energy-oriented associations. The studies that were examined all analyzed different aspects of soiling. One study, sponsored by the PowerLight Corporation in Berkeley California, found a daily loss of 0.2% in power output. The report also noted a 7.5% to 12% efficiency increase due to rain [2].

Another study, performed by Boston University's Department of Electrical and Computer Engineering, observed the loss of efficiency from soiling in Lovington, New Mexico. The area had an observed 24% drop in efficiency over the course of a month. The study also found that while rain is the primary cleaning agent for panels, it is not sufficient [3].

The Boston University Study also reported the costs and benefits of three current methods of cleaning solar panels. These methods include natural cleaning through rain and snowfall, manual cleaning, and cleaning by an electrodynamic system (EDS). In general, it was concluded that in order to maximize the cleaning effect of rain, the panels needed to have a glass shield and be oriented in the near vertical position. Manual cleaning by water and detergent was effective; however, it required costs set aside for labor (45.7% of the total cost) and fuel (20.5% of the total cost). An emerging technology, called an EDS, consists of interdigitated electrodes (made of indium oxide) in transparent dielectric film. The cleaning process is orchestrated by low power, three phase pulsed voltages (from 5 to 20 Hz). This process led to a reflectivity restoration of 90% after only a few minutes.

The University of Sonora analyzed the effect of naturally occurring dust and residue on the energy generation of solar panels[4]. A standard 'dirt' layer was chosen and was tested on three types of photovoltaic cells, monocrystalline, polycrystalline, and amorphous. The maximum reduction in electric production was 6% for monocrystalline and polycrystalline and 12% for amorphous.

An IEEE study conducted by P. Burton and B. King investigated the effects of different types of dirt on solar panel efficiency [5]. Different types and colors of dirt were tested with the emphasis on targeting dirt compositions that are found in the southwest of the United States. The study found that yellow colored dirt scattered light back into the solar panel and was less detrimental than the other dirt tested. The other three samples, all shades of red, did not perform as well[3].

A research group at the University of Colorado studied the effect of dust on the transmission of light through glass panels. The glass panels were similar to those used on PV panels so that the study could help quantify the efficiency loss of solar panels due to soiling. The results of the study further confirmed the need of a cleaning solution for solar panels. The researchers found a 6% loss in each gram per meter squared of dust added. The effect of light transmission on the efficiency of PV panels was not included in the study--causing a hindrance in the helpfulness of the study.

1.3 Statement of Purpose

The research gathered on soiling shows that solar panels need to be fully cleaned in order to collect the maximum energy possible. To address this need for a cleaning mechanism, our team has developed an automated cleaning system for solar panels. Our device will boost the efficiency by increasing the energy output of solar panels in a quick and cost-effective manner. The automation of the system will also reduce the risk of an operator injuring himself in a high-voltage environment.

A successful device will clean multiple solar panels in an array and increase their efficiency by at least the same amount that rainfall can. We aim to provide a non-wasteful approach to cleaning commercial sized solar panel systems by using minimal amounts of water and power while requiring little to no maintenance. This system will clean a single row of panels periodically. We estimate the fabrication costs of the final prototype to be approximately $500.

Chapter 2: Systems Level Overview

2.1 Customer Needs, System Level Requirements

Through our research, we identified three separate potential markets for this solar panel cleaning system. The first market consists of residential homeowners who have a small numbers of solar panels. The second group consists of large commercial organizations that operate large solar arrays in order to subsidize their energy output and improve their carbon footprint rating. The last significant market is multiple acre solar farms which consist of massive solar panel arrays (see Figure 2).

Figure 2: A small solar panel farm with hundreds of panels[5]

Each market offers different advantages and drawbacks. The main criterion for our potential market was ratio of the system's unit cost relative to the number of panels each system would be able to clean. Although the residential market has a large number of potential installations, each homeowner only owns a small number of panels. A small number of solar panels generate only a relatively small amount of electricity, so any potential cleaning system would need to be extremely low-cost. For this reason, we did not select this market because we believed we could not meet this goal within a reasonable number of iterations. The solar farm market had a larger scale of solar panels, thereby increasing the profit margins for a potential cleaning unit installation. Still, solar farms are less willing to collaborate with student design teams and are located prohibitively far away. The commercial market is the target with the most opportunity. Since Santa Clara University has an ideal example of a commercial solar installation, we were able to conduct testing at a reasonable price without spending any funding for traveling and creating a full prototype test system. As visible in Figure 3, SCU has several hundred solar panels deployed on the roofs of various facilities.

Figure 3: Commercial size solar arrays installed at SCU[6]

An example of a commercial array is the solar installation on the university's parking garage, as shown in Figure 4. The university parking garage has an array of over 1200 panels on top of it. Each panel array could be used to test the device after completion. These solar panels are installed on a skeletal metal structure which limits accessibility for human maintenance workers.

Figure 4: Solar Panels above SCU parking garage (Team Photo)

We would like to have a faster, more consistent clean compared to manual labor, and remove the safety concerns involved in cleaning solar panels in dangerous places. We wish to have the device clean an entire row of solar panels, increase the efficiency of a solar panel after cleaning, and present a competitive price for the number of panels cleaned. The system must also match the lifespan of a solar panel, approximately 30 years. And in keeping with the state of California's drought, we seek to use minimal amounts of water in the cleaning process.

2.2 Market Research

2.2.1 Customer Description

Primary Customer:

Our primary customers for this product are companies that operate large commercial solar arrays. These facilities have large numbers of panels to generate significant amounts of solar power. The companies running these arrays are highly motivated to keep their solar panels running at maximum efficiency. These companies have both the resources and incentives to implement our product. A top desire of these companies is to minimize the labor and fuel costs associated with the current methods of cleaning.

Secondary Customer:

The product design is scalable to use on residential solar panel installations. This further increases the potential market for this product. Residential owners wish that the design is pleasing to the eye and eliminates the risks of injury associated with the homeowner cleaning their panels.

Tertiary Customer:

Tertiary customer requirements call for making the product as ready as possible for mass manufacturing. Doing this requires making the product as aesthetic as possible and as easy to mount as possible. By doing so, the product is ready for mass production and widespread use.

Table 1: Breakdown of the Primary, Secondary and Tertiary Customer Needs

Primary Customer Needs	
**Main focus involves improving efficiency, power usage, and functionality.*	- Periodic cleaning of solar panels that maintains peak efficiency - Minimal power requirements - Automated operation - Low maintenance - Less than $600 system cost
Secondary Customer Needs	
**Main focus involves improving sustainability and cost-effectiveness.*	- No water usage - No maintenance - Less than $400 system cost - Smart Energy Tracker
Tertiary Customer Needs	
** Main focus involves improving ease of production and marketability.*	- Easily manufactured - Works in a variety of weather conditions - Aesthetically pleasing - Smooth installation - Less than $200 cost

2.2.2 Competition

Currently there exist a number of solutions for eliminating the effect of soiling on solar panels. The choices for automated cleaning solutions are numerous but impractical for most applications. The current automated systems, such as, the Kolchar X2 created by Sol-Bright and the Ecoppia E4, are large and expensive, as shown in figure 5. These systems are typically only feasible on massive solar farms where the large number of panels cleaned offsets their large costs. When it comes to cleaning solar panels on a smaller scale, other less efficient systems are commonly used.

Figure 5: Ecoppia E4 cleaning system[7] (Reproduced without permission)

The most common method is manual cleaning; this requires crews of workers to hand clean panels. The automated cleaning systems that are available for smaller scaled solar panel systems are systems, such as the sprinkler system manufactured by Heliotex, which can be inefficient and wasteful as shown in Figure 6.

Figure 6: Heliotex sprinkler system[8] (Reproduced without permission)

2.3 Design System Sketch

The initial design of the device was a rolling brush that traverses along an array of solar panels, as shown in Figure 7. The device would attach to the array using rollers that grip the frame of the panels and use them as rails to roll along the panel. The system cleans the panel using a spinning brush to clear any dust or debris. Ideally, the device would not use water and would not need to be connected to any source of water.

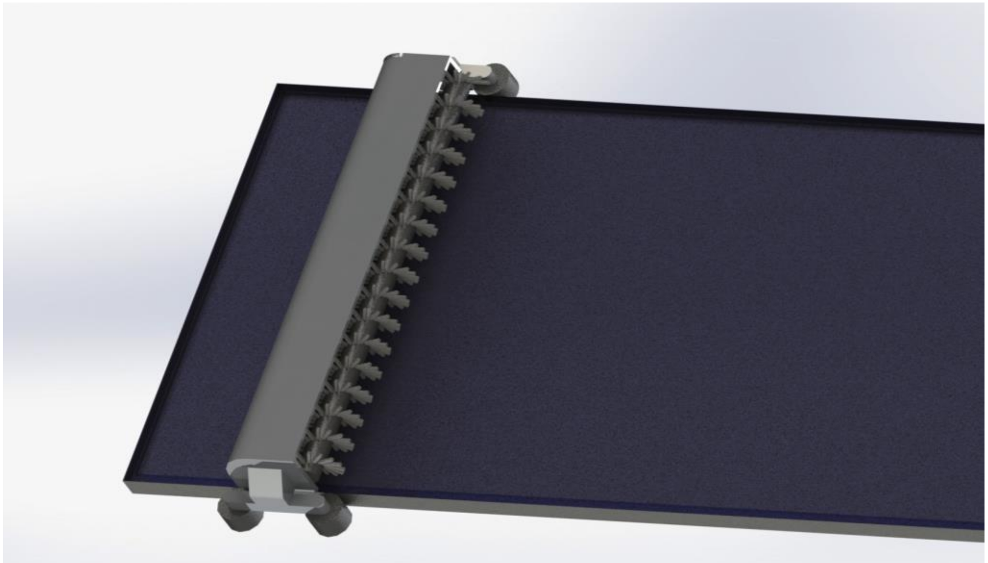
Figure 7: SPACE system design concept image

Our system would be implemented on commercial sized solar arrays, such as those found on school campuses and companies. The user of the device would install the system onto an array of panels and leave it there. The device will run on its own, without the need for human supervision or maintenance.

2.4 Functional Analysis

For our initial design we devised a system that moves along the length of an array of panels, cleaning the entire array. This design was selected primarily for its simplicity. Its component subsystems have been observed to function well in other applications. The device moves across a row of panels and cleans using a spinning array of brushes. The system will move using soft rubber wheels driven by an electric motor. The rotating brush system will be mounted on a rotating axle which is also spun by the main drive motor. Using a single motor is advantageous for both cost and simplicity. However, the drive motor will need to deliver high torque in order to function effectively. To reduce the stress on both the system and the panel surface, a series of lighter cleaning cycles will be used rather than a single more intense cleaning. This device will run across a row of panels and back to its original position.

The device will be powered by an internal battery. At the end of each cleaning cycle, the system will return to a docking station at the end of the panel where it will recharge the battery. The dock system will act as an extended platform next to the panels to allow the system to move off the panel surface so it does not obstruct sunlight from any part of the panel. The battery will have a shorter operational life than the majority of the other components. Battery replacement every few years will need to be part of the product's maintenance requirements.

The final design is a refinement of the initial design concept. The system uses a motorized brush to clean the surface of the panel array. The system is moved along the panel by two sets of motorized wheels, with one set located at either end of the device. The entire system is driven by a compact high-torque DC motor. The system uses a pair of custom gearboxes to transfer the mechanical energy to wheels and cleaning system.

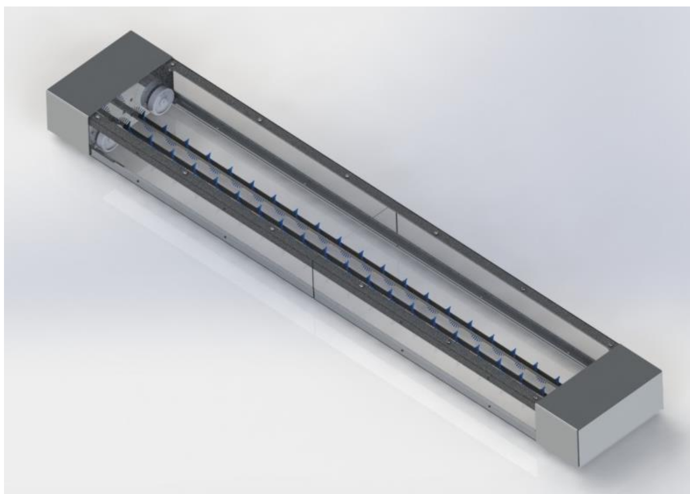

Figure 8: Final Design (pre-fabrication CAD image)

The device draws power from an internal rechargeable battery pack. Currently there is no automated solution for charging the system; however the charging system—as well as the docking station concept—have been identified as future development goals.

An external protective casing has been fitted to the system to improve the lifespan of the device and its subsystem. Constructed of transparent acrylic, the casing protects the system from rain and debris while allowing sunlight to pass through, minimizing any impact on solar energy production. The design of the casing was redesigned during production to enable easier fabrication. The new design is reflected in Figure 9.

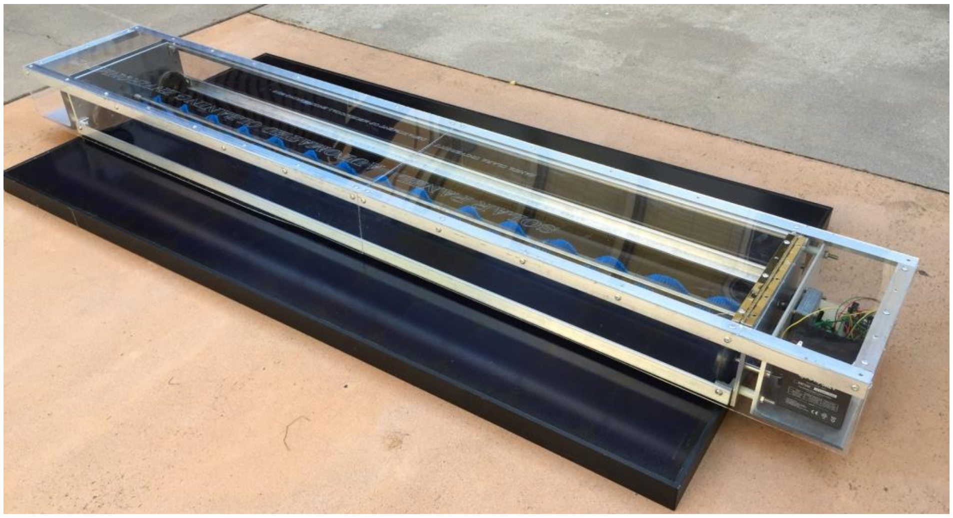

Figure 9: Final Prototype

The entire system is controlled by an onboard microcontroller which is paired with a dedicated motor controller. This control system is able to fully automate the system's cleaning process with the ability to schedule cleanings at any given time.

2.5 Benchmarking Results

The large decrease in efficiency of solar panels from soiling is a well-known phenomenon, and cleaning solar panels is not a new concept. There is a competitive market for solutions that keep solar panels operating at peak efficiency, including automated devices that clean numerous solar panels.

The most common method of cleaning solar panels is manual labor. Manual labor involves the owner of the solar panels, or an outside agency, cleaning their panels using similar methods that are used to clean glass. While this is an effective way to restore solar panels to their optimum efficiency, there are several drawbacks with the use of manual labor.

One major problem is the safety of the human laborers. Solar panels are commonly placed in hard to reach places without safe access for cleaners to work effectively. Another problem is the frequency of cleaning. Since hiring cleaners to continuously maintain the panels can be costly and time consuming, owners of solar systems will typically have their panels cleaned only once or twice a year (Jeffrey Charles, SCU Facilities Director, Personal Communication, Oct. 30, 2015). Since the amount of soiling on the panel increases daily, the panels should be cleaned every few days to maintain peak efficiency. If cleaning were done less frequently less power would be used by the cleaning, but power is lost since the solar panels are not working at full efficiency. The ideal cleaning frequency is difficult to approximate as soiling rates are dependent on local environmental conditions. A baseline cleaning period of two weeks should be sufficient for most solar installations.

Another current market solution for keeping solar panels clean is automated cleaning devices. An example of an existing automated cleaning device is the Kolchar X2 created by Sol-Bright. The design cleans solar panels by moving horizontally across an array of solar panels, cleaning the panels as it moves. Another example is the E4 Robot created by Ecoppia. The E4 is designed to clean solar arrays in desert conditions. It moves vertically across solar panels, wiping dust away as it travels.

The automatic panel cleaners that exist have issues that make them unappealing to certain customers. A major deterrent for many customers are the systems large unit cost. These machines are designed to operate on large solar farms that exist in remote locations. The prices of the designs are high because they can be offset by the vast number of panels they clean. However, a commercial or campus sized solar array does not have as many panels as a solar farm and cannot offset the high cost of these machines.

2.6 System Level Review

2.6.1 Key System Level Issues and Constraints

As a full system, the design needs to be able to last and function for the life of a solar panel. To make the system more cost efficient the system has to work for several years to make up the cost of the device. In order for the system to last long, everything on the device has to be weatherproof as well as not degrade in battery life. The system has to use a long life battery and be sturdy enough not to move in case of storms.

Another system level issue is cleaning efficiency. The device has to be able to consistently clean an array of solar panels without damaging the panels at all. No cleaning device can be used that could damage the panel or pick up particles that could damage the panel. Testing has to be done to ensure rocks or other materials that could be on the solar panels do not scratch the panel during the cleaning process.

The main design requirements for SPACE were cleaning effectiveness, automatic charging, and automatic operation. Each requirement was broken down into the necessary subsystems and design features. The general design layout is shown in Figure 10.

2.6.2 Layout of System-Level Design

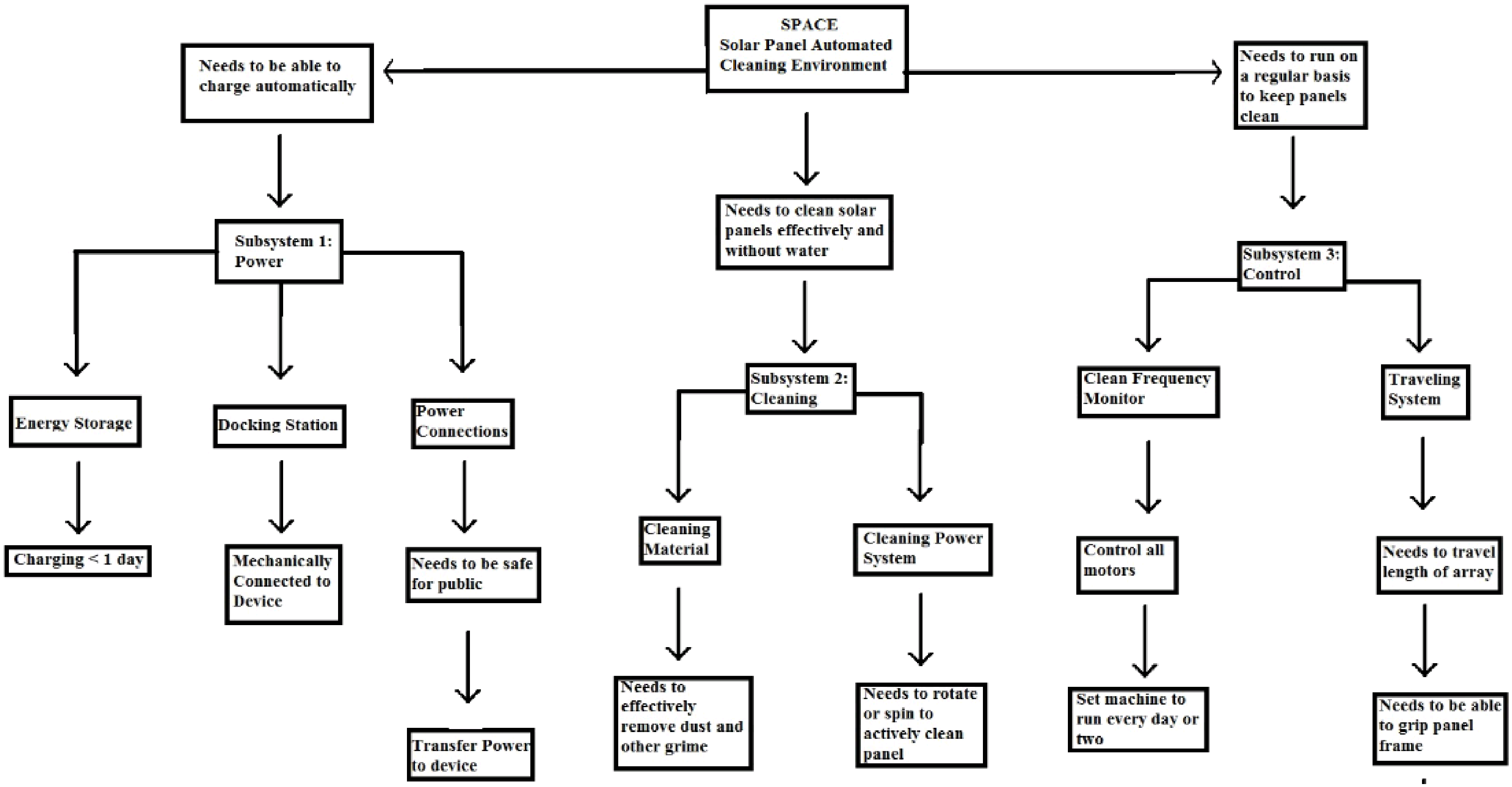

Figure 10: Layout of the system level design with main subsystems

2.7 Team and Project Management

2.7.1 Project Challenges

The main challenge faced by this project is ensuring that the system cleans solar panels effectively without water. The system must also deal with stringent power and weight constraints in order to function on top of the solar panels. A waterless brush design was chosen for simplicity and light weight. In order to compensate for the lack of water, the system uses soft spinning brushes with frequent cleanings to reduce the cleaning needed per pass.

Another major design challenge is ensuring that the power needed to clean is net positive in terms of energy generated by the panel per cleaning cycle. The simplified cleaning mechanism needs to use a single motor at a relatively low speed to reduce power consumption. The system chassis is constructed of aluminum to reduce the overall weight of the device.

2.7.2 Budget

The budget for the project was set at approximately $1300 but we have received a total of $2100 in funding. This budget was formulated around an initial prototype cost of $300 with the main prototype costing $600. The remaining funds were used for various development, fabrication, and testing costs. A more detailed breakdown of the current budget can be found in Appendix E.

2.7.3 Timeline

The development schedule for this project is based on the outline provided by the Santa Clara University's Department of Mechanical Engineering. Initial research and feasibility testing began in September 2015 with initial prototyping beginning in early January 2016. Full scale fabrication of the main prototype components was underway by the start of February. The following month our team began the system assembly process. The final assembly was delayed slightly due to design revisions and small fabrication issues. The prototype was completed by mid-April, slightly behind schedule. The testing process then proceeded through the remainder of April and May. A more detailed timeline is available in Appendix D-1.

2.7.4 Design Process

Our main considerations for this design were maximizing effectiveness and minimizing costs. With this in mind, we prioritized the design of the cleaning mechanism with the mounting and control systems being secondary. After testing a variety of cleaning methods on the panels of the 2009 SCU Solar House, a waterless brush design was found to clean to a sufficient level for a relatively low cost. To get the desired brush movement, the brush will be mounted on a rotating shaft that spans the panel. The chassis will move the shaft along the row of panels to clean the entire array. The design will be fairly simple and should be relatively easy to fabricate. The simplicity of the design will also reduce the maintenance required.

The mounting system consists of an array of wheels that fits around the edge of the solar panels. The wheels contact the top and sides of the panels. This allows the design to roll along the panels while preventing the system from falling off the panel. This wheel arrangement is a simple design and provides sufficient structural security for the design.

The control systems required by this device are minimal. The device will periodically move along the panel before returning. A simple microcontroller is sufficient to implement the required logic. The device will need to recognize the correct time to clean and then run the cleaning system. Additional sensors will be implemented in future iterations to safely shut down the system if it detects a person or object in its path.

2.7.5 Risk Mitigation

The solar cleaning system will be deployed on roofs and high structures. Despite the absence of people near the machine, there are risks and safety concerns to address. The main concern is the potential danger presented to people during operation. The device will be rather large and moving automatically, so it is possible that a person could be in the path of the device. This risk can be addressed by including a proximity sensor to shut down the system in the event an object is in the path of the system.

The power systems are a major safety concern. With the electric current in the system coupled with the panel's exposure to weather and rain, the system must be rugged. A short in the electrical system could be catastrophic, resulting in serious damage to the solar panels. To avoid this, all wiring will be inspected by electrical engineering staff to ensure it is safely installed.

2.7.6 Team Management

During the conceptual development phase of the project, the team collaborated in the brainstorming process. This presented a few issues when there were disagreements regarding which design ideas to proceed with. The benefits and drawbacks for each idea were discussed before the final concept was selected. Overall, this method allowed for the most variety in terms of ideas and the most feedback on each concept.

For the design of the system, individual team members were selected to design each particular subsystem. This allowed the design phase of the project to proceed quickly with team members working independently. The team then reconvened to ensure each design is compatible with the others before proceeding to fabrication.

Chapter 3: Subsystems Overview

3.1 Cleaning Subsystem

3.1.1 Cleaning Subsystem Role

The cleaning subsystem consists of the elements that will remove the dust and debris from the solar panel. The requirements for the cleaning system are that it cleans an array of solar panels efficiently and effectively while using little to no water. The system needs to be able to run two times per week to keep the solar system operating at peak efficiency.

3.1.2 Cleaning Subsystem Options

The major decision to be made for the design of the cleaning subsystem was the selection of the cleaning method. The design that was finally chosen was a set of brushes built into a spinning axle that will brush away any dust or debris on the panel's surface. The criteria for choosing this method were the effectiveness of cleaning, the cost of manufacturing (which includes the cost of the material itself) and the reliability of the material over the device's entire lifespan.

The options that were considered for the cleaning subsystem were both a variety of materials as well as methods of moving the cleaning material across the panels. The materials for cleaning that were considered were the bristles on a typical brush, the microfiber clothes found in car washes, just water or other cleaning solution, a sponge, and a mop head. The bristles of a brush were chosen because of their affordability, reliability, and ease of manufacturing. The bristles may be less effective than other options, but multiple passes will overcome the difference in efficiency. A close competitor for the cleaning material was the microfiber cloth. While the cloth may provide a more effective clean, the cloth's fiber will collect dirt and lose effectiveness, decreasing the overall lifespan of the device.

