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Dual Axis Solar Tracker With Automated Cleaning System

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ENTITLED

TWO AXES OF ROTATION SOLAR TRACKER WITH AUTOMATED CLEANING SYSTEM

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TWO AXES OF ROTATION SOLAR TRACKER WITH AUTOMATED CLEANING SYSTEM

By

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Matthew Kelley, Jonathan Lung, and Brian Weitzenkamp

SENIOR DESIGN PROJECT REPORT

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ABSTRACT

Photovoltaic panels are fundamental in the generation of renewable energy both on a local scale and a utility scale. The mounting systems for such panels can be costly, require large amounts of maintenance, and miss out on energy savings. Manual cleaning and single axis tracking systems leave more to be desired from such systems. In this paper, we propose, research, test and manufacture a two axes solar tracking system with integrated water cleaning to obtain the most energy savings possible from a single PV panel. Our work shows that two axis tracking combined with an automated cleaning system can provide more energy savings compared to a fixed panel system requiring manual cleaning. We have shown technical feasibility of a two axis tracking system as well as demonstrated simple design, testing, and construction of a water based cleaning system using a small water pump and PVC piping. As a result of such manufacturing and in order to improve efficiency, it is our future recommendation to integrate water and electrical home connections, create a customer experience mobile or web based application, and complete large scale long term testing.

Acknowledgments

This thesis is dedicated to our family and friends, for supporting us through all the hours spent researching, interviewing, worrying, designing, manufacturing, and revising our solar tracking system.

We would like to thank Dr. Godfrey Mungal for serving as a secondary reader on this thesis document. Without him, we would not have been able to present this thesis as polished and complete as possible.

The most important thanks goes to our project advisor, Dr. Peter Woytowitz. Without Pete, we would not have been able to identify a clear direction early on in the project life cycle. He is the best advisor a team could ask for, and we hope to have made him proud.

We would also like to thank our department chair, Dr. Hohyun Lee, and the rest of the MECH department for supporting our learning, personal development, and professional growth through our time at Santa Clara University.

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Nomenclature

Symbol	Meaning	Units
Θ	Rate at which the sun moves across the sky	[°/hour]
$\Delta\beta$	Rate at which the actuators can rotate the panel	[°/second]
t	Time needed to articulate the panel in line the sun	[second]
P	Force applied	[lbf]
A	Cross sectional area of the beam	$[in^2]$
M	applied moment	[lbf-in.]
y	Distance from the neutral axis	[in]
I	Moment of inertia of beam cross section	$[in^4]$
LSD	Least Significant Digit	N/A
FOS	Factor of Safety	N/A
U_o	Resolution error	$°C$
$U_{manufacturer}$	Manufacturing uncertainty	$°C$
U_d	Design stage uncertainty	$°C$

Chapter 1: Introduction

1.1 Project Objectives

Our goal is to design the most efficient individual solar panel system we can. We plan to engineer an autonomous solar tracking system to follow the movement of the sun. This system will pivot with two degrees of rotation in order to track the orientation of the sun throughout the day. To further improve the efficiency of the product the team will design and integrate a cleaning system. This independent autonomous apparatus will remove debris that settles on the panel. This will increase the effectiveness of the solar panel while not enhancing the labor required to sustain the panel. This panel is aimed to replace the small-scale static panels standard in off-grid rural settings.

Figure 1 is a detailed computer-aided-design model of the product at the end stage of the design process. These images display the final design the group has selected for the complete system. This report will detail the engineering process that led to this design.