An additional cleaning method that was considered was the use of compressed air. This method had the advantage of cleaning efficiently with no physical damage done to panels. However the necessary power and hardware requirements of the air pump and compression system would have likely made the system too heavy and costly to manufacture.

Figure 11: The Selected Brush Design Installed on Prototype

The options for methods of cleaning were mostly different options of moving the cleaning material. The criteria for the cleaning method were the same as the criteria for the cleaning material. The options considered were an axle that lies across the panel and spins, a disk that moves side to side like a buffing machine, a lock that applies constant pressure across the panel and drags the cleaning material across it similar to a sweeping broom, and a drip system that leaks cleaning solution down the sides of the panel. A spinning axle that lies across the panel was chosen because of its proven effectiveness in operations like a car wash.

The options for each method were evaluated using a selection matrix. The selection matrix for the cleaning subsystem can be seen in Appendix C-2.

3.1.3 Cleaning Subsystem Design Description

The final cleaning subsystem consisted of brushes that were spun at a faster RPM than the wheels of the system to provide a sweeping motion to remove dirt and dust from the solar panel surfaces. The brushes provided a method of cleaning without harming the glass surface of the panel, as well as eliminating the need for water.

Due to the length of the system, a brush that could span the length of a solar panel had to be manufactured. The brush was manufactured from existing roller brushes that are sold as replacements for vacuum brushes. The vacuum cleaner brushes provided a cleaning option that could be spun to provide a consistent clean across the entire panel. While the diameter of the brush was appropriate for its usage, the brushes had to be modified to enable them to be connected together in order to span the length of the system. The modifications to the brushes included cutting down the ends of the tubes to minimize gaps between the brushes and ensure a more thorough clean as well as drilling holes an inch into each side to enable connecting the tubes together. The tubes were connected together using small sections of shaft that were used as fasteners between each tube section.

Once the entire brush assembly was fastened together, it was connected to the device using the gear plates. Again smaller shafts were used to connect the cleaning brush into the gearbox allowing them to rotate when driven by the system. The brush roller and the connection to the gearboxes can be seen in Figure 12.

Figure 12: Cleaning system/ Gearbox interface

3.1.4 Cleaning Subsystem Detailed Analysis

While designing the system and gathering research on testing, the material used for the cleaning subsystem was analyzed to find the best choice. The different materials were assessed by finding which material provided a more thorough clean. The performance of each material was based on its cleaning capability on the Solar House’s panels, which are measured by Tigo Energy Systems. The materials tested were a broom, using simply water, a combination of water with a sponge, and finally using a mop without water.

The results from the test show that using a combination of water with another cleaning element was the most effective. However, the final design uses a brush system to reduce overall cost.

3.1.5 Cleaning Subsystem Testing

To further validate the gathered research from our literature review, our team analyzed data from the Santa Clara University 2009 Solar House. The house has 48 solar panels that have been operating since the house's installation on campus. Using a program created by Tigo Energy, the solar panels' daily output and solar insolation were recorded.

Our team identified over a 10% increase in energy generation immediately following the cleaning of the solar panels (see Figure 1). It should also be noted that when water was poured on the panel to simulate a rain effect, there was only a slight increase in efficiency compared to that in a full clean. A brush was tested without water to find a cleaning baseline without the use of water. This method worked better than just water, but worse than the full clean. All of the data was compared to control panels that were not cleaned in any way. See Appendix G-1 for the data used in Figure 13.

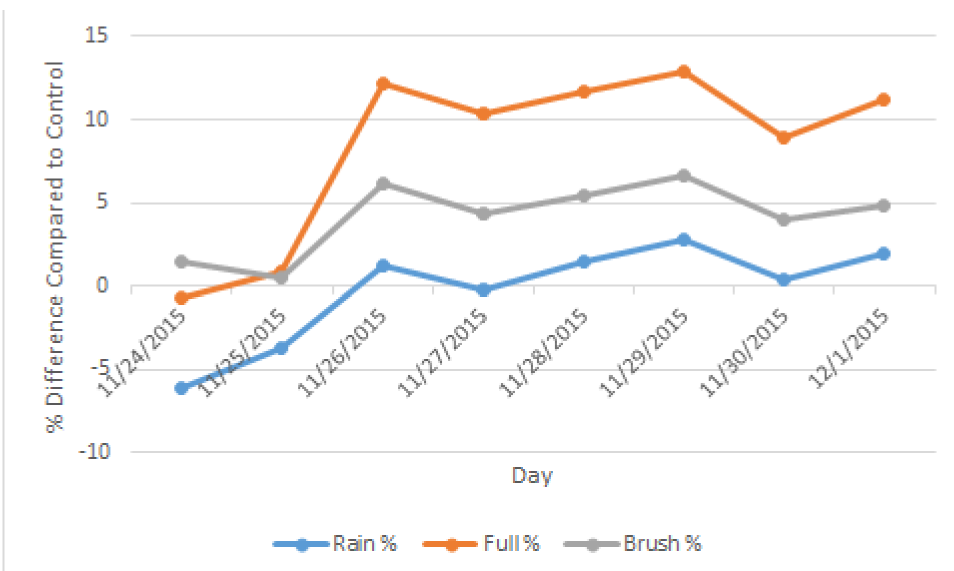

Figure 13: Improvement in Solar Energy Generation after Cleaning (App. G-1)

The results of the small scale testing on the Solar House's panels showed that the combination of using water and another cleaning element provided the best clean and that using just a brush was the second option beating out that of using just water. The data was measured against a control panel that was left untouched. To the team's knowledge, the panels on the Solar House had never been cleaned other than through rain. Data was recorded for the next week following the cleaning. Each material was tested as a percentage increase above that of the control panel. The results show that the combination of water and another cleaning element was around 10% higher, the brush was around 5% higher and the rain was around 2% higher. The dry mop is not reported because no noticeable difference could be found through observation.

3.2 Mechanical Power Subsystem

3.2.1 Mechanical Power Subsystem Role

The primary function of the power subsystem is to move the entire system along the length of a solar array. To achieve the needed range of motion, the subsystem must provide sufficient mechanical energy to the combined mass of the system and over frictional forces associated with the solar panel. Additionally, the power system must provide the mechanical energy to drive the cleaning subsystem. This subsystem should require minimal maintenance and no direct user interface.

3.2.2 Mechanical Power Subsystem Options

The initial design that was considered for the subsystem was a motor-driven chain to pull the system along the panels. This design was ultimately abandoned due to its high material costs as well as its relatively high complexity to implement.

Another considered design used of a high torque motor to drive a set of wheels mounted on the system. This design would allow the system to move along the panel without the need to additional infrastructure to be attached to the panel.

3.2.3 Mechanical Power Subsystem Design Description

The design that was selected was the motorized wheel design. This design uses a single drive motor to supply mechanical energy to a pair of wheels mounted on the system chassis. These wheels are mounted parallel to the desired direction of travel. The wheels rotate in either direction to move the cleaning system to the desired location on the solar panel. The axle of the drive wheels runs parallel to the axle of the cleaning brush allowing the two to be connected via a gear system.

The gearboxes are connected by the rotating brush as well as a long driveshaft that spans the length between the two gearboxes. The connection of these two systems eliminates the need for a secondary motor solely for the cleaning system in exchange for the implementation of the needed gear system. By using one motor, the system is reduced in complexity as well as cost. The gearbox system and drive shaft can be seen in Figure 14 and Figure 15.

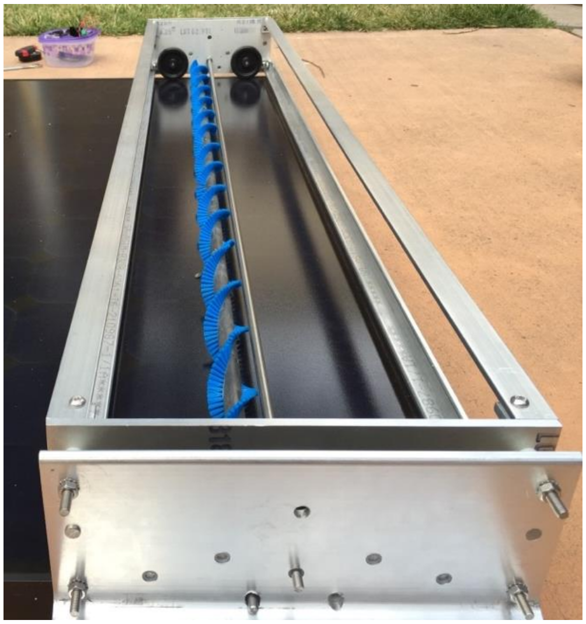

Figure 14: Driveshaft (right of brushes) transfers power across system

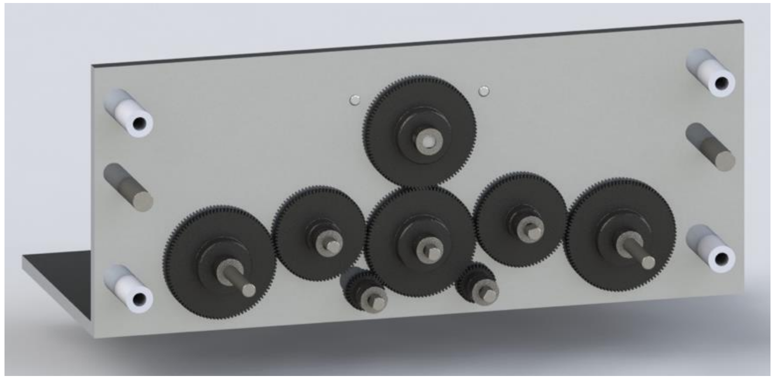

Figure 15: Rendered image of internal gear train

3.2.4 Mechanical Power Subsystem Detailed Analysis: Motor Choice

In order to ensure that the system would be able to move down the length of the panel, the motor chosen to drive the device needed to be able to provide the torque required. Calculations were done using the estimated weight of the system and the estimated driving force needed to push the brushes across the panel. The torque and horsepower were both calculated and used as the main criteria for choosing a motor. Other criteria included power required, the motor needed to be able to drive using a small 12 volt battery, and size, the motor needed to be compact enough that it could fit on the device without weighing the system down.

The calculations found the motor needed to be able to output 38 oz-in of torque and 0.0015 horsepower. The motor was chosen to be a 12 volt compact face mounted DC motor. The motor, shown in Figure 16, is rated to output 160 oz-in at 50 RPM and 0.008 horsepower.

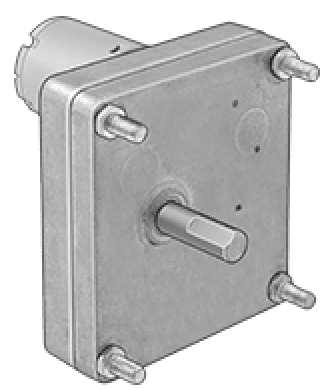

Figure 16: 12 Volt Face Mounted DC Motor

3.2.5 Mechanical Power Subsystem Testing

The Mechanical Power Subsystem was tested by ensuring each section worked individually as well as when interfaced with the other components. After fabrication each gearbox checked for gear tooth alignment and to make sure the gearboxes aligned across the span of the device.

Once the gearboxes were finished, the driving motor was attached to the Chassis Subsystem with the Mechanical Power Subsystem and used to test the system without the Cleaning Subsystem. Once it was determined the motor was able to drive the device along a panel, so the subsystem was combined with the rest of the subsystems.

3.2.5.1 FEA Analysis of the Drive Shaft

Introduction:

Project SPACE uses a drive shaft that spans the entire width of the device. The purpose of the drive shaft is to transfer power from the motor to the wheels. The motor is located on one side of the device where it turns a set of wheels. Another set of wheels needs to be turned by the motor on the other side of the device, the drive shaft transfers the power to drive the second set of wheels. The shaft is a ¼" in diameter and is 61.5" in length. Testing has to be done in order to determine the amount that the shaft will twist due to being powered from only one side. Excessive torsion will result in plastic deformation.

Assumptions:

The torque on the shaft should not exceed 38 oz.-in, which is the calculated torque required to move the device down the width of the solar panel. However, the shaft was simulated assuming the maximum possible driving torque of the motor. This was done to determine whether a device malfunction such as becoming stuck while the motor keeps turning would cause the drive shaft to fail.

The governing equation for the torque applied to the shaft is given in Equation 1. Torque is proportional to the polar moment of Inertia, J_T, and the shear stress, τ, while inversely proportional to the radius of the cross section, r. It is also worthwhile to note the angular displacement of a point on the end of the shaft. The angular displacement is a function of the torque applied, *T*, the length of the rod, *l*, the polar moment of inertia of the cross section, *J*, and the shear modulus, *G*. A modeling of the displacement analysis done in Solidworks can be seen in Figure 17.

$$T = \frac{J_T}{r}\tau \quad \text{(Eq. 1)}$$

$$\varphi = \frac{T\ell}{GJ_T} \quad \text{(Eq. 2)}$$

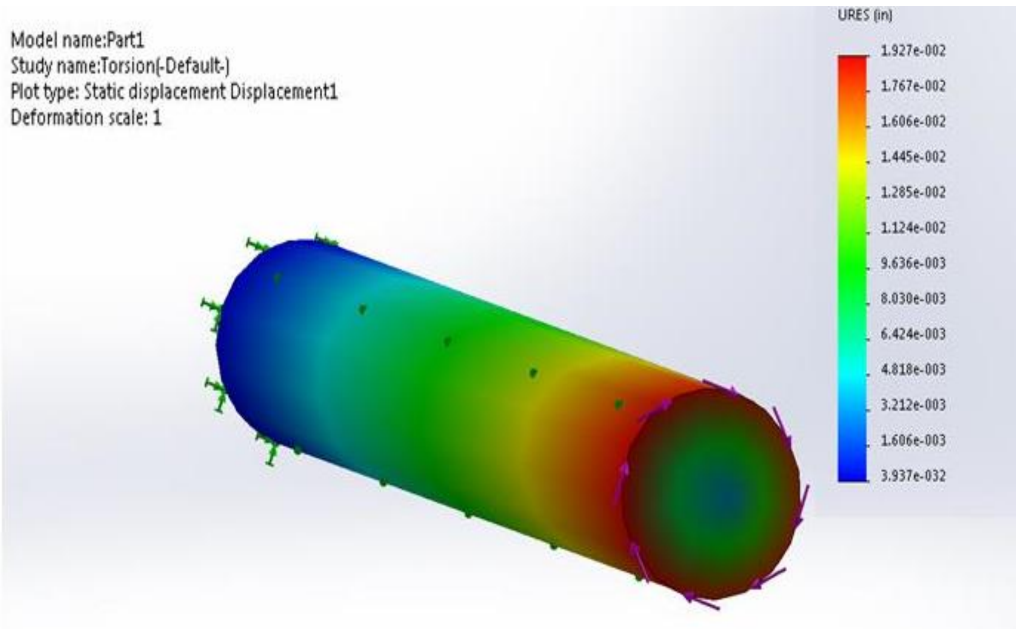

Figure 17: Solidworks FE driveshaft displacement analysis

Conclusion:

The results of the analysis on the drive shaft show a maximum deflection at 4.41 degrees. This deflection will occur at the end farthest away from the motor. The maximum deflection before the beam plastically deforms was calculated to be roughly 62 degrees. The calculation can be found in Appendix 1. Our analysis shows that the drive shaft can handle the torque of the motor.

3.2.5.2 FEA Analysis of the Spur Gears

Introduction:

This FE analysis was undertaken to evaluate the strength of the selected gears. The proposed nylon gears will be used to transmit power from the drive motor and so must endure stress. This analysis allows a simulation of the gears behavior under the torque they will experience. The data gathered from these simulations will allow the design team to make the final decision with regard to the gear material.

Assumptions:

This analysis was performed on a single gear from a larger gear train. This gear is the smallest in the gear train and therefore will experience the greatest stresses. A complete analysis of every gear is recommended to ensure adequate part performance.

In general, the gear teeth act very similarly to cantilever beams that are subjected to tangential and radial loads. As a result of these loads, gear teeth can fail due to either bending or contact stresses. The common modes of failure included tooth breakage, pitting, and scoring. For a diagram of the forces that act upon a gear tooth see below. The fundamental equation for the bending stress, s_a, is given in Equation 3, where W_t is the tangential load, P_d is the normal diametric pitch, J is the geometry factor bending strength, Y is the factor of safety and the *K's* are all loading, dynamic, and temperature factors. The fundamental equations (Eq 4. and Eq 5.) for the contact stresses, s_t, are given where F is the net face width, C_p is the elastic coefficient, I is the pitting resistant coefficient, C_H is the hardness coefficient, S_H is the safety factor for pitting and Z_N is the stress cycle for pitting. All of the variables used with similar denotations in Equation 3, such as the tangential load W_t, are the same. Lastly, a Finite Element Analysis was conducted in Solidworks to show the distribution of stress across the gears (see Figure 19).

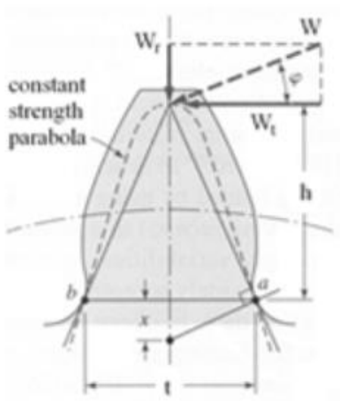

Figure 18: A Free Body Diagram of a Gear Tooth[6]

$$W_t K_o K_v K_s \frac{P_d}{F} \frac{K_m K_B}{J} \leq \frac{s_{at} Y_N}{S_F K_T K_R} \qquad \text{(Eq. 3)}$$

$$s_c = C_p \sqrt{W_t K_o K_v \frac{K_m}{dF} \frac{C_f}{I}} \qquad \text{(Eq.4)}$$

$$s_c \leq \frac{s_{ac}}{S_H} \frac{Z_N}{K_T} \frac{C_H}{K_R} \qquad \text{(Eq.5)}$$

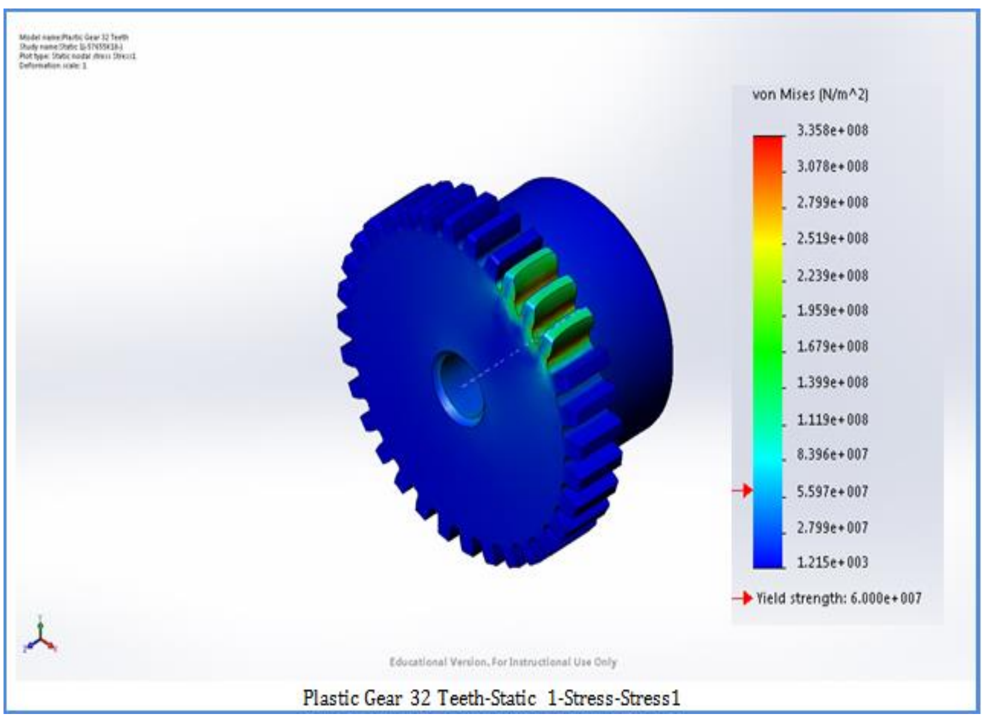

Figure 19: Solidworks FE spur gear stress analysis

Conclusion:

The conducted finite element analysis has shown the selected gears are able to withstand the necessary stresses without excessive deformation. Under a torque of approximately 0.833lbf-in the gear experienced a maximum deformation of 0.004583 in. This deformation reached a maximum along the teeth of the gears.

The nylon material is sufficient to be used in the design of the SPACE system. A follow up analysis to evaluate the lifespan on the gear is suggested.

3.3 Control Subsystem

3.3.1 Control Subsystem Role

The purpose of the control subsystem is to ensure that all of the mechanical pieces move in an efficient way. Most importantly, the control system has to be programmed in such a way that our prototype can clean completely from one side of the solar panel array to the other side consistently. More specifically, the control system is in charge of how quickly this process is done. The time of operation includes the time elapsed starting from acceleration to cruising speed from rest until a deceleration to a stop—as well as—the time between cycles. A microcontroller will have to be implemented in order to adjust how quickly the apparatus moves.

A stretch goal for the future projects is to design a user interface that allows the user to adjust how often the device cleans the panels. This requires more programming, but hopefully can be integrated into the control system that is already being used. Whatever controller is selected, it has to be able to perform both objectives.

3.3.2 Control Subsystem Options

The main concerns with control subsystems are cost of the controller and ability to perform the objectives that we desire. There are many options for us to choose from for programmable controllers with the best options for the project being the Arduino Mega or the Raspberry Pi 2 Model B+.

As can be seen in *Table 2* below, both are comparable in terms of specs and price; however, each is advantageous in different circumstances. The Raspberry Pi is a fully functional computer that is better on a software level; it has more RAM and greater versatility in handling different network connections. While the Arduino works better as purely hardware. It is more physically resilient and will not be damaged if the device is not powered down improperly. Furthermore, the Arduino will not need the same breath of libraries to be installed to begin operation. Lastly, our group is most accustomed to working in C than with Python in a Linux based operating system. Ultimately an Arduino based system was chosen as the microcontroller since the extra computing power seen in a Raspberry Pi at the moment would not be fully utilized.

Table 2: A Comparison of Specifications between OSEPP Uno R3 Plus, Arduino Uno, Arduino Mega and Rasperberry Pi

	OSEPP Uno R3 Plus	Arduino Uno	Arduino Mega AT2560	Raspberry Pi
Price	$26	$30	$55	$35
Size	75.0 mm x 54.0 mm x 15.5mm	76.0 mm x 64.0 mm x 19.0 mm	101.52 mm x 53.3 mm x 19.0 mm	86.0 mm x 54.0 mm x 17.0 mm
Memory	0.001 MB	0.002 MB	0.004 MB	512 MB
Clock Speed	16 MHz	16 MHz	16 MHz	700 MHz
On Board Network	None	None	None	Ethernet
Multitasking	No	No	No	Yes
Input Voltage	6-12 V	7-12 V	7-12 V	5 V
Flash	32 KB	32 KB	256 KB	2-16 GB
USB	One	One	One	Two
Operating System	None	None	None	Linux
Coding Language	Arduino (C)	Arduino (C)	Arduino (C)	Python

Since one of the key project goals was to keep the prototyping cost of the cleaner below $500 cost, the OSEPP Uno R3 Plus, a cheaper microcontroller with similar capabilities to an Arduino, was chosen.

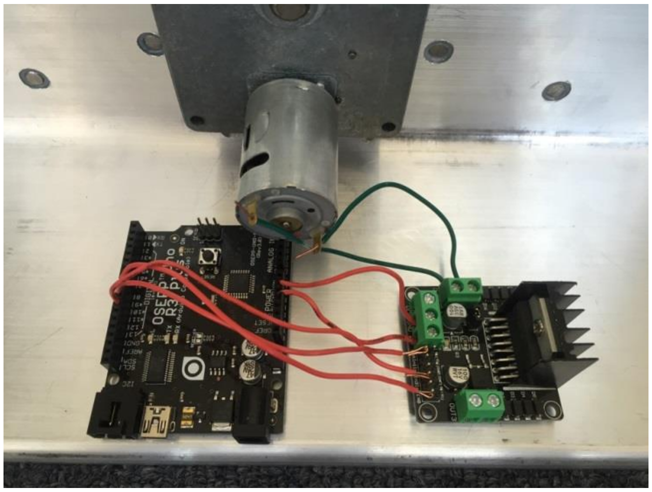

Figure 20: Control system hardware overview

3.3.3 Control Subsystem Design Description

The complete motor control system consists of the DC motor, L298N H-bridge controller, 12V Deep Cycle Lead Acid battery and OSEPP Uno R3 Plus. The DC motor acts as the load, the battery as the power source, the OSEPP as the microcontroller, and the L292N H-bridge as a power converter. A diagram of all the interconnections can be seen below.

On the H-bridge motor controller one row of three terminal pins is used to control one motor. For our project, the EA pin accesses a PWM interface and I1 and I2 will control the DC motor direction. Pins I1, I2, and EA were connected to the digital pins 8, 9, and 11 on the OSEPP Uno.

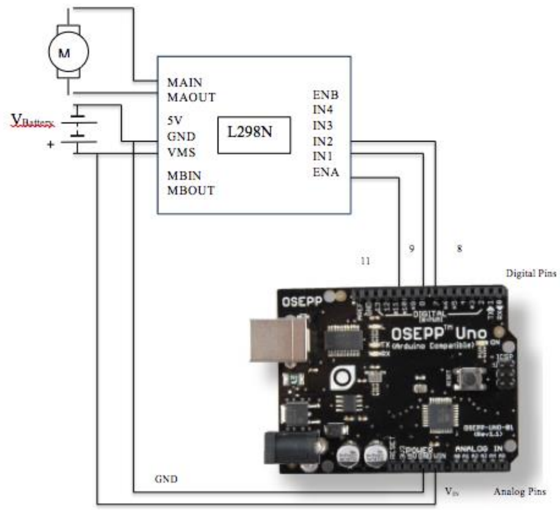

Figure 21: Diagram of the Interconnections Between the Control System Components

3.3.4 Control Subsystem Detailed Analysis

The motor controller or H-bridge is a DC to AC power converter that switches the direction of voltage potential across a load—or in this case the motor. In the diagram below, only two of the four transistors can be on during a cycle. When two diagonal transistors are turned on a voltage potential is generated (v_0 is positive when Q1 and Q2 are activated and negative when Q3 and Q4 are turned on). While no voltage potential across the load is generated when two transistors within the same column or row are both on. The effect of this switching will cause the angular velocity of the motor to change directions.

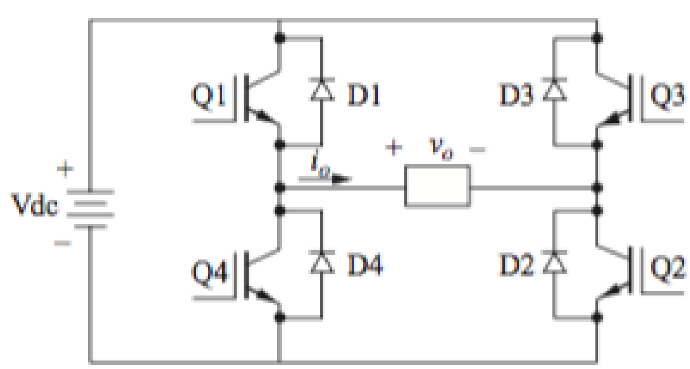

Figure 22: Diagram of a H-Bridge Detailing the Four Different Transistors

An Arduino code was written to activate rotations of the motor for a set length of time and display the direction that the motor was turning (see Appendix for the Code). Within the code, the analogWrite() function was used sets the speed of the input analog value, the digitalWrite() function to write a high or low value to the digital pin, the digitalRead() function to readout the value from a specific digital pin, and delay() to specify the amount of time for the operation of the command.

A stretch goal for the control system is to add a stand-alone PV unit to each cleaner to help the battery recharge. This unit will consist of a small solar panel that will be hooked up to a charge controller (either MPPT or PWM); this charge controller will have separate connections to the motor and the battery. A flowchart and a photograph of this concept implement in our design can been seen in the Figures below.

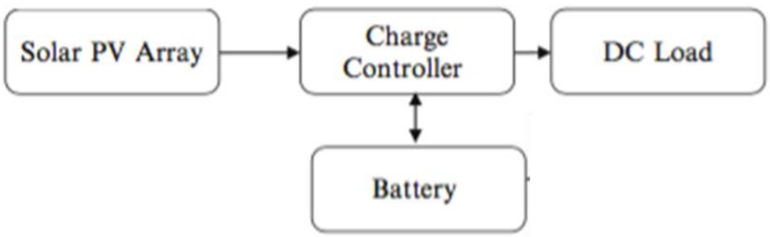

Figure 23: Flowchart of Stand-Alone PV System[7]

Figure 24: Photograph of Small PV Unit Implemented

3.3.5 Control Subsystem Testing

The majority of the testing for the control system testing was done by a combination of visual inspection of the motor and digital readouts and voltage output measurements across the system. Specifically, the visual inspection included looking for whether the current angular speed and direction of the motor rotations matched what was specified in the program. Also, the whole system was monitored to make sure the cleaner reached the ends of the panel in each cycle.

Chapter 4: System Integration

The initial prototype was designed to fit the length of the SunPower's 215 Solar Panel model. The panel was chosen due to its availability to the team for testing purposes. The length was taken into consideration when fabricating the Chassis Subsystem. Once all of the subsystems were completed, the prototype was assembled and prepared for testing.

4.1 Integration

While assembling the prototype, time was taken to secure the Mechanical Subsystem to the Cleaning Subsystem. Due to the stress from the brushes on the Cleaning Subsystem and the small contact area with the gears in the Mechanical Subsystem, the connection between these two subsystems was an area showing higher stress concentrations and the highest possibility for failure.

To fully secure the subsystem's together, the gears used in the Mechanical Subsystem were pinned to the shaft of the Cleaning Subsystem to prevent any possible slipping of the shaft within the gear. Additionally, the remaining gears were pinned to their shafts to prevent the problem from occurring anywhere within the gear train.

Once the Mechanical Subsystem and Cleaning Subsystem were secured, the rest of the system was assembled and the prototype was ready for testing.

4.2 Experimental Tests & Protocol

Due to the nature of the design project, significant time was taken to test the prototype and ensure it was successful in reducing the effect of soiling on panels. The system was tested using two solar panels; one of the panels was a control that was not dirtied and the other panel was artificially soiled and cleaned using the system. By comparing two panels at the same time, the results were not affected by the amount of incoming irradiance fluctuating during the time taken to test. The incoming irradiance was also measured and recorded to use in the analysis of the data.

In order to test the effectiveness of the device, a panel that was soiled was needed. Since waiting for a panel to get soiled naturally would have required a large amount of time, a method was used to artificially soil the panels. The panels were dirtied by spreading a mixture of 15 grams of naturally found dirt with half a liter of water on the surface of the panel and letting the mixture dry. Once the panel was dry, the remained on the panel in a way that is common on naturally soiled panels. The efficiency drop of the panel was similar to that found in the research, around 15%, indicating the process was a good replica of natural soiling. The test setup is shown in Figure 25.

Figure 25: System Testing Setup

4.2.1 Data Collected

The data that was collected during the tests was the Maximum Power Point (MPP) of the solar panels. Since the output voltage and current of a panel are related to each other by the load across the panel by Ohm's Law, the load across the panel can change the amount of power outputted by the panel. Figure 26 shows a typical IV curve of a solar panel and the combination of current and voltage that generates the MPP of the panel.

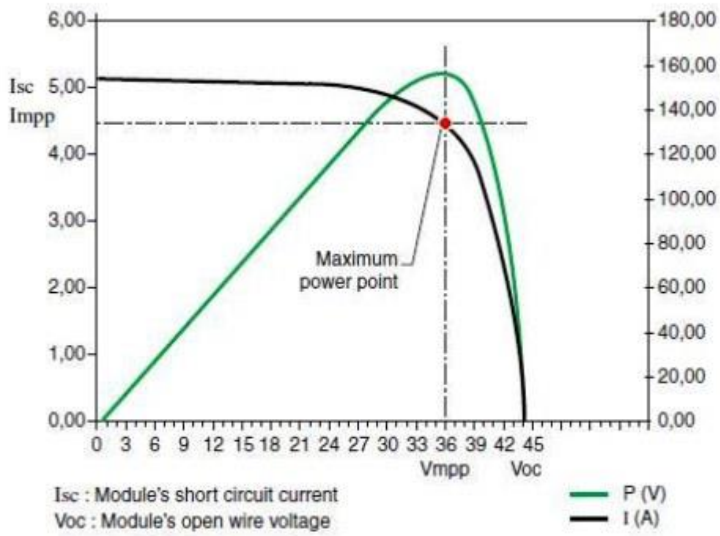

Figure 26: Typical IV Curve of a Solar Panel Showing MPP

The MPP was chosen as an indicator of a solar panel's performance because of its consistent relation to the actual power that can be delivered by the panel as well as its tie to the power generated by solar arrays in commercial use. In any application of solar panels for power generation, the panel system uses a device that tracks the MPP of the panels to output the maximum energy possible over the course of the day.

The MPP was measured using the Solmetric Analyzer, a device that records the IV curve of a panel. The device also records different characteristics of the panel such as the MPP, the voltage and current at the MPP, the open circuit voltage, and the short circuit current. The Solmetric Analyzer collects the data of a panel in a matter of seconds, allowing the team to record multiple measurements of both the control and the panel that was tested on within a very small time frame. Using the Solmetric Analyzer reduced the effect of the time difference affecting the results. Figure 27 shows the IV curve that is outputted by the Solmetric Analyzer.

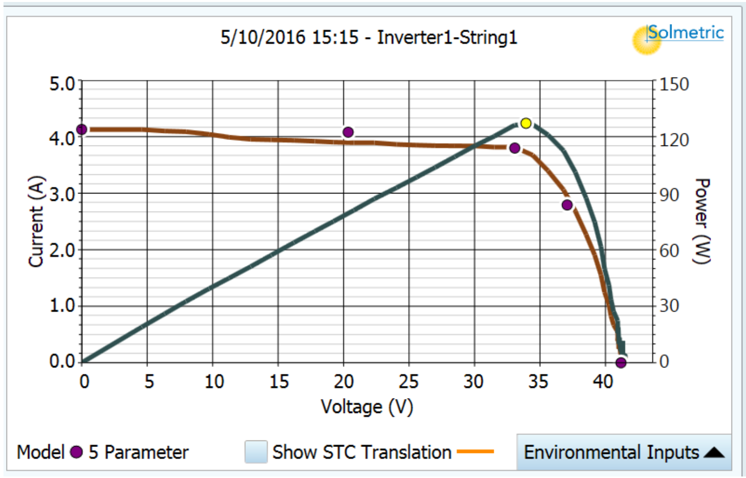

Figure 27: IV Curve Collected by Solmetric Analyzer

During the tests, the incoming irradiance was also measured. The power generated by the solar panels is directly related to the amount of incoming irradiance. The irradiance fluctuates during the day so it was important to measure the values in order to standardize the tests. By testing a control panel at the same time as the dirtied panel, the effect of irradiance was minimal. The irradiance was measured using a pyranometer, similar to the one shown in Figure 28.

Figure 28: Pyranometer

Besides from the effectiveness of the device, other aspects of the device were measured and recorded. The full list of measurements that were taken can be seen in Appendix F-1.

4.2.2 Testing Results

Using the data collected, the percentage increase was calculated. The results showed that the efficiency increase was directly related to the number of passes the device ran over the panel. After the device made two passes over the panel, which is one run of the system, a small increase of around 1% was found. However, after the device made another run, four passes over the panel in total, there was a 3.4% increase in panel efficiency.

Upon analyzing the panel that the system was tested on, the team noticed a pattern in the dirt left behind by the device. Figure 29 shows the panel that was tested. There was a large amount of dirt left in the center of the panel suggesting that the pressure along the length of the Cleaning Subsystem was not enough to hold the brush against the panel along its entire length. Also, the brushes rotate at a slow rate leaving streak marks of dirt behind showing where the brushes actually made contact. By increasing the RPM of the brushes and the pressure along the cleaning subsystem, the amount of dirt taken off per pass of the device can be increased.

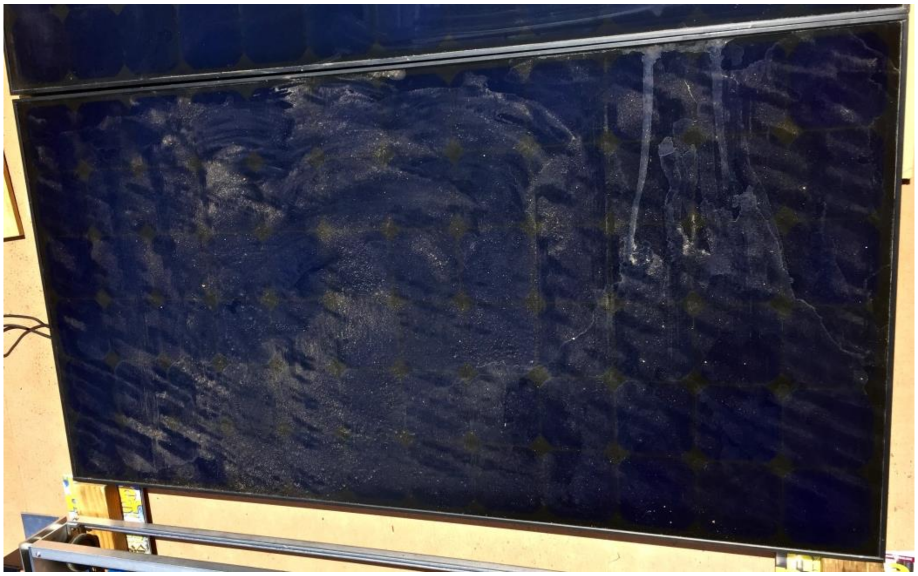

Figure 29: Dirty Panel after four Passes by System

The results of the test show that the amount of dirt that is removed is directly related to the number of passes the device makes over the panel. The device increased the efficiency of panels by an average of 3.41%. The results are based on roughly ten trials per pass. The total data collected can be found in Appendix G-3.

Chapter 5: Cost Analysis

5.1 Prototyping cost estimate

The initial project budget was formulated with the primary goal of creating two functional prototypes. The preliminary prototype has a total estimated fabrication cost of $400. The final prototype has a budget of approximately $600 allocated for fabrication and assembly. The overall estimate for the total development budget was $1300. A detailed breakdown of the project budget is located in Appendix 7.4. The project received funding from the SCU Undergraduate Fund as well as the ASME Venture Capital fund. The provided funding of $2100 exceeded our initial budget requests, requiring a revision of the project budget. The majority of the additional funds were allocated to improved prototype testing and a general purpose development fund to compensate for any unexpected cost overruns.

The main costs associated with both prototypes are the mechanical power and chassis systems. These systems require commercial purchased components including the main drive motor as well as fabricated components. The initial prototype serves as a proof of concept and a cost estimate of the final system. Once the first prototype was finished, improvements were incorporated directly into the first system eliminating the need for a second full prototype. The final fabrication and material costs were $562 for the finished system.

5.2 Production Cost

In order to determine an initial cost goal for the prototype, the potential energy savings were calculated to find a break-even point for the device. For this analysis, the SCU garage was used as a real-life example of a solar panel array. Above the top floor of the Santa Clara University garage is an array of solar panels 32 rows where each row has 39 panels. The garage solar panels are shown in Figure 4 from the garage view and Figure 30 shows the solar panel array from the Google Earth Satellite perspective.

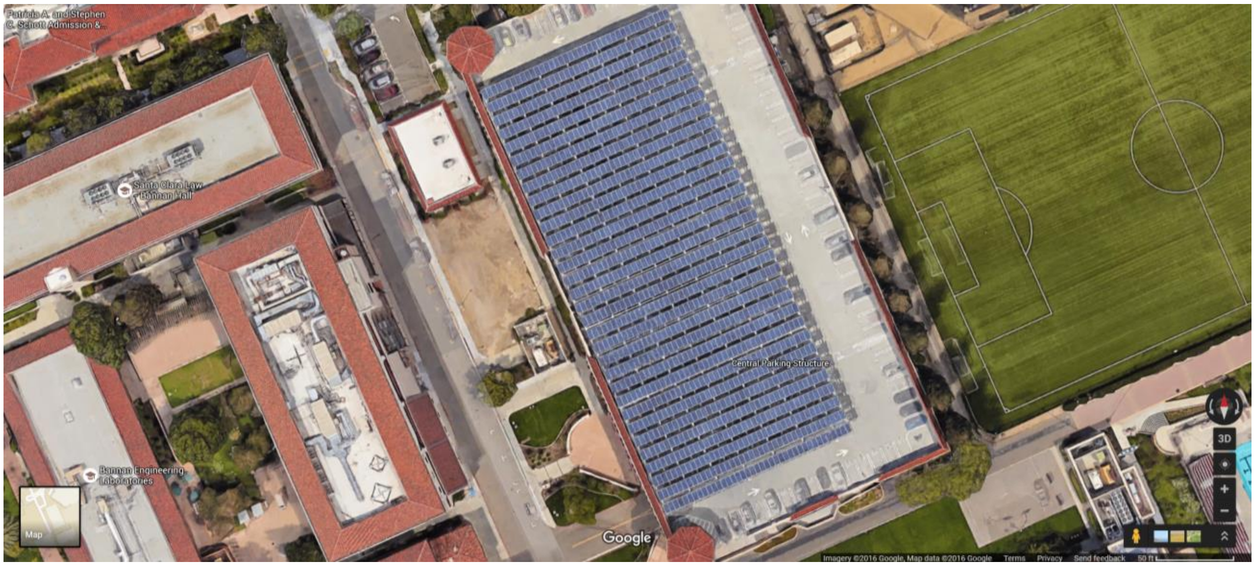

Figure 30: Image of Santa Clara University Garage (Google Earth)

Our device would be designed to move across a single row of panels, cleaning only the panels in that specific row. The Tigo Energy data from Section 3.1.5 was used in order to have more accurate energy generation for the Santa Clara area specifically. After our initial prototype construction and initial testing there was an efficiency increase of 3.5% with an estimated retail price of $700.

This efficiency increase is much lower than was intended and would reflect poorly on the break-even point of the device.

5.3 Customer Savings

In the Tigo energy data it was found that, on average, a solar panel would generate 340 kWh per year uncleaned. Data was averaged from previous years using panels that had not been cleaned. This power generation was increased by 12% due to the energy increase found in Figure 13 to assume that a clean panel would generate 380 kWh/year. The cost of electricity in the South Bay Area for commercial establishments is $0.17/kWh and, as mentioned above, a single row of solar panels on top of the garage has 39 panels.

After calculating the difference of 40 kWh/year for a row of 39 panels, the total cost savings is $270.50/year. This number was compared to the initial cost of the prototype in order to find the break-even point of various costs.

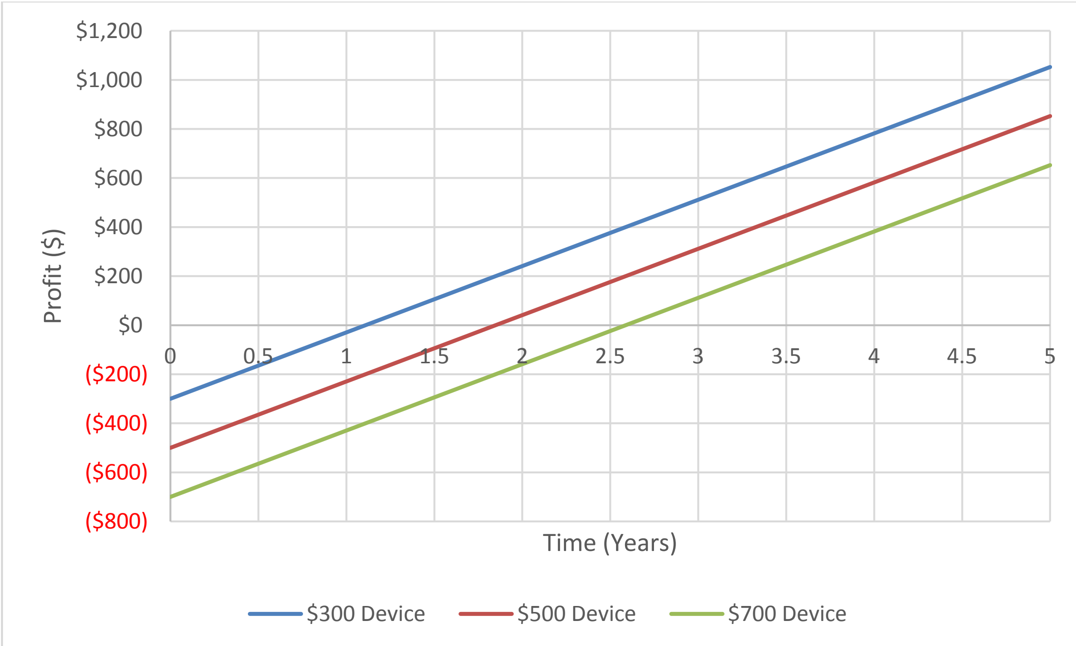

Figure 31: Break-even analysis for a $300, $500, and $700 Device

Under these assumptions a prototype costing $500 would break-even in less than two years and begin making a profit. It was decided that this would be a good benchmark for how much our prototype should cost given the cost of metal and the size of the initial device design.

This cost analysis does not take into account installation price or maintenance costs which could set the break-even point back slightly, but not significantly given the steepness of the curve.

Chapter 6: Business and Marketing Strategy for Project SPACE

6.1 Patent Search

After looking through several patents involving similar projects, many products exist that perform the task of cleaning solar panels. Knowing this information we do not intend to copy any patented work or infringe on any intellectual property. We are creating our own design to the problem without any help from other designs.

6.2 Introduction to Business Plan

The Solar Panel Automated Cleaning Environment, or SPACE system, is a low cost option for maintaining solar panel efficiency. Solar panels, through normal operation, accumulate layers of dust and debris which reduces the efficiency of its photo-voltaic cells. One case study performed by Google on its own solar installations, discovered an efficiency drop of as much as 36%. This represents a significant loss of energy and potential financial savings.

The traditional solution to this issue is the use of manual labor to clean the surfaces of each panel. While effective, manual cleaning is slow, expensive and there are often long time periods between cleanings where the panels lose efficiency. The SPACE system eliminates all of these concerns by offering an affordable automated solution. Once installed, the SPACE system can clean an entire row of panels quickly and effectively. The automated nature of the system allows it clean at a much greater frequency, ensuring the panels are continuously operating at peak performance.

While there are several automated cleaning systems on the market today, none of them can compete with SPACE's low price point and low operating costs. Current competitors such as the Heliotex sprinkler and the Ecoppia E4, are large, bulky, and expensive to install, often costing tens of thousands of dollars for an installation[7]. The SPACE system has a lower unit cost and can be installed for a fraction of the price.

6.2.1 Product Description

Project SPACE is designed to increase the efficiency of the energy generated by solar panels by reducing the amount of soiling on the panel. The system uses spinning brushes to clean solar panels automatically and safely over long periods of time. The device is designed to operate on arrays of solar panels without human intervention. Project SPACE is designed to be a cheap, low maintenance replacement for human labor.

6.2.2 Potential Markets

Due to Project SPACE's ability to clean long arrays of solar panels and its relatively low cost, the system will be targeted for commercial sized solar energy systems as a main market. Commercial energy systems are typically businesses or school campuses. They have numerous panels lined up in arrays but, unlike solar farm sized energy systems, cannot afford expensive cleaning systems. Smaller, more personal, energy systems are another option for a market. However, these systems typically contain only a few panels. The small size of these systems makes an automatic cleaning system more expensive than a typical owner can afford. Commercial sized arrays are the targeted market because of the size of the solar energy systems and affordability of the device.

6.2.3 The Team

6.3 Goals and Objectives

The long term goal of this company is to become the primary supplier of automated solar panel cleaning systems in the United States.

The current objective is to establish a foothold in the California solar market. We hope to establish a 30% market share within the next 5 years, before expanding to other regions.

6.4 Description of Technology

The SPACE system's main advantage is its low cost of fabrication and operation while retaining cleaning effectiveness. The low-impact brush design allows for a thorough clean while avoiding damage to the sensitive photo-voltaic cells. The brush design also eliminates any need for water creating an environmentally conscious solution to panel soiling.

However, the main draw of the system is its ability to automatically clean the solar array on a programmable schedule. Rather than waiting months between cleans, the system can clean as frequently as needed without human intervention. This saves users the hassle of periodically hiring and allocating time from their schedule for a crew of human cleaners. The SPACE system eliminates the efficiency loss issue for its users, saving them money and allowing them to focus on more important issues.

6.5 Potential Markets

The main market for current automated cleaning systems is solar panel farms. These farms operate tens of thousands of panels making manual cleaning a logistical nightmare. Thousands of cleaning systems are sold to remedy this issue. Even a single solar farm could require hundreds of systems indicating a large source of potential revenue.

The SPACE system is targeted at a different market, namely commercial solar arrays. These arrays consist of several hundred panels installed on the roofs of corporate offices and parking structures. Commercial installations represent roughly 30% of current solar energy production within the United States. The smaller nature of these installations has deterred the more expensive cleaning systems, which are cost restricted to the larger solar farms. This largely untapped market represents a perfect opportunity for SPACE to enter the industry and establish a foothold. Once SPACE has established itself in the commercial market, the company will have sufficient funds to push into the solar farms as well as residential solar markets. From there, the company seeks to expand into numerous foreign markets.

6.6 Competition

The main competition for our device is manual labor and other automated solar panel cleaners. For comparisons between manual labor, automated cleaning competitors, and project SPACE the Santa Clara University garage will be used in order to standardize all cleaning solutions. This array is an example of the commercial market that we intend to market towards excluding residential and solar farm markets. On top of the garage there is an array of solar panels with 39 panels in each row and 32 rows in the full array. The cleaning solutions will be estimated using these specifications

For manual labor since there is very little established standard for the market the cleaners tend to vary from the owner of the solar panels cleaning them to companies that clean panels for a price. This technique tends to have the least up front cost, but could cost more depending on the amount of panels that can be cleaned by a single device. When solar panels are cleaned by the owner the only cost comes from materials which can cost as low as $1/panel. The low cost is balanced by the time expended by cleaning a solar panel which can be several minutes per panel. At two minutes/panel the entire array would take 41.8 hours of work without any breaks. This is an excessive amount of time for one person to spend to clean the panels although the option works better for residential markets.

Getting a service to clean the panels typically costs much more, but can be done much faster with multiple people working. The same amount of time might be spent to clean all of the panels, but more people are sharing the time while the cost per panel is around $7. For the garage example the total cost of cleaning the entire array, each time it is cleaned, is $8736. The high cost of the single clean creates large periods of time in-between cleaning, reducing the amount of efficiency in the panels. The Santa Clara garage solar panel array is cleaned twice a year.
A large concern with using manual labor to clean panels is the risk that is involved with the locations solar panels can be in. The garage panels are placed on a skeleton structure above the top floor, exposed to the ground below. Laborer have to harness in and stand on very tall ladders in order to minimize the liability of the cleaning process as well as risk dropping objects onto the cars below.

The automated solar panel cleaning market is diverse, but not able to be sold in retail situations. For comparisons to project SPACE the Heliotex cleaner and the Ecoppia E4 will be looked at.

Figure 32: Heliotex Cleaner[8](Reproduced without permission)

Heliotex is a sprinkler system that can be used with a detergent to regularly clean the panels without contact to the panel itself. Heliotex is the only automated solution found that markets towards US markets, specifically California and Arizona. Heliotex supplied a spreadsheet for estimating the cost of their product for a variable amount of solar panels. For the array on the garage the lifetime cost was $37,440. This number did not vary on length of lifespan as it is dependent on the installation and quantity of the product. The largest cost in the system was from detergent which would be put onto the solar panels and given the location on top of a garage would fall onto cars below.

Figure 33: Ecoppia E4 Cleaner[7](Reproduced without permission)

The Ecoppia E4 is a product that moves horizontally across a row of panels with each machine cleaning a single row of panels. Project SPACE operates in a similar fashion without using water. This product though has only been implemented in solar farms in the Middle East and given that its headquarters is in Israel might not extend to the US. The price of installing the device is probably higher than that of Heliotex given the increased complexity of the design and each row requires an individual cleaner.

6.7 Sales/ Market Strategies

6.7.1 Advertising

In order to penetrate the market project SPACE will begin advertising at Santa Clara University accommodating the solar panels that are on campus. Because of the close working relationship this project has with the school it represents a perfect opportunity to cross the “chasm” into the main consumer market. Using the University as a reference project SPACE will be able to advertise to the early majority of the market and gain a larger foothold in the market. Advertising will be to commercial businesses with thousands of solar panels that are arranged in rows between 20-30 panels.

6.7.2 Salespeople

In the early phases of the advertising plan sales will be performed by the four core members of project SPACE while only relations with the University are necessary. When manufacturing begins more people will be necessary in order to accommodate the growing amount of customers. Predominantly sales will be conducted in the Silicon Valley and central California where there is more particulates in the air meaning more need.
The sales will have to be conducted with clear communication since deals with solar panel owners will range in the tens of thousands of dollars. One device will have to be installed to each row of panels meaning that specifics in number of devices as well as height of the solar panels need to be established.

6.7.3 Distribution

In the early phases of the advertising plan sales will be performed by the four core members of project SPACE while only relations with the University are necessary. When manufacturing begins more people will be necessary in order to accommodate the growing amount of customers. Predominantly sales will be conducted in the Silicon Valley and central California where there is more particulates in the air meaning more need.

The sales will have to be conducted with clear communication since deals with solar panel owners will range in the tens of thousands of dollars. One device will have to be installed to each row of panels meaning that specifics in number of devices as well as height of the solar panels need to be established.

6.8 Manufacturing

The prototype for project SPACE was entirely developed in the Santa Clara Machine shop by the four members involved in the project which speaks to the simplicity of the design and the ease to manufacture the device. With the initial plan of developing for the school and nearby business project SPACE can be manufactured in the Silicon Valley but should be moved to a cheaper area when larger quantities of the device are needed. While producing for the school no inventory will be kept since the University will be the only client, but when project SPACE expands into the nearby market 50 devices will be kept in inventory. The most complicated section, the gear box, can be kept fully assembled while the chassis is merely L-beams that can be kept at different sizes in inventory and assembled when orders are filled. The prototype for project SPACE was completed in approximately 10 hours of individual work time. This does not include R&D time and time spent learning to do specific machining functions. Completing another so to be ready for inventory would take 4 hours with multiple people working on manufacturing.

In order to begin manufacturing approximately 50 machines will have to be made to accommodate the schools solar panels. This will probably cost $10,000 in order to make the project successful since some of the R&D cost has already been spent. Once successful cleaning is implemented on the University campus project SPACE will expand to other companies in the Silicon Valley and central California with high number of solar panels.

6.9 Production Cost and Price

The prototype was separated into four main subsystems that were assembled separately and then combined to form the final prototype. The budget for fabrication of the assembly was split into the main subsystems and can be seen in Table 3.

Table 3: Fabrication Cost by Subsystem

EXPENSES				
Category	Description			Cost
Cleaning	Brushes, mounting shafts			$185
Chassis	Aluminum frame connecting the gearboxes			$235
Control	Micro-controller and additional sensors			$57
Gear System	Gears, axles, bushings			$85
	Total Prototype			$562

Table 3 shows the final fabrication cost of the prototype was $562. However, this cost does not include any other considerations that would arise if the product was sold in market such as labor costs, profit margin, and any reduction in cost due to mass manufacturing methods. The amount these numbers factor in is dependent on the quantity of the systems that are created on an annual basis.

As the company breaks into the market, the amount of commercial sized systems that the company has as clients would affect the amount of devices created and the cost of each device. Initially, there may only be one or two commercial sized arrays that would need devices for their campus. An estimate for the number of devices created for each commercial system would be around 32 units.

The retail cost of the system would initially be higher as the company got started. As the demand for the devices rises, however, the retail cost would drop as the company grows in capacity and manufacturing ability. Initially the system would need to be retailed for around $900 per unit. This cost was found by assuming that it would take four hours of labor to manufacture each unit, and each hour of labor was worth $20. The profit margin for a device retailed at $900 would be $258 without including any reduction in material cost due to buying in bulk. The actual profit margin would be around $300. This would be enough profit for the company to survive as it grew into larger markets and increased the amount needed to produce.

The goal for the final retail cost would be around $700. This retail cost would become feasible as more units are produced and the material price for each system drops due to buying in bulk. Additionally, as the company expands to allow for the increase in production, the hours spent creating the device would reduce to two hours which would reduce labor costs and increase the profit margins on a $700 device.

Both retail costs, $900 and $700, would be significantly cheaper than other commercially available solar panel cleaning solutions. The price for the Heliotex cleaner for a commercial system of 32 arrays would by around $35,000. The SPACE Project would cost either $28,800 for a $900 device or $22,400 for a $700 system. The large difference between the cost of Project SPACE and its competitors show its ability to function at a competitive level relative to the more complex and expensive market solutions.

6.10 Service and Warranties

Project SPACE is being designed to function on a solar panel for 7 years servicing and repairs will have to be performed when the system malfunctions. The parts that Project SPACE predicts to be the weakest are the gears and the brushes. The gears can be replaced by taking one of the outer walls without having to remove any other piece. The gear, plus the axle it sits on can replace the broken gear or axle and the outer piece put back on. The modular design of the brushes allow for each individual brush to be replaced if damaged. When one piece malfunctions the device can be taken apart, with the gear box still intact and an individual brush replaced. This repair is more intensive then replacing an individual gear, but each roller brush should last for 10 years of use.

6.11 Financial Plan and Return of Investment

In order to determine an approximate Return of Investment (ROI), the Tigo Energy data was used for the amount of energy generated by a solar panel in the Silicon Valley. In the Tigo energy it was found that on average a solar panel would generate 340 kWh per year uncleaned. Data was averaged from previous years using panels that had not been cleaned. This power generation was increased by 12% due to the energy increase found in Figure 7 to assume that a clean panel would generate 380 kWh/year. The cost of electricity in the South Bay Area for commercial establishments is $0.17/kWh and as mentioned above a single row of solar panels on top of the garage has 39 panels.

After calculating the difference of 40 kWh/year for a row of 39 panels the total cost savings is $270.50/year. This number was compared to the initial cost of the prototype in order to find the break-even point of various costs.

Under these assumptions a prototype costing $500 would break-even in less than two years and begin making a profit. It was decided that this would be a good benchmark for how much our prototype should cost given the cost of metal and the size of the initial device design.

This cost analysis does not take into account installation price or maintenance costs which could set the break-even point back slightly, but not significantly given the steepness of the curve.

The initial system costs may require a loan on the part of the customer in order to finance the purchase. However as stated above, it is a relatively short period until the device breakeven in terms of savings.

After our initial prototype construction and initial testing there was an efficiency increase of 3.5% with an estimated cost of $700. This efficiency increase is much lower than was intended and would reflect poorly on the break-even point of the device.

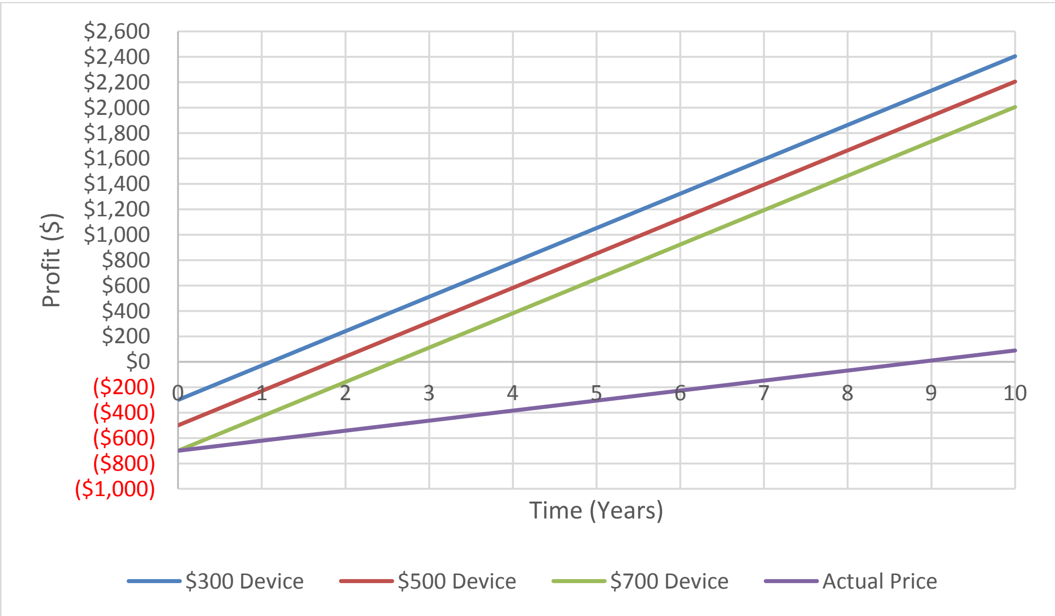

Figure 34: Break-even analysis including the actual price and efficiency of the device

As shown in figure 34, the device would take almost 9 years in order to break even which is unacceptable for our device. A higher efficiency increase per cleaning is being investigated in order to increase the steepness of the profit line. When design modifications are made the actual prototype line should look more like the approximated ROI lines.

Chapter 7: Engineering Standards and Realistic Constraints

7.1 Economic Constraints

The financial considerations associated with the creation of the system are the largest constraint on the project. The manufacturing and operational costs of the system cannot exceed the financial savings from the improved solar panel efficiency. If the system cannot save enough money to offset its costs, there is no point to implementing the product in the first place. Furthermore, the system's unit cost must be low enough to attract potential customers. As a consumer product, the system is a significantly larger investment than the use of human laborers for solar panel cleaning. Any cost reductions will improve the chances of this product succeeding financially.

In ideal conditions this system will operate for long periods of time, potentially longer than a decade. During this time, the system must maintain its cost effectiveness for its entire lifespan. Eliminating maintenance costs is critical to achieving this goal.

7.2 Environmental considerations

The functionality of this system has potentially huge implications for environmental preservation efforts. Our system has the potential to boost the production of existing solar panels all around the world. Not only does this improve the current solar energy systems, but it also makes any future investments in solar power a more attractive proposition.

This system is a financially viable method of reducing the world's demand for fossil fuels. If fully implemented, this system could prove to be significant in the struggle against climate change.

7.2.1 Economic and Environmental Case Study

Furthermore, a short case study was conducted by our group to analyze the added costs and added emissions that would be associated with a 10% decrease in solar panel output in the San Jose Area. This study was modeled after a similar one done by the Rocky Mountain Institute, called The Economics of Grid Defection[9]. In this study, they measured the economic and environmental benefits of installing an optimized PV system (options ranged from 500 to 600 kW) with a backup diesel generator (around 150 kW). In our study, the systems would be responsible for matching a commercial load of roughly 1600 kWh/d with a 237 kW peak. Finally, the mean differences in generated emissions and expected costs between two systems of roughly a 10% difference in PV outputs were tabulated in Tables 4 and 5.

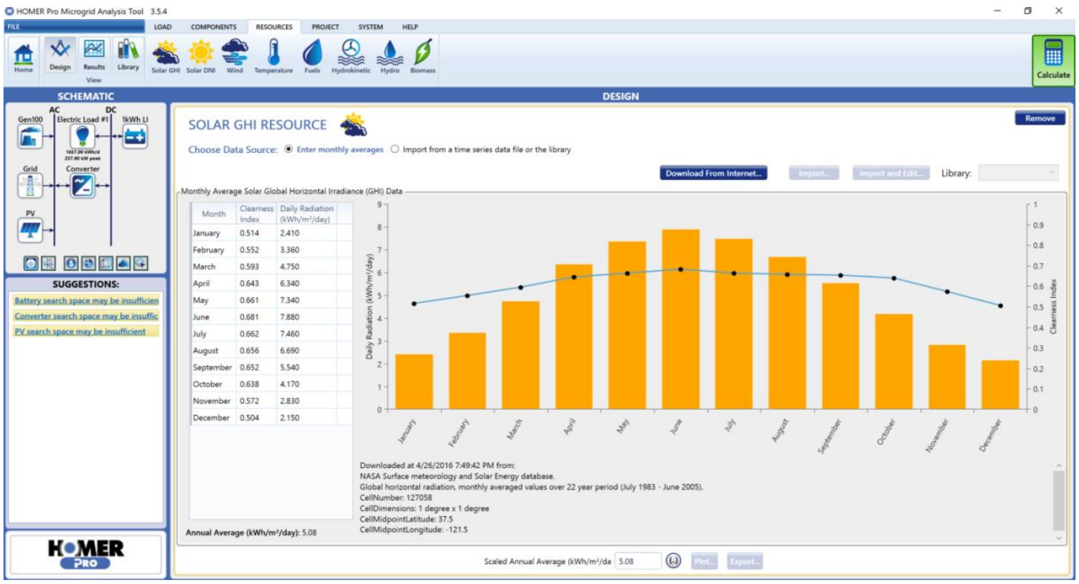

Figure 35: Homer model architecture and annual global horizontal irradiance used for simulation[9]

Table 4: A Breakdown in the Amount of Added Costs (Capital, Annual, NPC, etc.) Associated with a 10% Decrease in Solar Panel Production[9]

Cost Summary	**Generated at Max Power (605 kW PV)**	**Added Cost and Production to Compensate for 10% Loss**
Total NPC	$2,144,040	$9,111
LCOE	$ 0.393/kWh	$ 0.077/kWh
Total Capital Cost	$1,401,357	$168,070
Total Annual Cost	$227,181/yr	$44,574/yr
Total O&M Cost	7,130/yr	$198.7/yr
Total Annual Replacement Cost	27,632/yr	$6,647/yr
Operating Cost	$78,692/yr	$8,489/yr
PV Production	713,878 kWh/yr	64,899 kWh/yr

Table 5: A Breakdown in the Amount of Added Emissions [kg/yr] Associated with a 10% Decrease in Solar Panel Production[9]

Emissions Summary	Generated at Maximum Power (605 kW PV)	Added Due to 10% Output Power Loss in PV
Carbon Dioxide	126,851 kg/yr	12,813 kg/yr
Carbon Monoxide	313 kg/yr	31.5 kg/yr
Sulfur Dioxide	250 kg/yr	26.0 kg/yr
Nitrogen Oxide	2,794 kg/yr	282.0 kg/yr

7.3 Sustainability

In tandem with the environmental concerns, a great deal of attention has been paid to the sustainability of our system. As solar energy is considered a clean source of renewable energy, our system too must meet various criteria for sustainability.

Foremost in our design considerations was the decision to minimize water usage in the cleaning process. The state of California is currently experiencing a severe drought with all excessive water usage being eliminated throughout the state.

The Bureau of Land Management of Nevada found that it takes 16,689 gallons of water per megawatt to clean PV panels [10]. This number will be used with the assumption that the 16,689 gallons are for two cleans a year for all panels in question. According to the California Solar Initiative, California generated 256 megawatts of electricity in 2014[11]. Given this information and the cost of water in Santa Clara being $4.18/ 748 gallons of water, the cost savings on water can be calculated in all of California[12] 256 MW x 16,689 Gallons/MW x $4.18 / 748 Gallons =$23,875.09 saved by not using water to clean solar panels in California. This does not take into account, though, how precious water is to California after the drought was declared a state of emergency in early 2014. Conserving water in any way possible helps California have more water for people to drink. The amount of water used in cleaning solar panels due to the calculations above is 4,272,384 gallons.

Solar arrays in California represent a large portion of our potential market and the design was adjusted accordingly. Along these same lines, our design does not implement the use of any chemical cleaner or solvents. Our team concluded that, while a potentially useful feature, the use of chemicals would be detrimental to the environment around the solar panel installation.

7.4 Manufacturability

With the design of any commercial product, manufacturability was a large concern during the development of our system. Improving the ease of manufacture has two main benefits for the cleaning system. In many cases, improving manufacturability entails the use of simpler parts and less expensive processing for the creation of each part. This leads to a reduction in the overall cost of the system as the components become cheaper to make. The second benefit our system receives is reductions in maintenance costs. A simpler system has fewer areas for potential failure and therefore less costs associated with maintaining that system. By streamlining the system for production, we may improve the overall lifespan by reducing the needed complexity of the system.

7.5 Safety Concerns

Human safety is another area where we believe our system can have a strong impact. The majority of solar panel installations are inaccessible locations such as the top of buildings or large structures. In many cases these installations do not take into consideration the need to access the panels for cleaning. Often human workers are required to use climbing harnesses in order to work on these installations high above the ground. In 2014, falls and slips accounted for 30% of work related fatalities in California[13]. If human workers wish to clean a set of panels, not only must they cope with the scale of the solar installation but they must take extreme care with every step they take to avoid a potentially deadly fall. There are massive safety, liability and insurance concerns associated with this type of work. Our system has the potential to eliminate this unnecessary risk to human life as well the associated liability hassle.

Our system has also been designed to maintain safety at all times during its operating lifespan. The system is securely mounted to the solar panel preventing it from becoming a falling hazard.

The future addition of several sensors on board the device to initiate a shutdown would prevent the system from causing harm should any person or animal cross into the path of the system.

Chapter 8: Summary and Conclusions

8.1 Overall Evaluation of the Design

The goal of Project SPACE is to create an automated solar panel cleaner that will address the adverse impact of soiling on commercial photovoltaic cells. Specifically, we hoped to create a device that will increase the efficiency of a soiled panel by 10% while still costing under $500 and operating for up to 7 years. Furthermore, a successful design should operate without the use of water and require only yearly maintenance.

The current apparatus utilizes a brush cleaning system that cleans on set cleaning cycles. It uses a rolling brush to clean as it horizontally translates across an array of panels. The device is mounted on a set of battery powered-motorized wheels. At the end of the panel, there would be a docking station for it to recharge.

Beyond improving the efficiency, we hope that our design will continue to expand the growth of solar energy globally. An efficient cleaner would not only help communities' transition into using cleaner alternative fuel sources, but help society, as a whole, move closer toward providing everyone the opportunity to harness reliable energy.

8.2 Suggesting for Improvement / Lessons

The current design functions relatively well, however there are several areas for improvement. First and foremost is the cleaning system. The system only improves solar panel efficiency by 3.5% far short of the original goal of 10%.

Two modifications have been identified that would likely improved system functionality. The cleaning brush currently spins at 36 RPM which, in testing, has proven to be too slow to achieve the necessary cleaning effectiveness. To resolve this issue, a new motor with sufficient RPM or a modified gear train ratio should be implemented.

Another observation of the testing phase was the lack of cleaning effectiveness at the center point of the brush. The working theory is that the brush is unable to exert sufficient pressure at that point and requires additional structural reinforcement. The addition of fixed supports at one or more points along the cleaning brush should be sufficient to overcome the pressure issue. This may, in turn, require more torque on the part of the motor, potential requiring a higher performance motor. The revised design can be seen in the concept image in Figure 36.

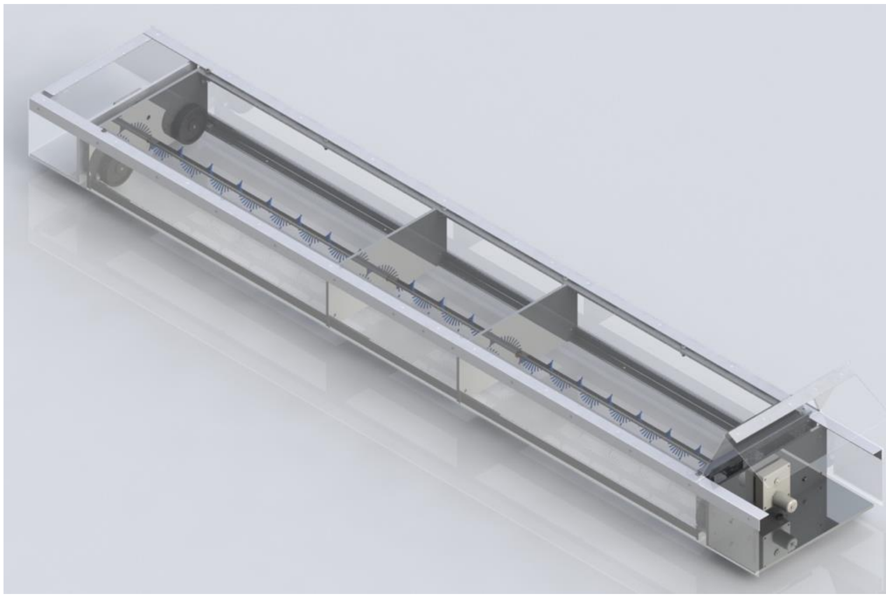

Figure 36: Prototype concept with Additional Center Support Plates

8.3 Wisdom to Pass On

First and foremost, the team discovered that when designing a product for fabrication it is absolutely necessary to plan out every aspect of the design to the smallest detail. The designer must account for how every screw, nut, and bolt will fit together and must try and anticipate potential issues that will arise in the actual assembly of the product. There were several points in our fabrication process where the areas of the design that were not fully completed caused large issues. This lack of anticipation cost the team a great deal of time and money in order to correct the resulting design problems.

Another key takeaway is the need for extensive feasibility testing. In the construction of our cleaning system the selected brush was subjected to minimal testing. Had we been more thorough, we would have discovered the brush requires a certain RPM and pressure to operate efficiently. Correcting this issue required a large amount of redesigning to maintain the targeted cleaning efficiency.

Finally, our team learned the importance of delegation and parallel development. Our initial tendency was to focus the entire team on one aspect of the design at a time. These smaller portions of the design did not require the full team and, as a result, wasted time that could have been spent improving other aspects of the design. If smaller groups had been assigned parts of the design to work on in parallel, the entire design process would have likely gone much smoother with a better final product.

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[3] Sayyah, A,. Horenstein M., and Mazumder M. "Mitigation of Soiling Losses in Concentrating Solar Collectors." 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) (2013): 404-408. Print.

[4] Burton, D., and Bruce H. King. "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types." IEEE Journal of Photovoltaics IEEE J. Photovoltaics 4.3 (2014): 890-98. Print.

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Translation: Solar energy will supply electricity to northern Chile

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[15] Cabanillas R.E. and Munguia H.. "Dust accumulation effect on efficiency of Si photovoltaic modules" Journal of Renewable and sustainable energy 3, 043114 (2011). Print

APPENDICES

Appendix A-1 Annotated Bibliography

[1] Kimber, A., L. Mitchell, S. Nogradi, and H. Wenger. "The Effect of Soiling on Large Grid-Connected Photovoltaic Systems in California and the Southwest Region of the United States." 2006 IEEE 4th World Conference on Photovoltaic Energy Conference (2006): n. pag. Print.

This 2005 study measured the efficiency loss in large PV systems in California and additional Southwest regions. The article is especially useful to our research given it was performed in our region of focus, California. The results of the study further confirm the need for our design; the study reported a linear loss of efficiency in California due to the soiling of PV panels with a daily loss of 0.2%.

This was useful in determining the potential economic demand for our product.

[2] Boyle, Liza, Holly Flinchpaugh, and Michael Hannigan. "Impact of Natural Soiling on the Transmission of PV Cover Plates." 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) (2013): n. pag. Print.

A research group at the University of Colorado studied the effect of dust on the transmission of light through glass panels. The glass panels were similar to those used on PV panels so that the study could help quantify the efficiency loss of solar panels due to soiling. The results of the study further confirm the need of a cleaning solution for solar panels. The researchers found a 6% loss in each gram per meter squared of dust added. The effect of light transmission on the efficiency of PV panels was not included in the study--causing a hindrance in the helpfulness of the study.

This source further confirmed that there is a great need for a product like ours in the solar industry.

[3] Sayyah, Arash, Mark N. Horenstein, and Malay K. Mazumder. "Mitigation of Soiling Losses in Concentrating Solar Collectors." 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) (2013): 404-408. Print.

A study, conducted in 2013 by the Department of Electrical and Computer Engineering at Boston University, reported the costs and benefits to three current methods of cleaning solar panels. These methods include natural cleaning through rain and snowfall, manual cleaning, and cleaning by an EDS. In general, it was concluded that in order to maximize cleaning effect of rain, the panels needed to have a glass shield and be oriented in the near vertical position. Manual cleaning by water and detergent was effective; however, it required costs set aside for labor (45.7% of the total cost) and fuel (20.5% of the total cost). An emerging technology, called an EDS (electrodynamic system), consists of interdigitated electrodes (made of indium oxide) in transparent dielectric film. The cleaning process is orchestrated by low power, three phase pulsed voltages (from 5 to 20 Hz). This process led to a reflectivity restoration of 90% after only a few minutes.

This article helped us determine the best available solution to cleaning panels.

[4] Burton, Patrick D., and Bruce H. King. "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types." IEEE Journal of Photovoltaics IEEE J. Photovoltaics 4.3 (2014): 890-98. Print.

This article, published with the IEEE involves the effects of different types of dirt on solar panel efficiency. Different types and colors of dirt were tested with the emphasis in targeting dirt compositions that are found in the southwest of the United States. The study found that yellow colored dirt scattered light back into the solar panel and so was less detrimental than the other dirt tested. The other three samples, all shades of red, did not perform as well.

This article was useful to see how different types of dirt were measured and in what locations dirt affects efficiency the most.

[5] R. E. Cabanillas and H. Munguia. “Dust accumulation effect on efficiency of Si photovoltaic modules” Journal of Renewable and sustainable energy 3, 043114 (2011). Print

The University of Sonora analyzed the effect of naturally occurring dust and residue on the energy generation of solar panels. A standard ‘dirt’ layer was chosen and was tested on three types of photovoltaic cells, monocrystalline, polycrystalline, and amorphous. The maximum reduction in electric production was 6% for monocrystalline and polycrystalline and 12% for amorphous.

This article is helpful in determining which panels will be most effective to clean.

Appendix B-1 Hand Calculations

Total Lost Potential Lost Revenue for a Single Panel and an Array of Panels

Single Panel

Cost of kWh in California = 15 cents

Yearly Output 2m Solar Panel = ~730 kWh

Total monetary generation: ~ $110/year

Assuming efficiency loss of 12% [Cabanillas]
Lost potential revenue = $13.2

Array of Panels

SCU uses 32 rows of ~15 panels each for garage array

Lost yearly revenue per row = $198
Lost revenue over 7 years = $1386 - Our design must cost less than this amount to be viable

Total yearly revenue lost by array = $6,336

Appendix B-2 Arduino Code for Motor Control

```
% Can Be Applied For Two Motors
int enA = 11;
int in1 = 12;
int in2 = 13;
int enB = 10;
int in3 = 8;
int in4 = 9;

void setup() {
   // set all the motor control pins to outputs
  Serial.begin(9600);
  pinMode(enA, OUTPUT);
  pinMode(in1, OUTPUT);
  pinMode(in2, OUTPUT);
  pinMode(enB, OUTPUT);
  pinMode(in3, OUTPUT);
  pinMode(in4, OUTPUT);
}

void clockwise()
{
  digitalWrite(enA,LOW);
  digitalWrite(in1,LOW);
  digitalWrite(in2,LOW);
```

```
  digitalWrite(in1,HIGH);
  digitalWrite(in2,LOW);
  digitalWrite(enA,HIGH);
}

void brakeA()
{
  digitalWrite(enA,LOW);
  digitalWrite(in1,LOW);
  digitalWrite(in2,LOW);
  //digitalWrite(in1,HIGH);
  //digitalWrite(in2,LOW);
  digitalWrite(in1,HIGH);
  digitalWrite(in2,HIGH);
  digitalWrite(enA,HIGH);

}

void counterClockwise()
{
  digitalWrite(enB,LOW);
  digitalWrite(in3,LOW);
  digitalWrite(in4,LOW);
  digitalWrite(in3,HIGH);
  digitalWrite(in4,LOW);
  digitalWrite(enB,HIGH);
}

void brakeB()
{
  digitalWrite(enB,LOW);
  digitalWrite(in3,LOW);
  digitalWrite(in4,LOW);
  //digitalWrite(in1,HIGH);
  //digitalWrite(in2,LOW);
  digitalWrite(in3,HIGH);
  digitalWrite(in4,HIGH);
  digitalWrite(enB,HIGH);

}

void loop()
{
  clockwise();
  Serial.println("Clockwise");
  Serial.println(digitalRead(enA));
  Serial.println(digitalRead(in1));
  Serial.println(digitalRead(in2));
  delay(2000);
```

```
  brakeA();
  Serial.println("Brake");
  Serial.println(digitalRead(enA));
  Serial.println(digitalRead(in1));
  Serial.println(digitalRead(in2));
  delay(2000);
  counterClockwise();
  Serial.println("Counter Clockwise");
  Serial.println(digitalRead(enB));
  Serial.println(digitalRead(in3));
  Serial.println(digitalRead(in4));
  delay(2000);
  brakeB();
  Serial.println("Brake");
  Serial.println(digitalRead(enB));
  Serial.println(digitalRead(in3));
  Serial.println(digitalRead(in4));
  delay(2000);

}
```

Appendix C-1 Product Design Specifications/ Requirements

Design Project: Automated Solar Panel Cleaner

Team: SPACE Date: 19 November 2015 Revision: 3.0

Datum description: Human Labor Conditions **

*Datum is based on the performance on human worker as a baseline
**See *"Mitigation of Soiling Losses in Concentrating Solar Collectors"* for more information on the human labor statistics

Table 6: PDS/Requirements (System Level)

Elements/Requirements			**Parameters**	
	Revision Date	UNITS	DATUM*	TARGET-RANGE
Electrical Requirments				
Efficiency Increase	11/16/15	%	10	10
Power Consumption	11/16/15	kWh	N/A	0.25
Cleaning Effectiveness				
Cleaning cycle time	11/16/15	sec	300	10
Water usage	11/16/15	liters	3.5	0
Device Lifespan	11/16/15	years	N/A	7
Physical Dimensions				
Size (Length, Width, Depth)	11/16/15	m^3	N/A	2 x 0.4x 0.1
Weight	11/16/15	kg	80	30
Financial Estimate				
Manufacture Cost	11/16/15	$	n/a	150
Selling Cost	11/16/15	$	300	200
Mode of Operation				
Operating Temperature Range (Min,Max)	11/30/15	Degrees C	(0, 40)	(0,46)
Maximum Wind Speed	11/30/15	m/s	20	35
Aesthetics	11/16/15	Quality	N/A	Fair
Yearly Inspections	11/16/15	visits/year	3	0

Table 7: PDS/Requirements Subsystem Level

Subsystems Specifications			**Parameters**	
	Revision Date	UNITS	DATUM*	TARGET-RANGE
Maintenance of Cleaning System				
Replacement of Mircofiber Brushes	12/2/15	visits/year	12	12
Cleaning Fluid usage per year (if utilized in final design)	11/16/15	liters/use	2	0
Maintenance of Mechanical Power System				
Replacement of Gear Train	12/2/15	visits/year	1	1
Replacement of Axel	12/2/15	visits/year	1	1
Maintenance of Control System (Not in DATUM System)				
Replacement of PID Controller	12/2/15	visits/year	n/a	2
Replacement of Battery	12/2/15	visits/year	n/a	1
Replacement of USB Attachment	12/2/15	visits/year	n/a	1
Operation Specifications				
Speed of Cleaning Cycle	12/2/15	hr/cycle	5	1
Speed of Motor	12/2/15	RPM	30	30
Torque of Motor	12/2/15	Nm	5	5
Power Consumption of Control System				
PID Controller	12/2/15	W	n/a	6
Supply of Battery (Lithium Ion)	12/2/15	W	n/a	60
Replacement of USB Attachment	12/2/15	W	n/a	5

Appendix C-2 Decision Matrices

Table 8: Scoring Matrix (Cleaning Subsystem)

	TARGET or	DESIGN IDEAS: Cleaning Subsystem																			
CRITERIA	**FACTOR**	**1 = Baseline**		**Drip System**		**Sponge/Wiper**		**Microfiber Cloth**		**Bristles**		**Windshield Wiper**		**Vibration+Press.**		**Swiffer**		**Chemicals**		**Pressurized Water**	
Time – Design	1	1		5		5		5		5		5		5		5		5			
Time – Build	1	1		5		5		5		5		5		5		5		5			
Time – Test	1	1		2		2		2		2		2		2		2		2			
Time Score	10		10		40.00		40.00		40.00		40.00		40.00		40.00		40.00		40.00		0.00
Cost – Prototype	1	$ 1.00																			
Cost – Production	1	$ 1.00																			
Cost Score	10		10		0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00		0.00
Weight	2.7777778	3	8.33333	5	13.88889	5	13.88889	5	13.88889	5	13.88889	5	13.88889	4	11.11111	5	13.88889	5	13.88889	3	8.333333
Speed of Cleaning	2.7777778	3	8.33333	2	5.555556	4	11.11111	5	13.88889	5	13.88889	5	13.88889	5	13.88889	5	13.88889	2	5.555556	5	13.88889
Effectiveness	18.055556	3	54.1667	2	36.11111	3	54.16667	3	54.16667	2	36.11111	3	54.16667	2	36.11111	2	36.11111	2	36.11111	3	54.16667
Water Usage	9.7222222	3	29.1667	5	48.61111	5	48.61111	3	29.16667	3	29.16667	4	38.88889	5	48.61111	5	48.61111	2	19.44444	1	9.722222
Power Usage	18.055556	3	54.1667	4	72.22222	4	72.22222	3	54.16667	3	54.16667	4	72.22222	2	36.11111	5	90.27778	5	90.27778	3	54.16667
Safety	11.111111	3	33.3333	5	55.55556	5	55.55556	5	55.55556	5	55.55556	5	55.55556	5	55.55556	5	55.55556	2	22.22222	5	55.55556
Autonomy	15.277778	3	45.8333	5	76.38889	5	76.38889	5	76.38889	5	76.38889	5	76.38889	5	76.38889	3	45.83333	4	61.11111	4	61.11111
Aesthetics	4.1666667	3	12.5	5	20.83333	5	20.83333	4	16.66667	4	16.66667	5	20.83333	3	12.5	4	16.66667	5	20.83333	5	20.83333
Cost	18.055556	3	54.1667	5	90.27778	5	90.27778	2	36.11111	3	54.16667	2	36.11111	2	36.11111	5	90.27778	4	72.22222	3	54.16667
	TOTAL		300.0		399.4		423.1		330.0		330.0		361.9		306.4		391.1		321.7		351.9
	RANK																				
	% MAX		70.9%		94.4%		100.0%		78.0%		78.0%		85.6%		72.4%		92.4%		76.0%		83.2%
	MAX	**423.1**																			

Table 9: Scoring Matrix (Mechanical Subsystem)

	TARGET or	DESIGN IDEAS: Mechanical Subsystem											
CRITERIA	**FACTOR**	**1 = Baseline**		**Motor-Driven Chain**		**Mounted Wheels**		**Separate Rails**		**4 Fly Cables**		**Windshield Wiper**	
Time – Design	1	1		5		5		5		5		5	
Time – Build	1	1		5		5		5		5		5	
Time – Test	1	1		2		2		2		2		2	
Time Score	10		10		40.00		40.00		40.00		40.00		40.00
Cost – Prototype	1	$ 1.00		$2.00		$ 2.00		$ 4.00		$ 5.00		$ 5.00	
Cost – Production	1	$ 1.00		$2.00		$ 2.00		$ 4.00		$ 5.00		$ 5.00	
Cost Score	10		$ 10.00		20.00		20.00		40.00		50.00		50.00
Weight	2.7777778	3	8.33333	5	13.8888889	5	13.88889	3	8.333333	5	13.88889	3	8.333333
Speed of Cleaning	2.7777778	3	8.33333	3	8.33333333	4	11.11111	5	13.88889	5	13.88889	5	13.88889
Effectiveness	18.055556	3	54.1667	2	36.1111111	3	54.16667	3	54.16667	3	54.16667	3	54.16667
Water Usage	9.7222222	3	29.1667	5	48.6111111	5	48.61111	5	48.61111	3	29.16667	4	38.88889
Power Usage	18.055556	3	54.1667	4	72.2222222	4	72.22222	3	54.16667	2	36.11111	3	54.16667
Safety	11.111111	3	33.3333	5	55.5555556	5	55.55556	5	55.55556	5	55.55556	5	55.55556
Autonomy	15.277778	3	45.8333	5	76.3888889	5	76.38889	5	76.38889	5	76.38889	5	76.38889
Aesthetics	4.1666667	3	12.5	5	20.8333333	5	20.83333	4	16.66667	5	20.83333	4	16.66667
Cost	18.055556	3	54.1667	5	90.2777778	5	90.27778	2	36.11111	2	36.11111	2	36.11111
	TOTAL		300.0		382.2		403.1		303.9		266.1		284.2
	RANK												
	% MAX		74.4%		94.8%		100.0%		75.4%		66.0%		70.5%
	MAX	**403.1**											

Appendix C-3 Sketches

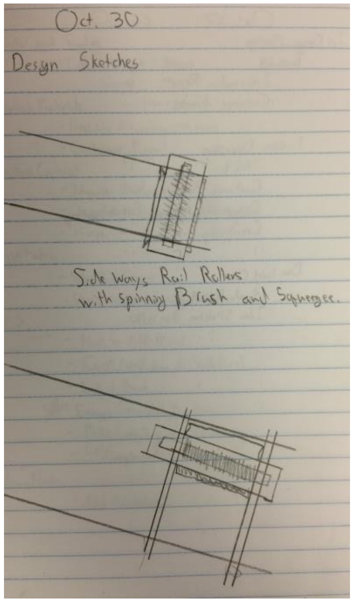


Figure 39: Sketch of Full System

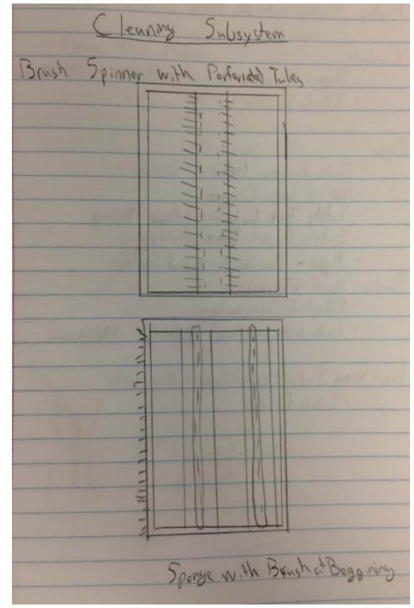


Figure 37: Sketch of Cleaning Subsystem

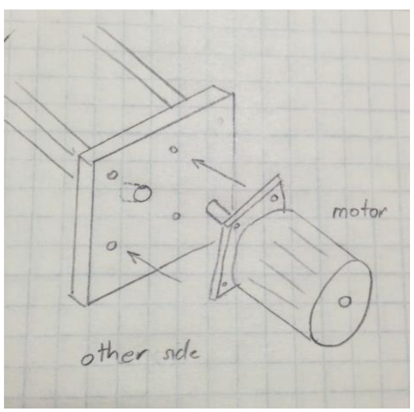


Figure 38: Sketch of Motor Connection

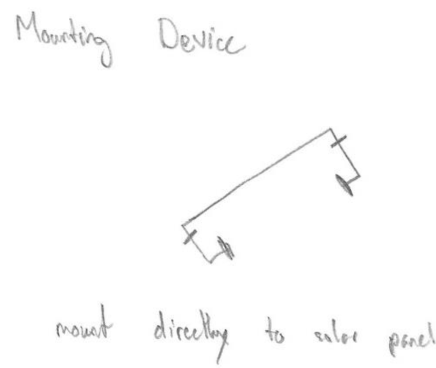


Figure 40: Sketch of Mounting System

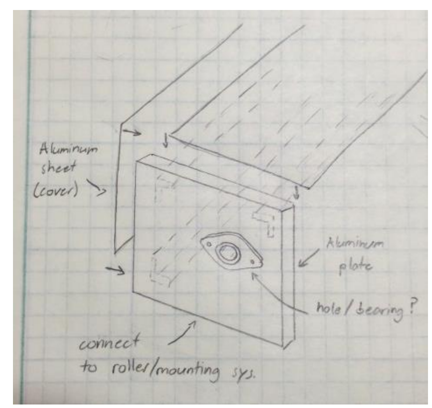
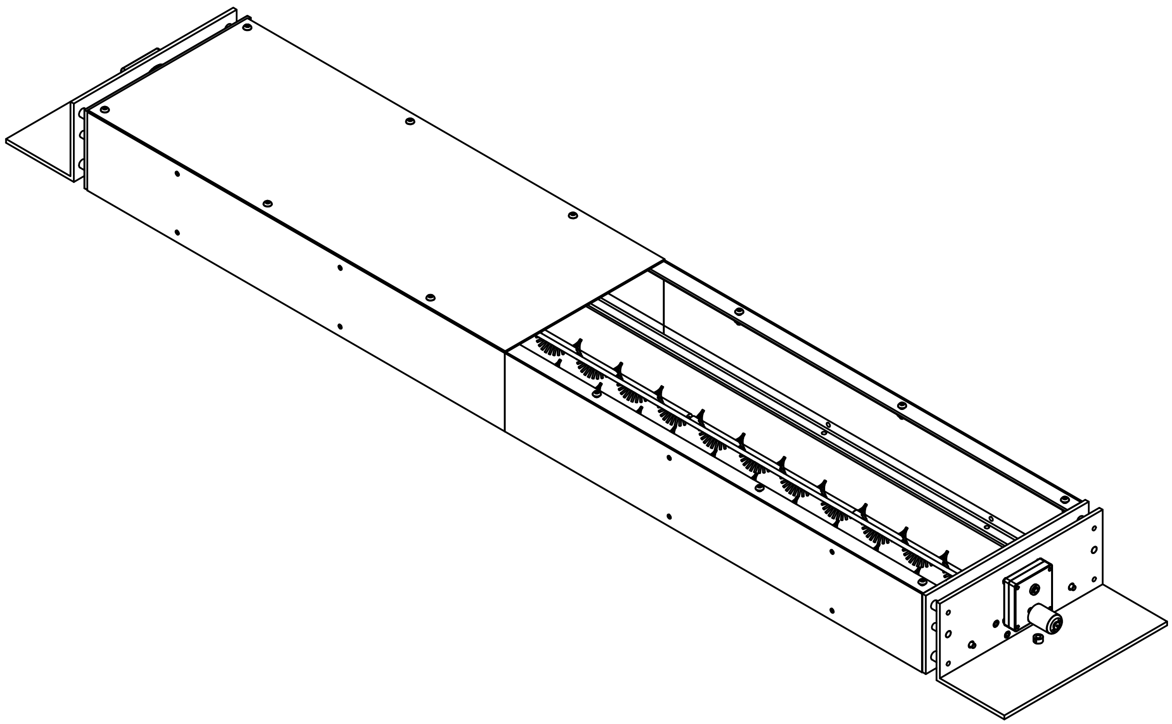


Figure 41: Sketch of Gear System

2 1

B B



One top plate removed to show detail

A A

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Project SPACE
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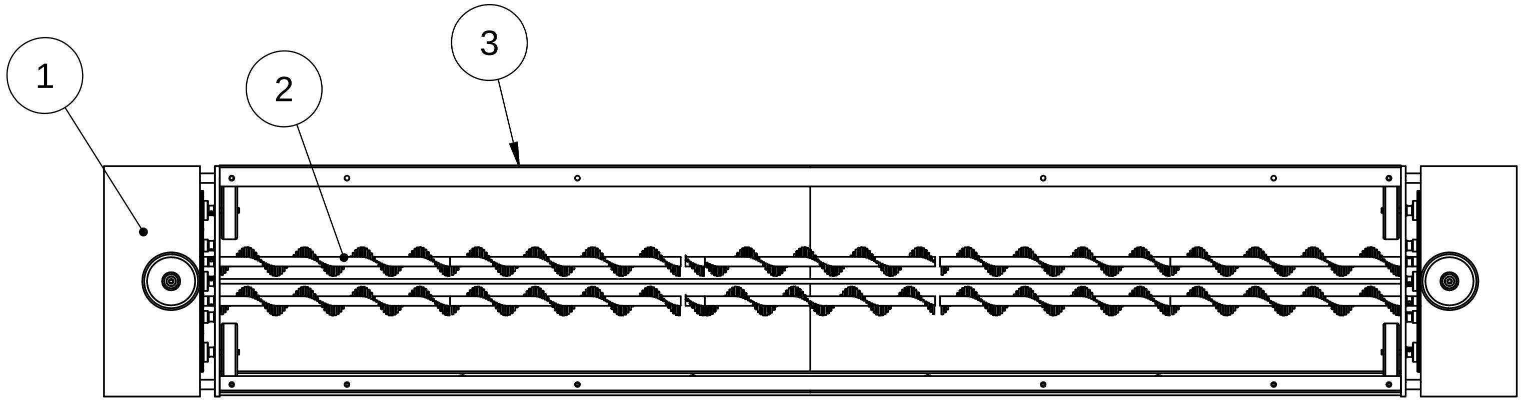
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See Drwg	COMMENTS:			SIZE A — DWG. NO. AS-1 — REV 1
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:10 — SHEET 1 OF 3

2 1

Bill Of Materials

Number	Item Name	Item Number	Quantity
1	Wheel Assembly	WS-1	2
2	Cleaning Assembly	CA-1	2
3	Chassis Assembly	CHA-1	1



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	CHECKED			
	ENG APPR.			MAIN ASSEMBLY
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See Drwg	COMMENTS:			SIZE A · DWG. NO. AS-1 · REV 1
FINISH				
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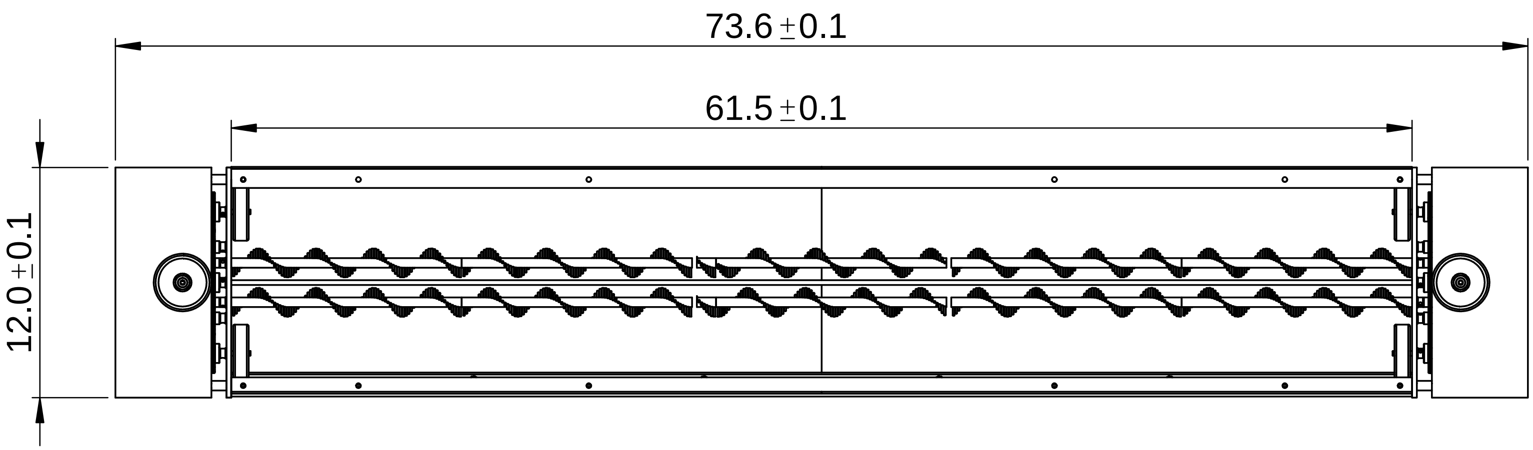
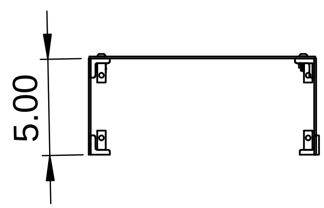
ASSEMBLY DIMENSIONS



Bottom View



Side View

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.0
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL 0±0.05
THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL See Drwg

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	3/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Project SPACE

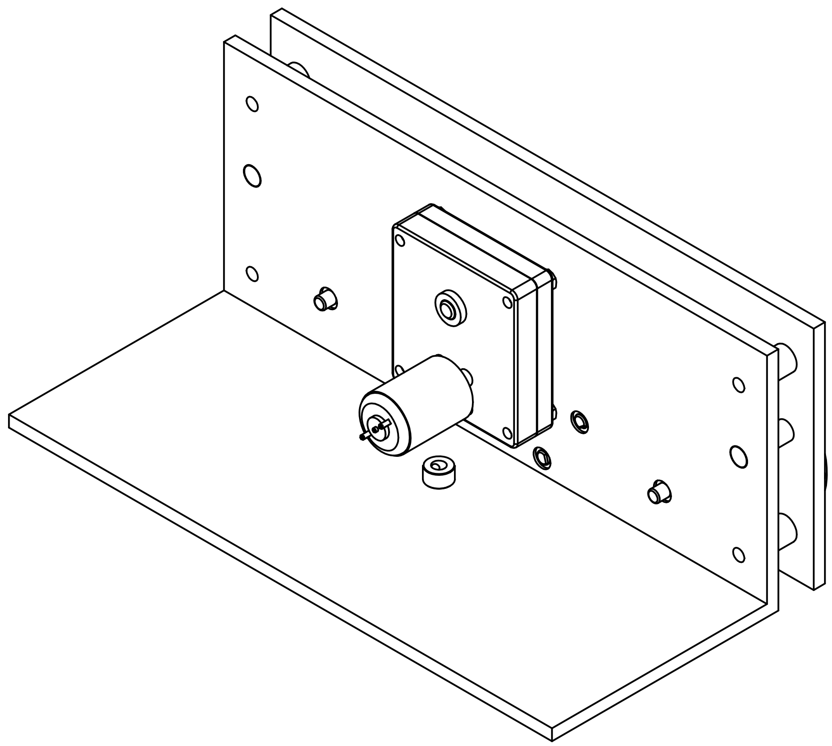
TITLE: MAIN ASSEMBLY

SIZE	DWG. NO.	REV
A	AS-1	1

SCALE: 1:10 SHEET 3 OF 3

2 | 1

B



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	CHECKED			WHEEL ASSEMBLY
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See Drwg	COMMENTS:			SIZE A / DWG. NO. WS-1 / REV 2
FINISH DO NOT SCALE DRAWING				SCALE: 1:3 / SHEET 1 OF 3

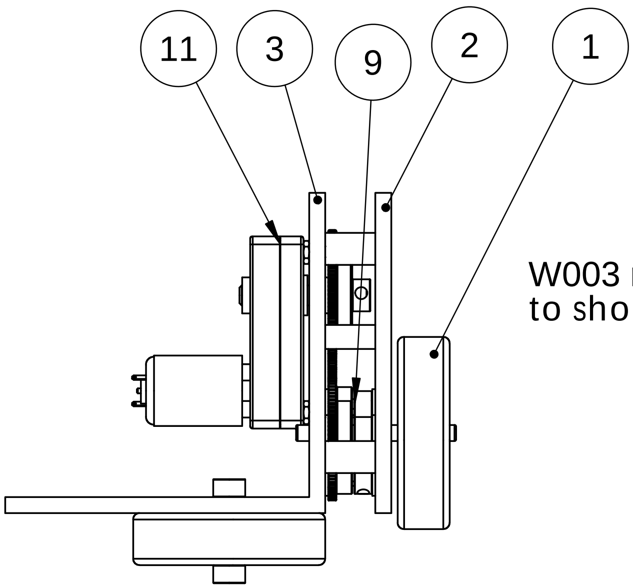
2 | 1

2 | 1

B | B

BILL OF MATERIALS

#	Item Name	Item Number	Quantity	Manufacturer	Manufacturing #
1	Polypropylene Wheels	W001	6	McMaster-Carr	2781T72
2	Aluminum Plates	W002	2	N/A	N/A
3	L Brackets	W003	2	N/A	N/A
4	Shaft 1/4 Steel	W007	14	Servo City	634094
5	Gear 96 Tooth Nylon	W010	8	Servo City	SPBD48-24-96
6	Gear 84 Tooth Nylon	W011	4	Servo City	SPBD48-24-84
7	Gear 32 Tooth Nylon	W012	4	Servo City	SPBD48-24-32
8	Wheel Shaft	W016	6	Servo City	634094
9	1/4 Shaft Collar	W018	15	McMaster-Carr	9414T6
10	3/8" Steel Dowel Pin	W019	4	Servo City	634216
11	Electric Motor	CS001	1	McMaster-Carr	6409K18
12	1/4" -2" SS Bolt	N/A	4	McMaster-Carr	92949A884
13	1/4" Hex Lock Nut	N/A	4	McMaster-Carr	90675A005



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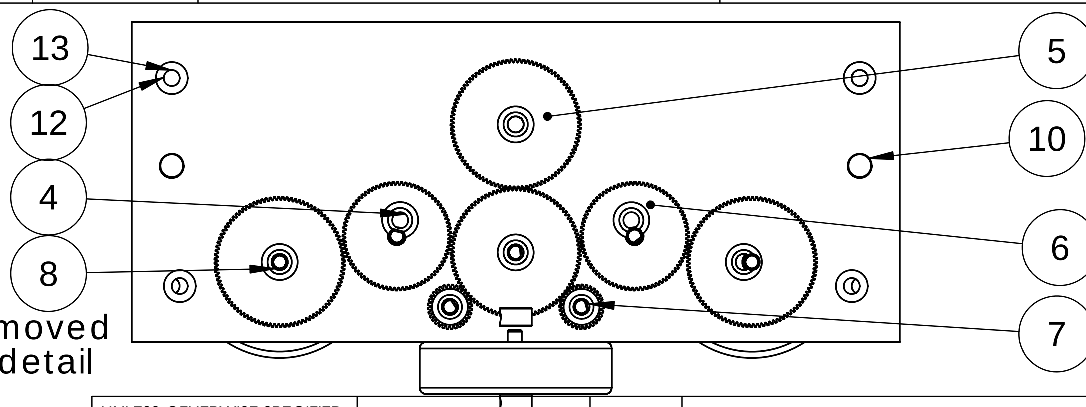

A | A

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	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL See Drwg	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Project SPACE

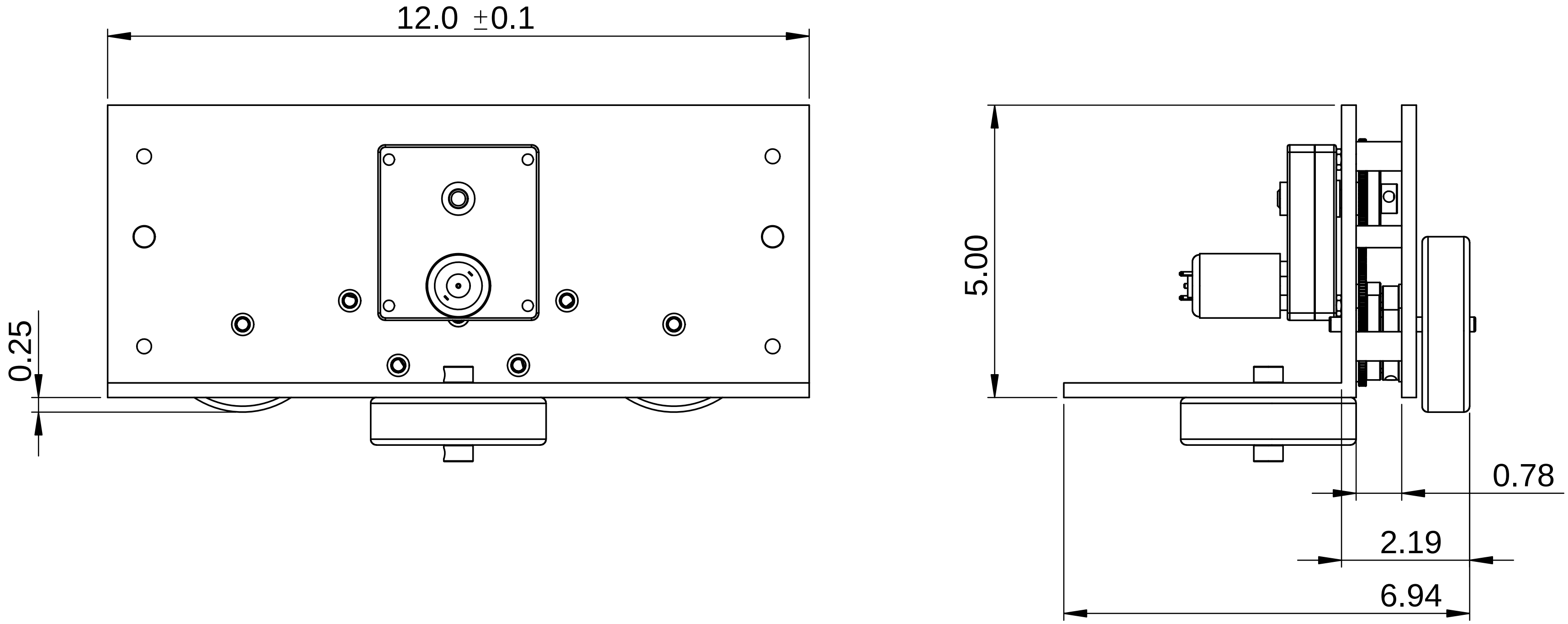
TITLE:

WHEEL ASSEMBLY

SIZE	DWG. NO.	REV
A	WS-1	2
SCALE: 1:3		SHEET 2 OF 3

2 | 1

DIMENSIONS



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Project SPACE
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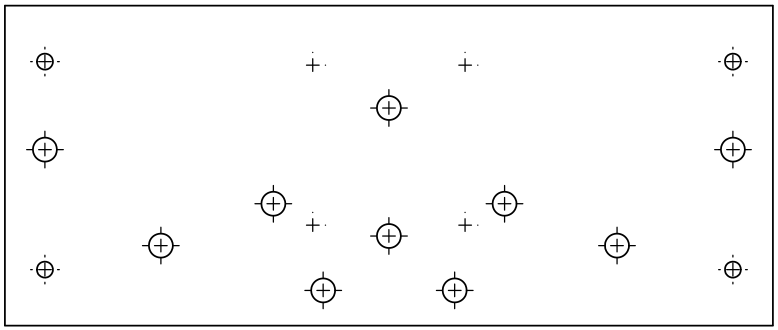
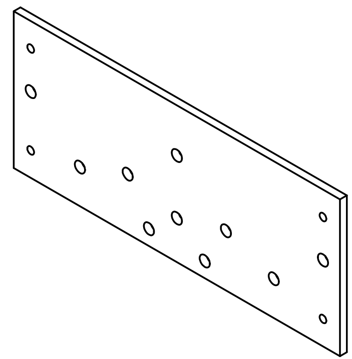
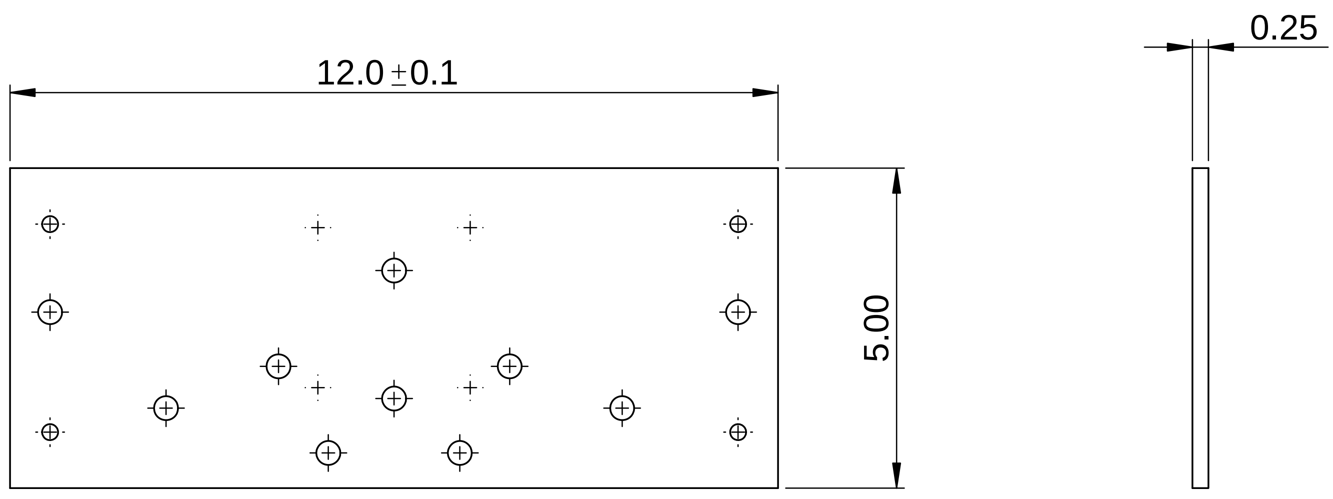
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See Drwg	COMMENTS:			SIZE A · DWG. NO. WS-1 · REV 2
FINISH DO NOT SCALE DRAWING				SCALE: 1:3 · SHEET 3 OF 3





UNLESS OTHERWISE SPECIFIED:		NAME	DATE	Project SPACE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL±0.0 ANGULAR: MACH± BEND ± TWO PLACE DECIMAL 0±0.05 THREE PLACE DECIMAL 0±0.005	DRAWN	EV	2/9/2016	TITLE: WHEEL PLATE DESIGN
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 6061 Aluminum	COMMENTS:			SIZE A · DWG. NO. W002 · REV 1
FINISH DO NOT SCALE DRAWING				SCALE: 1:3 · SHEET 1 OF 3

DIMENSIONS



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.0
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL 0±0.05
THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 6061 Aluminum

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

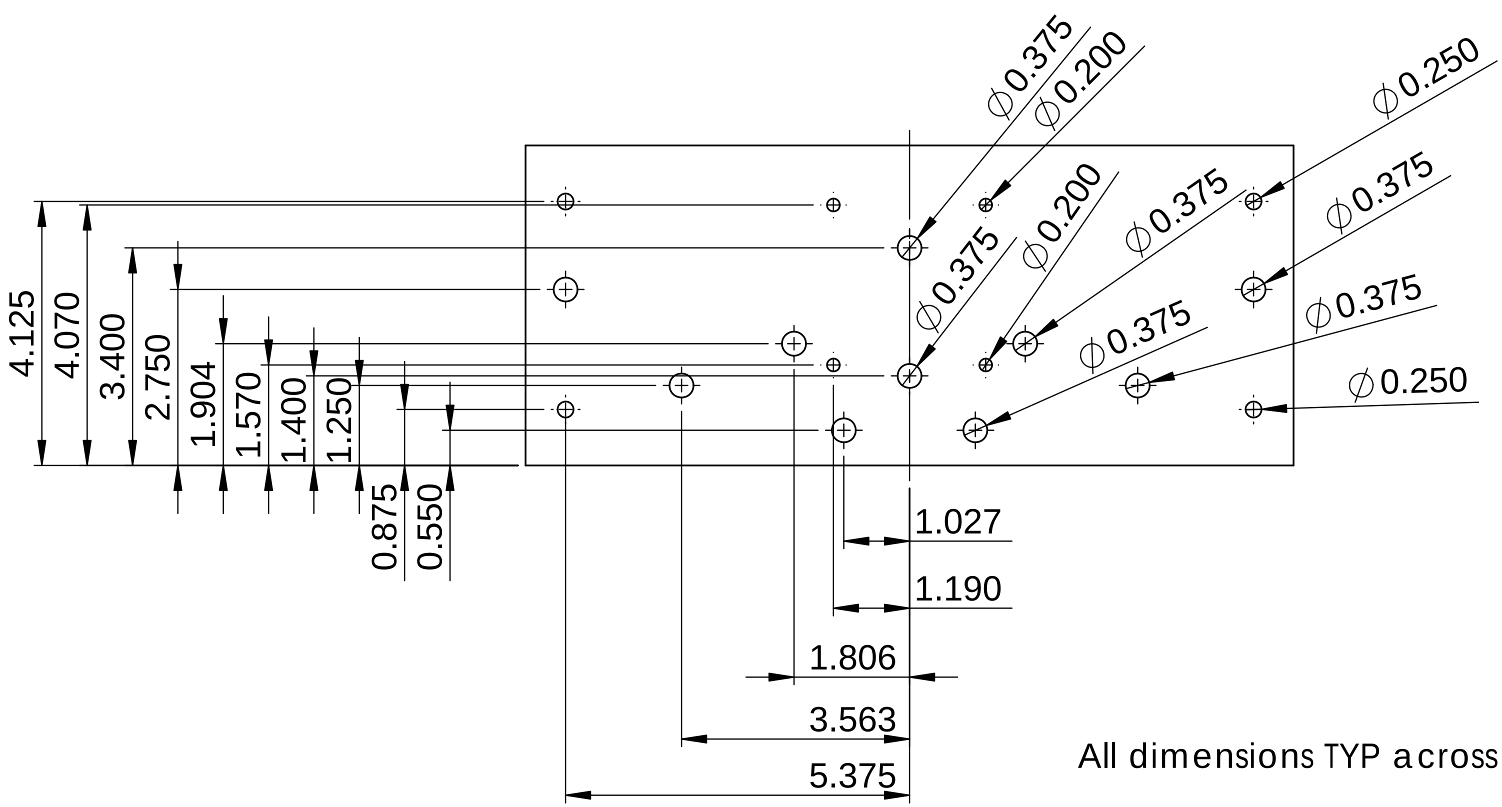
Project SPACE

TITLE: WHEEL PLATE DESIGN

SIZE	DWG. NO.	REV
A	W002	1

SCALE: 1:3 SHEET 2 OF 3

HOLE DIMENSIONS



All dimensions TYP across centerline`

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±0.0
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL 0±0.05
THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 Aluminum

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Project SPACE

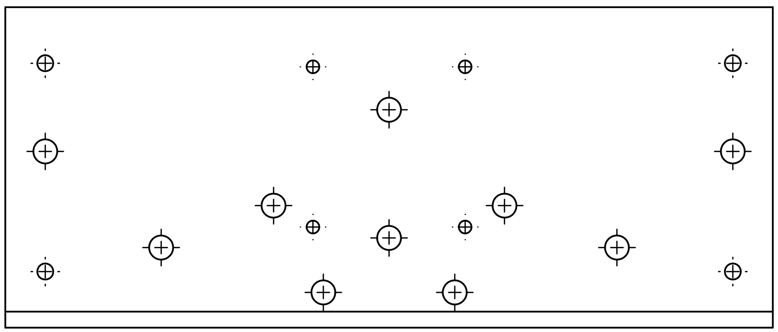
TITLE: WHEEL PLATE DESIGN

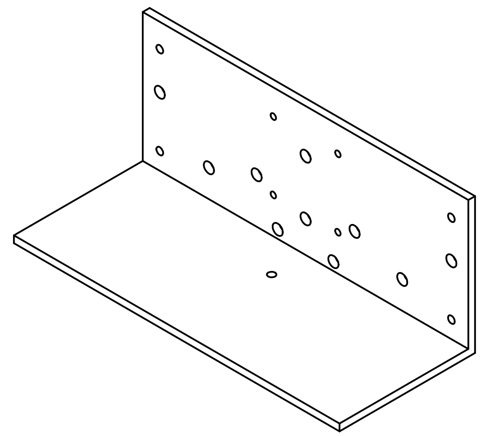
SIZE	DWG. NO.	REV
A	W002	1

SCALE: 1:3 | SHEET 3 OF 3

2 1

B B





A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±0.0
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL 0±0.05
THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 Aluminum

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

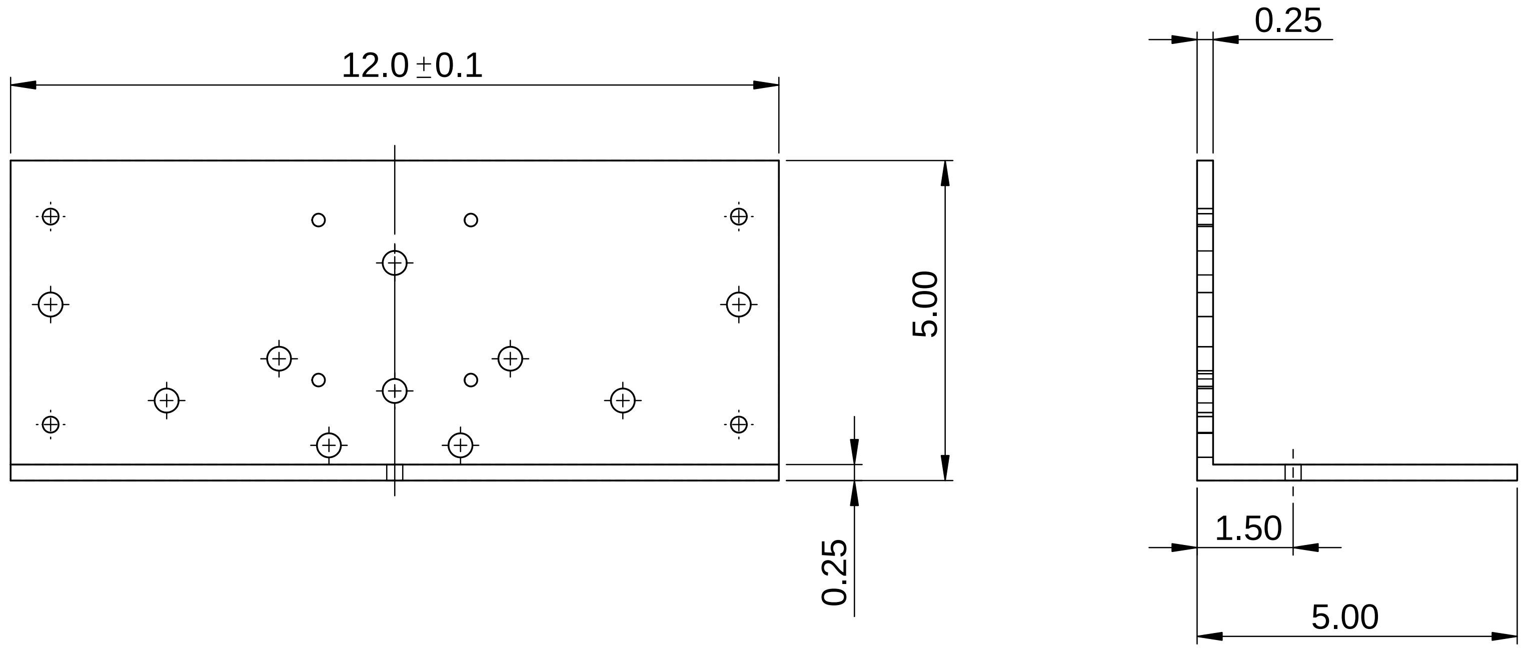
Project SPACE

TITLE: L BRACKET

SIZE	DWG. NO.	REV
A	W003	1

SCALE: 1:3 SHEET 1 OF 3

2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.0
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL 0±0.05
THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
6061 Aluminum

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	2/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Project SPACE

TITLE: L BRACKET

SIZE A | DWG. NO. W003 | REV 1

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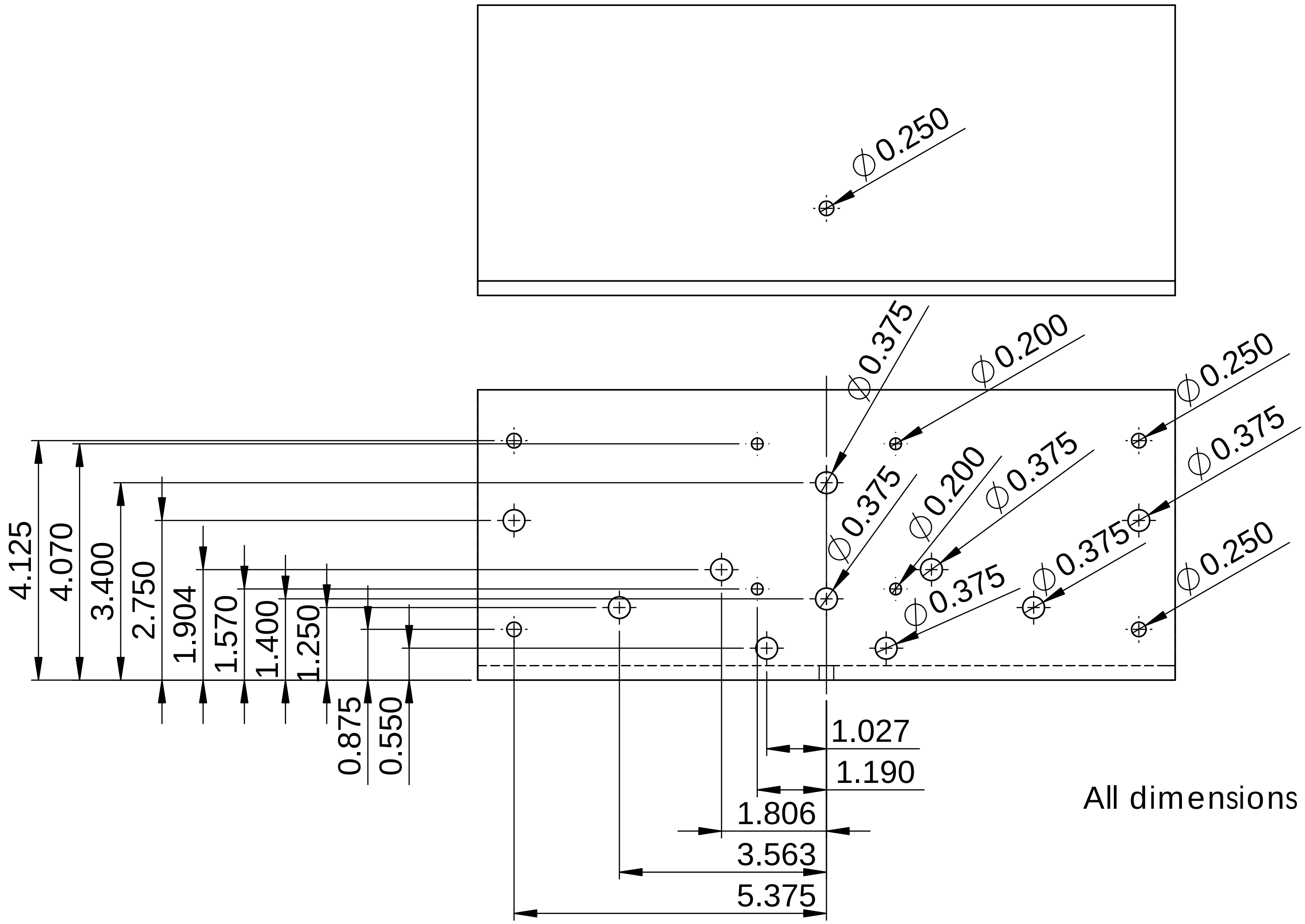

All dimensions TYP across centerline`

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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL 6061 Aluminum	COMMENTS:			SIZE A; DWG. NO. W003; REV 1
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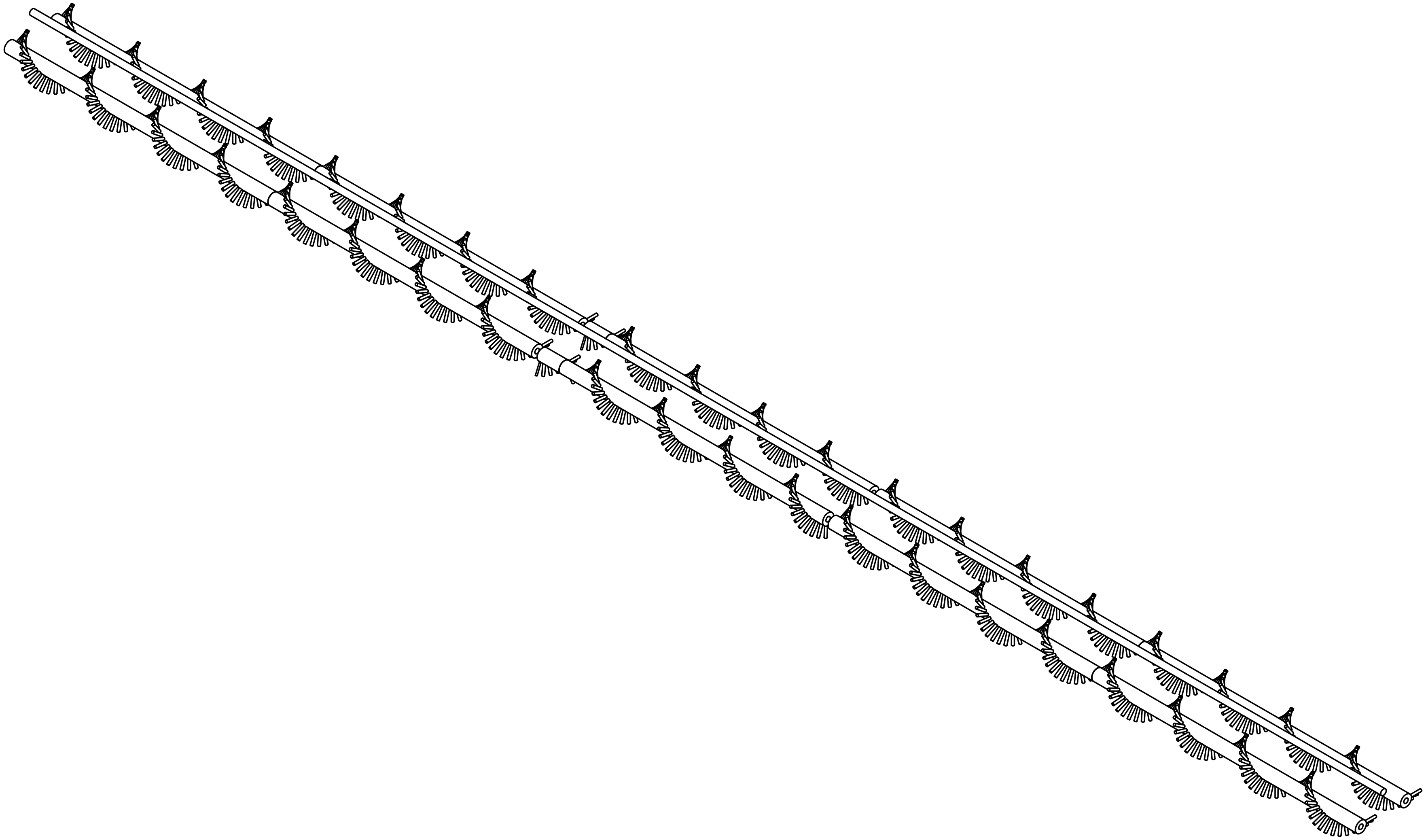
2		1	
B			B
A			A
2		1	



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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See Drwg	COMMENTS:			SIZE A | DWG. NO. CA-1 | REV 1
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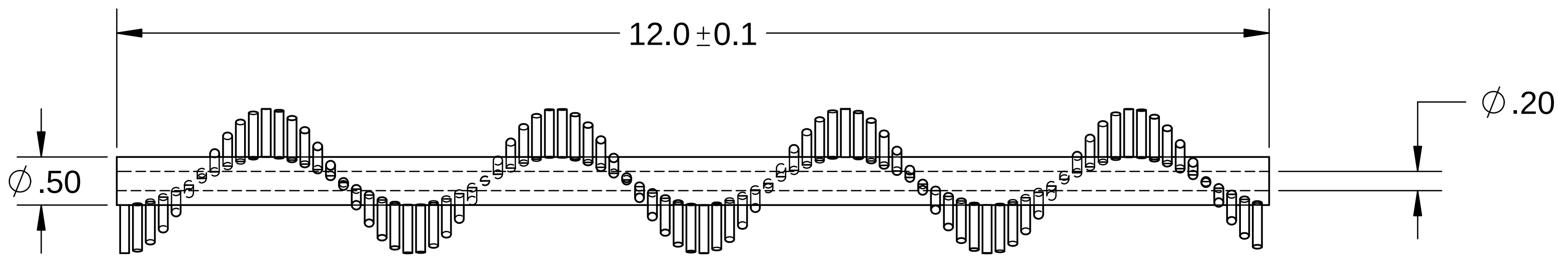

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	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS: ROLLER BRUSH IS MODIFIED FROM HOOVER PART #440006053			SIZE A / DWG. NO. CA03 / REV 1
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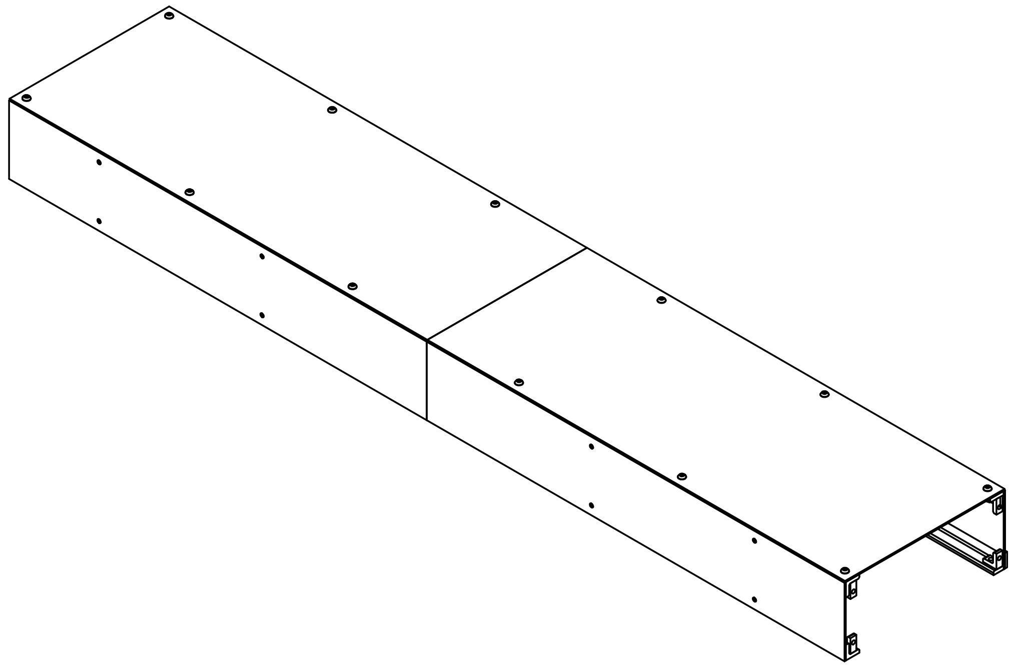
DO NOT SCALE DRAWING				

Standard Views



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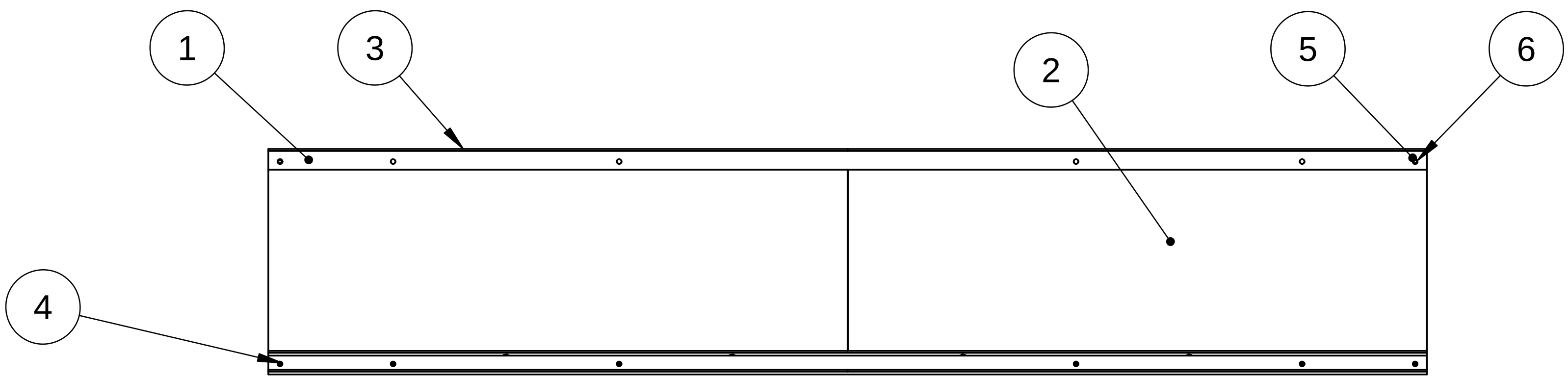
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL See DRWG	COMMENTS:			SIZE A · DWG. NO. CHA-1 · REV 1
FINISH DO NOT SCALE DRAWING				SCALE:10 · SHEET 1 OF 3

Bill of Materials

#	Item Name	Item Number	Quantity	Manufacturer	Manufacturing #
1	Cross-Beam	CH-005	4	N/A	N/A
2	Top Plate	CH-006	2	N/A	N/A
3	Side Plate	CH-007	4	N/A	N/A
4	Bracket	CH-008	8	N/A	N/A
5	1/4" - 1/2" SS Bolt	N/A	28	McMaster-Carr	98164A065
6	1/4" Hex Lock Nut	N/A	28	McMaster-Carr	90675A005



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TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL See Drwg

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DJ	3/12/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Project SPACE

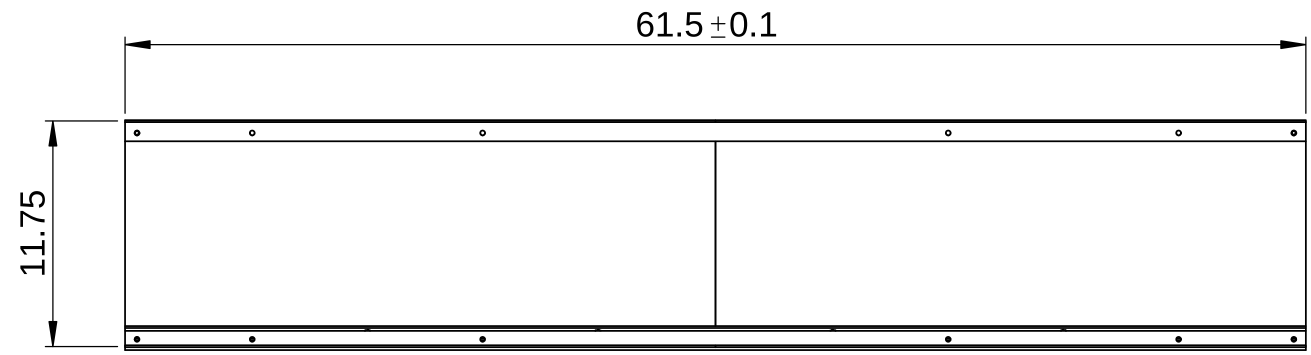
TITLE:

CHASSIS ASSEMBLY

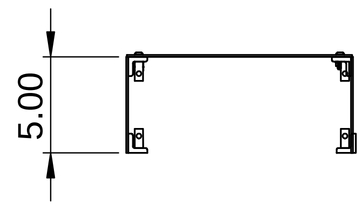
SIZE	DWG. NO.	REV
A	CHA-1	1

SCALE: 1:10 SHEET 2 OF 3

Assembly Dimensions



Bottom VIew



Side View

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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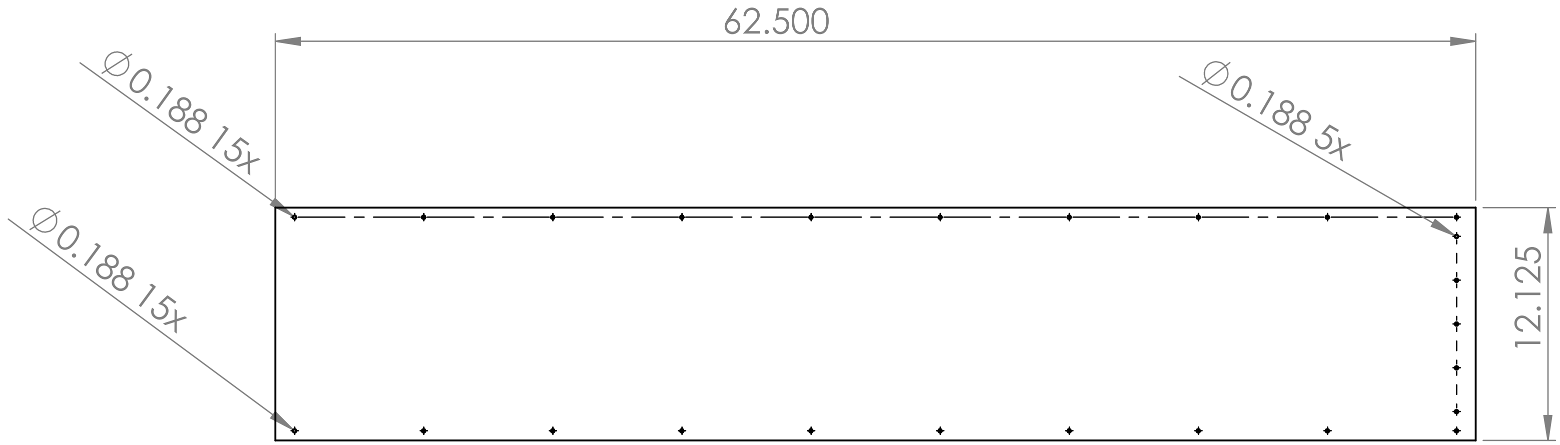
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL See Drwg	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Project SPACE

TITLE:

CHASSIS ASSEMBLY

SIZE	DWG. NO.	REV
A	CHA-1	1
SCALE:1:10		SHEET 3 OF 3



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.0
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acryllic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	EV	5/9/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Project SPACE

TITLE: ACRYLLIC TOP

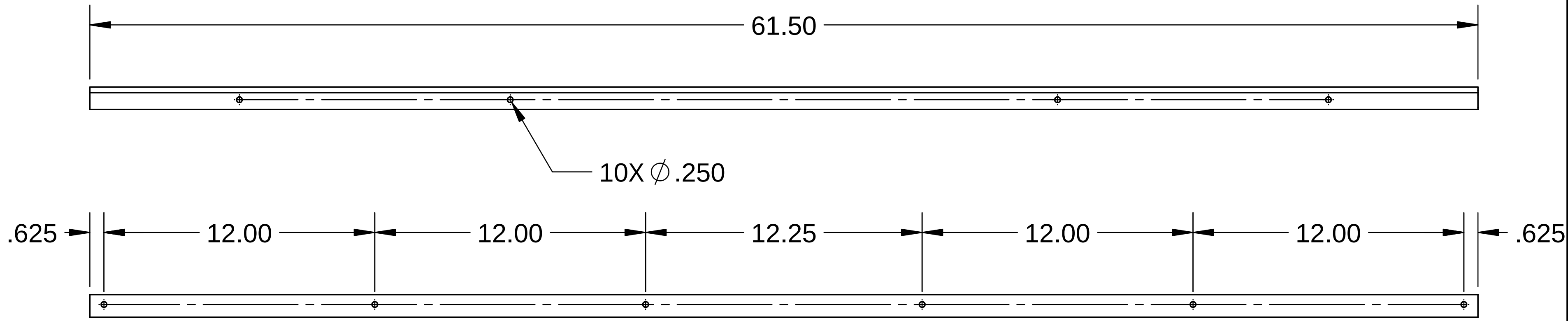
SIZE A

DWG. NO. C003

REV 1

SCALE: 1:10

SHEET 1 OF 2



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THREE PLACE DECIMAL 0±0.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 2021 Aluminum Angle

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	MB	3/15/2016
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

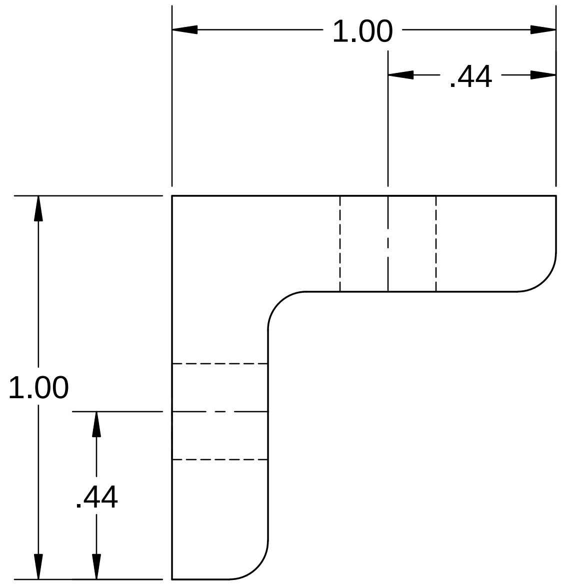
Project SPACE

TITLE:

CROSS BEAMS

SIZE	DWG. NO.	REV
A	CH005	1

SCALE: 1:7 | SHEET 1 OF 2



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	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL 2021 Aluminum Angle	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Project SPACE

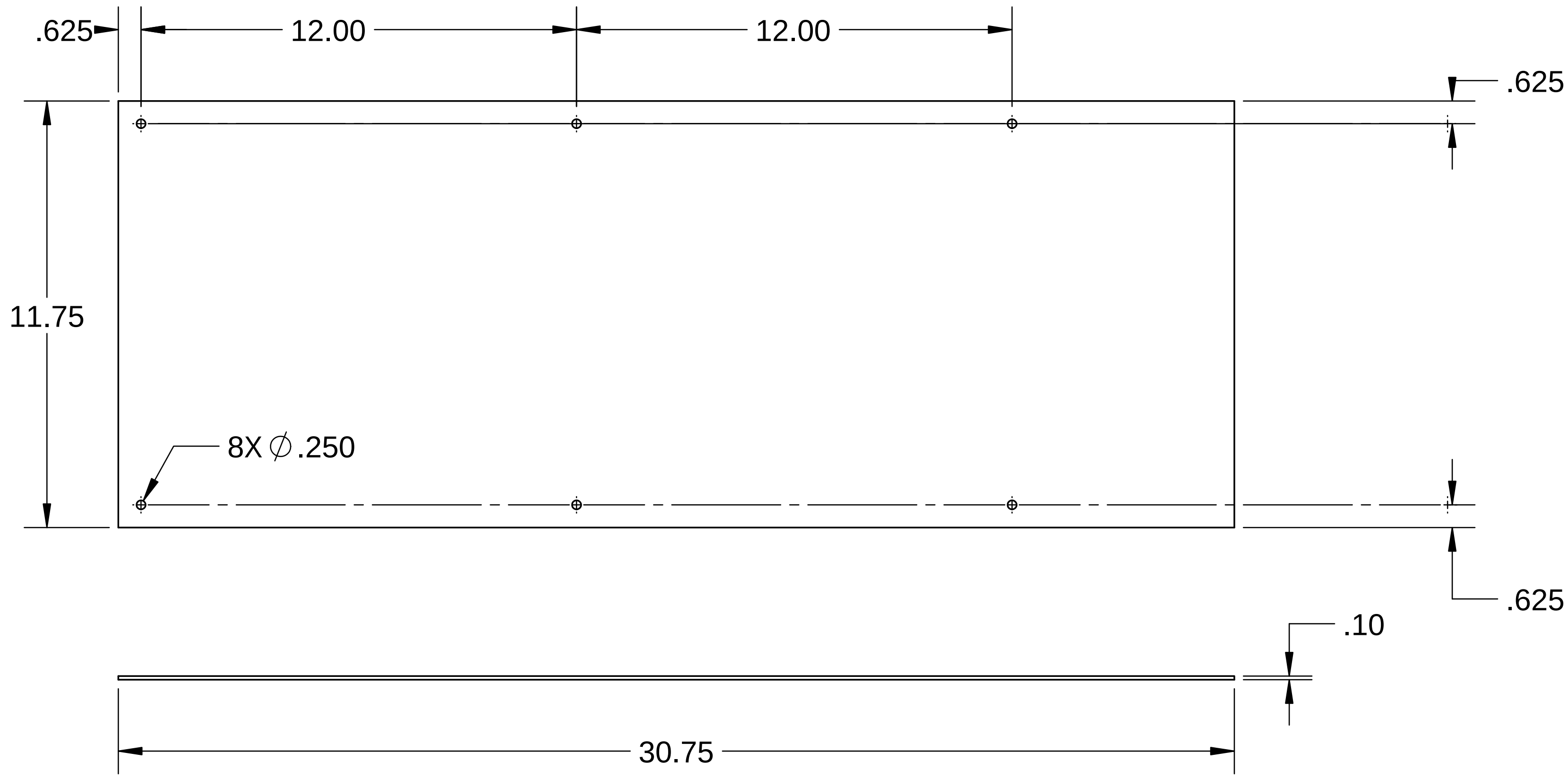
TITLE:

CROSS BEAMS

SIZE	DWG. NO.	REV
A	CH005	1

SCALE: 2:1

SHEET 2 OF 2



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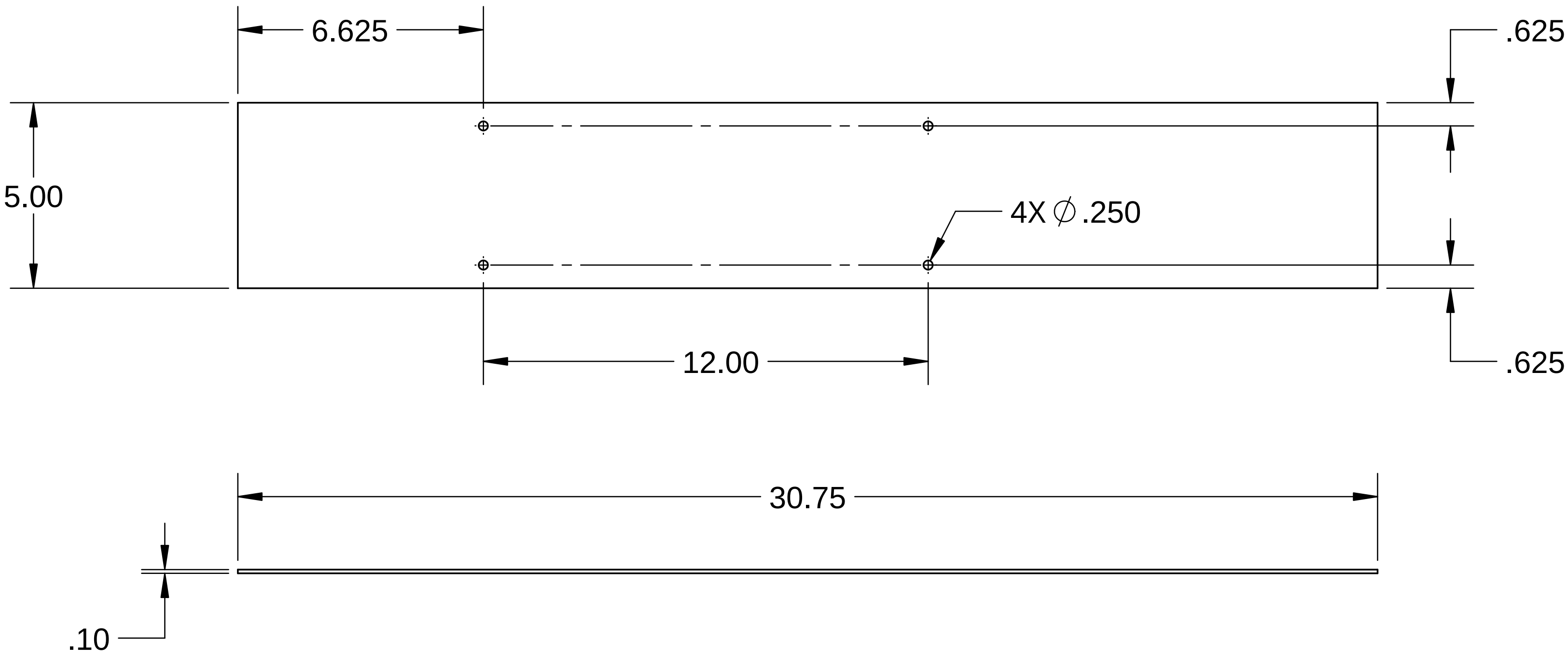
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL Acrylic	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

Project SPACE

TITLE:

TOP PLATE

SIZE	DWG. NO.	REV
A	CH006	
SCALE: 1:5		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
INTERPRET GEOMETRIC TOLERANCING PER:	COMMENTS:		
MATERIAL Acrylic			
FINISH			
DO NOT SCALE DRAWING			

Project SPACE

TITLE:

SIDE PLATE

SIZE	DWG. NO.	REV
A	CH007	1
SCALE: 1:5		SHEET 1 OF 1

Appendix D-1 Product Development Timeline

Table 10: Project Development Timeline

Schedule Item	Description	Due Date	Hard Due Date
FALL QUARTER			
Design Notebook	MECH 194- Have one	10/6/15	
Preliminary Design Concepts	Basic ideas to run by Marks analyze pros & cons of each	10/9/15	
Oral Presentation- MECH 194	Fall timeline, budget, constraints, objectives		10/13/15
Roelandts Grant Application	Grant for Science and Technology	10/9/15	10/15/15
Undergraduate Funding	Give to Marks for revision	10/16/15	10/23/15
Customer Needs Report	Information summary and customer needs/market research report		10/27/15
Explore design concepts	Everyone come up with 3 designs		10/28/2016
Design Ideas	12 Ideas with sketches and brief description (3/person)		11/10/15
Venture Capital Funding	ASME presentation funding pitch	11/14/15	
Safety Review	Review of safety issues related to building, storing, testing		11/17/15
CDR Draft	Submit mock up, design notebooks, review		11/17/15
Design Notebook	Turn in used notebook		12/1/15
Conceptual Design – Oral	10min formal PPT presentation design review		12/1/15
Conceptual Design Report – Written	6-10 page report		12/9/15
WINTER QUARTER			

Begin Detailed Drawings	CAD Drawings for quoting	¼/16	
Begin Initial Prototype	Create first prototype	1/10/16	
Deliver initial prototype	Finish first initial prototype	1/30/16	
Begin main prototype	Full fabrication	2/1/16	
SPRING QUARTER			
Finish Prototype for Testing	Prototype fabricated and ready for testing	4/10/16	
Begin prototype evaluation	Test functionality, etc.	4/10/16	
Ready for Design Presentation	Prototype and testing is done. Presentation Ready		5/6/16

Appendix E-1 Project Budget Breakdown

Table 11: Project Budget Breakdown

Subsystem	**Item**	**Cost**
Power	Energy Storage	$100.00
	Power subsystems	$100.00
Cleaning	Cleaning System	$200.00
	System Housing	$100.00
	Panel Mounting	$250.00
	Cleaning Fluid	$50.00
Control	Controller System	$100.00
	Motor Systems	$300.00
	Gear system	$100.00
	Total:	$1,300.00
Funding Sources	SCU Undergraduate Funding & ASME Venture Capital	$2,100.00

Appendix F-1 Experimental Protocol

Table 12: Experimental Protocol and Results

Elements/Requirements	Location/Time	Equipment	Accuracy	Trials	UNITS	Expected Outcome	Experimental Results	Formula/ Assumptions	Man Hours
Electrical Requirments									
Efficiency Increase	Latimer Energy Labs/ 2:00 Tuesday, Thursday	Solar Panels/SolmetricDevice/ Dirt/Pyranometer	See Attached	50	%	10	3.4 after four passes	Measure MPP	7
Power Consumption	Latimer Energy Labs/ 2:00 Tuesday, Thursday	Multimeter	0.5 % + 3	5	kWh	0.25	Negligible	Measure Voltage and Current used and calculate power	1
Cleaning Effectiveness									
Cleaning cycle time	Latimer Energy Labs/ 2:00 Tuesday, Thursday	StopWatch	0.01 sec	1	sec	180	10	Measure Time to cross Solar Panel Length	0.5
Physical Dimensions									
Size (Length, Width, Depth)	Alviso 430/ 2:15 Monday	Tape Measure	0.0625"	1	m^3	2 x 0.4x 0.1	2 x 0.4x 0.1	Measure Length and Width of Final Prototype	0.5
Weight	Machine Shop/ 2:15 Monday	Large Scale	1	1	kg	30	25	Can balance device on scale or someone can hold it and subtract body weight	0.5
Mode of Operation									
Aesthetics	Alviso 430	NONE		1	Quality	Fair	Good	NONE	0.5
Subsystems Specifications	Location/Time	Equipment	Accuracy	Trials	UNITS	Expected Outcome		Formula/ Assumptions	Man Hours
Maintenance of Cleaning System									
Replacement of Mircofiber Brushes	Alviso 430/ 2:00 Saturday	SPACE Device/Battery Charger	NONE	1	visits/year	1	None Noticed	Continuously run device suspended without wheels touching and check for break in bristles	2
Operation Specifications									
Speed of Cleaning Cycle	Latimer Energy Labs/ 2:00 Tuesday, Thursday	StopWatch/Solar Panels	0.01 sec	5	hr/cycle	1	0.5	Measure time to cross one Solar Panel Width and extrapolate.	1
Speed of Motor	Latimer Energy Labs/ 2:00 Tuesday, Thursday	Stop Watch	0.01 sec	1	RPM	30	30	Calculate using distance traveled and size of the wheel	1
Power Consumption of Control System									
PID Controller	Latimer Energy Labs/ 2:00 Tuesday, Thursday	Multimeter	0.5 % + 3	5	W	6	24	Measure Voltage and Current needed and calculate power usage	1
Supply of Battery (Lithium Ion)	Latimer Energy Labs/ 2:00 Tuesday, Thursday	Multimeter	0.5 % + 3	5	W	60	60	Measure Voltage and Current needed and calculate power usage	1

Appendix G Experimental Data

Appendix G-1 Tigo Energy Data

Table 13: Tigo Energy Full Data

	B1	B2	B3	B4	B5	B6	A8	A9
	Rain Clean (kWh)	Rain Clean (kWh)	Full Clean(kWh)	Full Clean (kWh)	Brush Clean (kWh)	Brush Clean (kWh)	Control (kWh)	Control (kWh)
11/24	0.24592	0.26202	0.26655	0.27078	0.27155	0.27733	0.26945	0.27167
11/25	0.50633	0.53103	0.53867	0.54782	0.54202	0.54107	0.53938	0.53815
11/26	0.59465	0.61783	0.66057	0.6824	0.63858	0.63283	0.59688	0.60092
11/27	0.59703	0.62402	0.66618	0.68387	0.6417	0.63565	0.61253	0.61115
11/28	0.5925	0.61462	0.65458	0.67363	0.62947	0.62432	0.59083	0.59838
11/29	0.59042	0.61052	0.65057	0.66938	0.62552	0.62045	0.58078	0.58808
11/30	0.31992	0.33173	0.34663	0.36018	0.33687	0.338	0.3231	0.32603
12/1	0.55502	0.56688	0.60455	0.6195	0.5789	0.57495	0.55088	0.55028

Table 14: Tigo Energy Averaged Data Average

	B1-2	B3-4	B5-6	A8-9
	Rain Ave (kWh)	Full Ave (kWh)	Brush Ave (kWh)	Control Ave (kWh)
11/24/2015	0.26202	0.268665	0.27444	0.27056
11/25/2015	0.53103	0.543245	0.541545	0.538765
11/26/2015	0.61783	0.671485	0.635705	0.5989
11/27/2015	0.62402	0.675025	0.638675	0.61184
11/28/2015	0.61462	0.664105	0.626895	0.594605
11/29/2015	0.61052	0.659975	0.622985	0.58443
11/30/2015	0.33173	0.353405	0.337435	0.324565
12/1/2015	0.56688	0.612025	0.576925	0.55058

Table 15: Tigo Energy Percent Difference from Control Data (% diff. from control)

	Rain %	Full %	Brush %
11/24	-6.13173	-0.7004	1.434063
11/25	-3.72797	0.831531	0.515995
11/26	1.22558	12.11972	6.145433
11/27	-0.21493	10.32705	4.385951
11/28	1.506042	11.68843	5.430496
11/29	2.744555	12.92627	6.597026
11/30	0.388212	8.885739	3.965307
12/1	1.883468	11.16005	4.784954

Appendix G-3 Solmetric Data Analysis

Table 16: Panel Efficiency Data

Panel 1					Panel 2			
				Control				
Irradiance	time of day	Pmax (watts)	Power/ Irradiance		Irradiance	time of day	Pmax (Watts)	Power/ Irradiance
930	0.5416667	155.8	0.167526882		940	0.54375	152.7	0.162446809
950.5	0.5479167	149.7	0.157496055		944	0.5444444	153.4	0.1625
952.5	0.5479167	149.4	0.156850394		948	0.5451389	153.5	0.161919831
953	0.5486111	149	0.156348374		952	0.5458333	152.6	0.160294118
949.5	0.5493056	147.8	0.155660874		953.5	0.5465278	152.7	0.160146827
949.5	0.55	146.7	0.15450237		949	0.5513889	149.4	0.157428872
945.5	0.5506944	148	0.156530936		947.5	0.5520833	149.5	0.157783641
946	0.5506944	147.5	0.155919662		944	0.5590278	148.9	0.157733051
950.5	0.5604167	145.2	0.152761704		946	0.5527778	148.8	0.157293869
950	0.5604167	145.1	0.152736842		946.5	0.5534722	148.5	0.156893819
953	0.5611111	145.9	0.153095488		943.5	0.5541667	148	0.156862745
953	0.5618056	145	0.152151102		947	0.5548611	148.8	0.157127772
954	0.5618056	145.3	0.15230608		944	0.5645833	147.8	0.156567797
948.5	0.5631944	144.5	0.152345809		940	0.5652778	147.2	0.156595745
952	0.5631944	144.5	0.151785714		940	0.5659722	146.4	0.155744681
949	0.5638889	144.1	0.151844046		940	0.5659722	146	0.155319149
0					940	0.5666667	146.5	0.155851064
Clean Panel					Dirty Panel			
911	0.5993056	137.8	0.151262349		916	0.5965278	121.4	0.132532751
908	0.6	137.6	0.15154185		915	0.5972222	116.8	0.127650273
904	0.6	138.1	0.152765487		915	0.5972222	120.4	0.131584699
903	0.6	136.7	0.151384275		915	0.5979167	118.7	0.129726776
902	0.6006944	136.6	0.151441242		916.5	0.5979167	118.9	0.129732679
902	0.6006944	137.1	0.151995565		916.5	0.5979167	118.9	0.129732679
901.5	0.6027778	137.2	0.152190793		905.5	0.6013889	117.4	0.129652126
899.5	0.6034722	136.7	0.151973319		905.5	0.6020833	117.5	0.129762562
897	0.6041667	137.4	0.153177258		905	0.6020833	117.8	0.130165746
				2 Passes				
Clean Panel					Dirty Panel			
859	0.6222222	133.5	0.155413271		850	0.6243056	112.7	0.132588235
860	0.6229167	134.7	0.156627907		850	0.6243056	114.1	0.134235294
852	0.6229167	133.3	0.156455399		856	0.625	113.7	0.132827103
847	0.625	131.6	0.155371901		845	0.6270833	112.8	0.133491124
845.5	0.6256944	131.1	0.15505618		844	0.6277778	113	0.133886256
844.5	0.6263889	130.9	0.15500296		840.5	0.6277778	112	0.133254015
				4 Passes				
Clean Panel					Dirty Panel			
815	0.63125	125.9	0.154478528		834	0.6298611	114	0.136690647
824	0.6326389	126	0.152912621		837.5	0.6298611	113.8	0.135880597
831.5	0.6326389	128.7	0.154780517		835	0.6298611	114.2	0.136766467
823	0.6347222	126.7	0.153948967		824	0.6333333	112.1	0.136043689
821.5	0.6354167	126.4	0.153864881		822.5	0.6340278	115.6	0.140547112
824.5	0.6354167	127.1	0.154154033		819	0.6340278	112.5	0.137362637

Appendix H Commercialization Report

Department of Mechanical Engineering
Santa Clara University

MECH 194 - Advanced Design I
Fall 2015
Date: June 10, 2016

Solar Panel Automated Cleaning Environment:
Commercialization Plan

Prepared by:
Matt Burke
Ryan Greenough
Daniel Jensen
Elliot Voss

SPACE:
Solar Panel Automated Cleaning Environment
Commercialization Plan

Matt Burke, Ryan Greenough, Daniel Jensen, Elliot Voss

Department of Mechanical Engineering
Santa Clara University
2016

Abstract

The SPACE system is a versatile design with a large potential commercial market. The system is currently tailored for large commercial solar arrays. In time the design could adapted to the residential and solar farm markets, further expanding the number of potential customers. The SPACE system is superior to its competitors, offering a compact design at much more affordable price point. The SPACE system offer users a superior return on investment while eliminating unnecessary hassle.

Table of Contents

1 Introduction

1.1 Background and Motivation

Over the past ten years, the United States has seen a large increase in the reliance on solar power as a source of energy. The United States alone consumes approximately 4,146 terawatts hours a year of electrical energy. Less than 1% of this energy came from solar energy; however, solar energy represents 30% of all new energy generation capacity created every year. California was not only a leading producer of solar power over that span, but was responsible for almost 50% of the total solar power generated in the United States according to the Department of Energy [1].

Because of the increasing demand for solar energy, the efficiency of solar panels is more important than ever. However, solar panels are very inefficient; a typical efficiency for converting solar energy to useable energy is 11% to 15%. The majority of efficiency loss in solar panels is due to the soiling of the panel's photovoltaic cells. This accumulation of dirt on the panels is a well-documented effect that can cause a loss of efficiency as high as 27% annually [2].

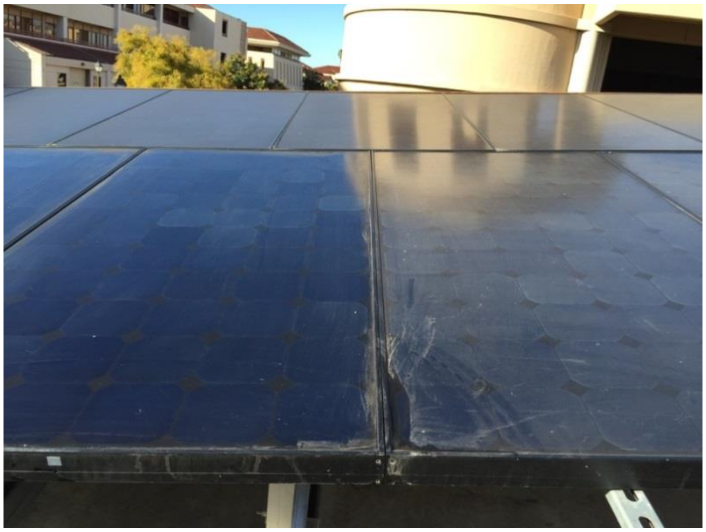

Figure 42: Cleaned panel (left) vs. Soiled panel (right)

Project SPACE is an automated solar panel cleaner that aims to improve the efficiency of existing solar panel arrays. The system cleans the surface of each panel to increase the energy generation. Once implemented on commercial solar panel arrays the system aims to improve each panels' energy production by an average of 10 percent. The system is designed to be implemented on large commercial arrays, but the design is scalable to all manners of solar installations. Besides reducing maintenance costs and improving power production, this system will reduce the need for fossil fuels and reduce the nation's impact on global warming, as well as, eliminate the potential dangers for human cleaners.

1.2 Statement of Purpose

The research gathered on soiling shows that solar panels need to be fully cleaned in order to collect the maximum energy possible. To address this need for a cleaning mechanism, our team has developed an automated cleaning system to maintain solar panels. Our device will boost the efficiency by increasing the energy output of solar panels in a quick and cost-effective manner. The automation of the system will also reduce the risk of an operator injuring himself in a high-voltage environment.

A successful device will clean multiple solar panels in an array and increase their efficiency by at least the same amount that rainfall can. It aims to provide a non-wasteful approach to cleaning commercial sized solar panel systems by using minimal amounts of water and power while requiring little to no maintenance. This system will clean a single row of panels periodically. We estimate the fabrication costs of the final prototype to be approximately $500.

2 Goals and Objectives

The long term goal of this company is to become the primary supplier of automated solar panel cleaning systems in the United States.

The current objective is to establish a foothold in the California solar market. We hope to establish a 30% market share within the next 5 years, before expanding to other regions.

3 Description of Technology

The SPACE system's main advantage is its low cost of fabrication and operation while retaining cleaning effectiveness. The low-impact brush design allows for a thorough clean while avoiding damage to the sensitive photo-voltaic cells.

However, the main draw of the system is its ability to automatically clean the solar array on a programmable schedule. Rather than waiting months between cleans, the system can clean as frequently as needed without human intervention. This saves users the hassle of periodically hiring and allocating time from their schedule for a crew of human cleaners. The SPACE system eliminates the efficiency loss issue for its users, saving them money and allowing them to focus on more important issues.

4 Potential Markets

The main market for current automated cleaning systems are solar panel farms. These farms operate tens of thousands of panels making manual cleaning a logistical nightmare. Thousands of cleaning systems are sold to remedy this issue. Even a single solar farm could require hundreds of systems indicating a large source of potential revenue.

The SPACE is targeted a different market, namely commercial solar arrays. These arrays consist of several hundred panels installed on the roofs of corporate offices and parking structures. Commercial installations represent roughly 30% of current solar energy production within the United States. The smaller nature of these installations has deterred the more expensive cleaning systems which are cost restricted to the larger solar farms. This largely untapped market represents a perfect opportunity for SPACE to enter the industry and establish a foothold. Once SPACE has established itself in the commercial market, the company will have sufficient funds to push into the solar farms as well residential solar markets. From there the company seeks to expand into numerous foreign markets.

5 Competition

The main competition for our device is manual labor and other automated solar panel cleaners. For comparisons between manual labor, automated cleaning competitors, and project SPACE the Santa Clara University garage will be used in order to standardize all cleaning solutions. This array is an example of the commercial market that we intend to market towards excluding residential and solar farm markets. On top of the garage there is an array of solar panels with 39 panels in each row and 32 rows in the full array. The cleaning solutions will be estimated using these specifications

For manual labor since there is very little established standard for the market the cleaners tend to vary from the owner of the solar panels cleaning them to companies that clean panels for a price. This technique tends to have the least up front cost, but could cost more depending on the amount of panels that can be cleaned by a single device. When solar panels are cleaned by the owner the only cost comes from materials which can cost as low as $1/panel. The low cost is balanced by the time expended by cleaning a solar panel which can be several minutes per panel. At two minutes/panel the entire array would take 41.8 hours of work without any breaks. This is an excessive amount of time for one person to spend to clean the panels although the option works better for residential markets.

Getting a service to clean the panels typically costs much more, but can be done much faster with multiple people working. The same amount of time might be spent to clean all of the panels, but more people are sharing the time while the cost per panel is around $7. For the garage example the total cost of cleaning the entire array, each time it is cleaned, is $8736. The high cost of the single clean creates large periods of time in-between cleaning, reducing the amount of efficiency in the panels. The Santa Clara garage solar panel array is cleaned twice a year.

A large concern with using manual labor to clean panels is the risk that is involved with the locations solar panels can be in. The garage panels are placed on a skeleton structure above the top floor, exposed to the ground below. Laborer have to harness in and stand on very tall ladders in order to minimize the liability of the cleaning process as well as risk dropping objects onto the cars below.

The automated solar panel cleaning market is diverse, but not able to be sold in retail situations. For comparisons to project SPACE the Heliotex cleaner and the Ecoppia E4 will be looked at.

Figure 43: Heliotex Cleaner(Reproduced without Permission)

Heliotex is a sprinkler system that can be used with a detergent to regularly clean the panels without contact to the panel itself. Heliotex is the only automated solution found that markets towards US markets, specifically California and Arizona. Heliotex supplied a spreadsheet for estimating the cost of their product for a variable amount of solar panels. For the array on the garage the lifetime cost was $37,440. This number did not vary on length of lifespan as it is dependent on the installation and quantity of the product. The largest cost in the system was from detergent which would be put onto the solar panels and given the location on top of a garage would fall onto cars below.

Figure 44: Ecoppia E4 Cleaner(Reproduced without Permission)

The Ecoppia E4 is a product that moves horizontally across a row of panels with each machine cleaning a single row of panels. Project SPACE operates in a similar fashion without using water. This product though has only been implemented in solar farms in the Middle East and given that its headquarters is in Israel might not extend to the US. The price of installing the device is probably higher than that of Heliotex given the increased complexity of the design and each row requires an individual cleaner.

6 Sales/Marketing Strategies

6.1 Advertising

In order to penetrate the market project SPACE will begin advertising at Santa Clara University accommodating the solar panels that are on campus. Because of the close working relationship this project has with the school it represents a perfect opportunity to cross the "chasm" into the main consumer market. Using the University as a reference project SPACE will be able to advertise to the early majority of the market and gain a larger foothold in the market. Advertising will be to commercial businesses with thousands of solar panels that are arranged in rows between 20-30 panels.

6.2 Salespeople

In the early phases of the advertising plan sales will be performed by the four core members of project SPACE while only relations with the University are necessary. When manufacturing begins more people will be necessary in order to accommodate the growing amount of customers. Predominantly sales will be conducted in the Silicon Valley and central California where there is more particulates in the air meaning more need.

The sales will have to be conducted with clear communication since deals with solar panel owners will range in the tens of thousands of dollars. One device will have to be installed to each row of panels meaning that specifics in number of devices as well as height of the solar panels need to be established.

6.3 Distribution

Project SPACE will be based out of the Silicon Valley, California and will initially only market towards local companies to bring down shipping and traveling costs. Fortunately the Silicon

Valley has a large presence in solar energy generation creating a large market in which to sell to. Project SPACE will adopt a direct marketing approach contacting commercial business and educating them on the benefits of cleaning solar panels. This will create a new for an automated solution to avoid the amount of time needed to clean large arrays of panels in populated areas.

7 Manufacturing Plans

The prototype for project SPACE was entirely developed in the Santa Clara Machine shop by the four members involved in the project which speaks to the simplicity of the design and the ease to manufacture the device. With the initial plan of developing for the school and nearby business project SPACE can be manufactured in the Silicon Valley but should be moved to a cheaper area when larger quantities of the device are needed. While producing for the school no inventory will be kept since the University will be the only client, but when project SPACE expands into the nearby market 50 devices will be kept in inventory. The most complicated section, the gear box, can be kept fully assembled while the chassis is merely L-beams that can be kept at different sizes in inventory and assembled when orders are filled. The prototype for project SPACE was completed in approximately 10 hours of individual work time. This does not include R&D time and time spent learning to do specific machining functions. Completing another so to be ready for inventory would take 4 hours with multiple people working on manufacturing.

In order to begin manufacturing approximately 50 machines will have to be made to accommodate the schools solar panels. This will probably cost $10,000 in order to make the project successful since some of the R&D cost has already been spent. Once successful cleaning is implemented on the University campus project SPACE will expand to other companies in the Silicon Valley and central California with high number of solar panels.

8 Product Cost and Price

The prototype was separated into four main subsystems that were assembled separately and then combined to form the final prototype. The budget for fabrication of the assembly was split into the main subsystems and can be seen in Table 1.

Table 17: Fabrication Cost by Subsystem

EXPENSES				
Category	Description			Cost
Cleaning	Brushes, mounting shafts			$185
Chassis	Aluminum frame connecting the gearboxes			$235
Control	Micro-controller and additional sensors			$57
Gear System	Gears, axles, bushings			$85
	Total Prototype			$562

Table 1 shows the final fabrication cost of the prototype was $562. However, this cost does not include any other considerations that would arise if the product was sold in market such as labor costs, profit margin, and any reduction in cost due to mass manufacturing methods. The amount these numbers factor in is dependent on the quantity of the systems that are created on an annual basis.

As the company breaks into the market, the amount of commercial sized systems that the company has as clients would affect the amount of devices created and the cost of each device. Initially, there may only be one or two commercial sized arrays that would need devices for their campus. An estimate for the number of devices created for each commercial system would be around 32 units.

The retail cost of the system would initially be higher as the company got started. As the demand for the devices rises, however, the retail cost would drop as the company grows in capacity and manufacturing ability. Initially the system would need to be retailed for around $900 per unit. This cost was found by assuming that it would take four hours of labor to manufacture each unit, and each hour of labor was worth $20. The profit margin for a device retailed at $900 would be $258 without including any reduction in material cost due to buying in bulk. The actual profit margin would be around $300. This would be enough profit for the company to survive as it grew into larger markets and increased the amount needed to produce.

The goal for the final retail cost would be around $700. This retail cost would become feasible as more units are produced and the material price for each system drops due to buying in bulk. Additionally, as the company expands to allow for the increase in production, the hours spent creating the device would reduce to two hours which would reduce labor costs and increase the profit margins on a $700 device.

Both retail costs, $900 and $700, would be significantly cheaper than other commercially available solar panel cleaning solutions. The price for the Heliotex cleaner for a commercial system of 32 arrays would by around $35,000. The SPACE Project would cost either $28,800 for a $900 device or $22,400 for a $700 system. The large difference between the cost of Project SPACE and its competitors show its ability to function at a competitive level relative to the more complex and expensive market solutions.

9 Service and Warranties

Project SPACE is being designed to function on a solar panel for 7 years servicing and repairs will have to be performed when the system malfunctions. The parts that Project SPACE predicts to be the weakest are the gears and the brushes. The gears can be replaced by taking one of the outer walls without having to remove any other piece. The gear, plus the axle it sits on can replace the broken gear or axle and the outer piece put back on. The modular design of the brushes mean that each brush can be individually replaced if they break. When one piece malfunctions the device can be taken apart, with the gear box still intact and an individual brush replaced. This repair is more intensive then replacing an individual gear, but each roller brush should last for 10 years of use.

10 Financial Plan and ROI

In order to determine an approximate ROI the Tigo Energy data was used for the amount of energy generated by a solar panel in the Silicon Valley. In the Tigo energy it was found that on average a solar panel would generate 340 kWh per year uncleaned. Data was averaged from previous years using panels that had not been cleaned. This power generation was increased by

12% due to the energy increase found in Figure 7 to assume that a clean panel would generate 380 kWh/year. The cost of electricity in the South Bay Area for commercial establishments is $0.17/kWh and as mentioned above a single row of solar panels on top of the garage has 39 panels.

After calculating the difference of 40 kWh/year for a row of 39 panels the total cost savings is $270.50/year. This number was compared to the initial cost of the prototype in order to find the break-even point of various costs.

Under these assumptions a prototype costing $500 would break-even in less than two years and begin making a profit. It was decided that this would be a good benchmark for how much our prototype should cost given the cost of metal and the size of the initial device design.

This cost analysis does not take into account installation price or maintenance costs which could set the break-even point back slightly, but not significantly given the steepness of the curve.

The initial system costs may require a loan on the part of the customer in order to finance the purchase. However as stated above, it is a relatively short period until the device breakeven in terms of savings.

After our initial prototype construction and initial testing there was an efficiency increase of 3.5% with an estimated cost of $700.

This efficiency increase is much lower than was intended and would reflect poorly on the break-even point of the device.

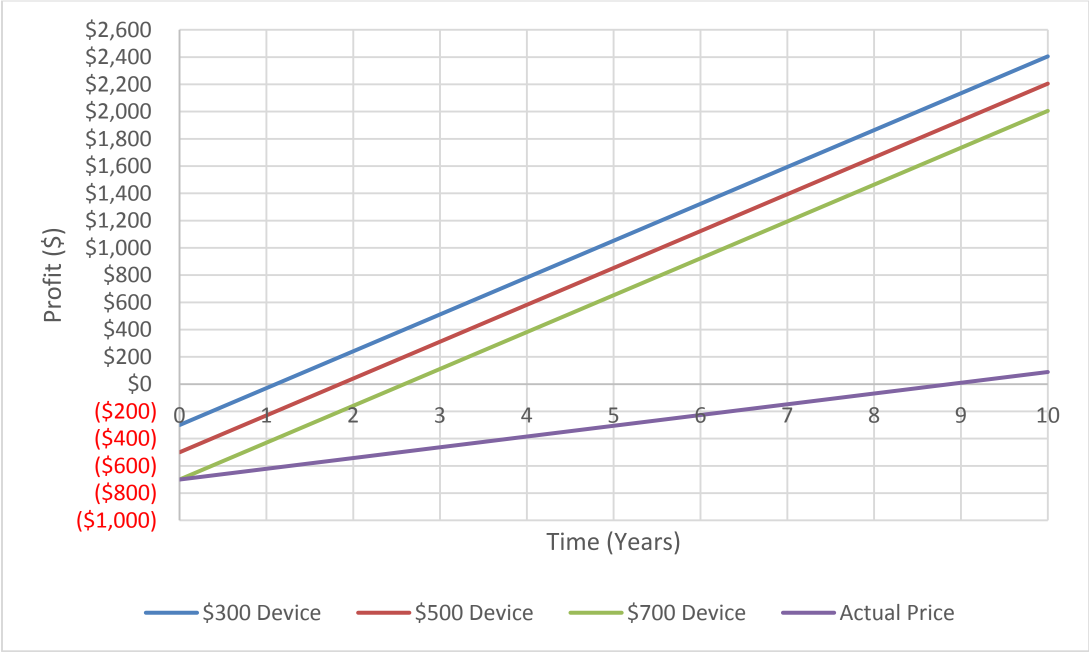

Figure 45: Break-even analysis including the actual price and efficiency of the device

The device would take almost 9 years in order to break even which is unacceptable for our device. A higher efficiency increase per cleaning is being investigated in order to increase the steepness of the profit line. When design modifications are made the actual prototype line should look more like the approximated ROI lines.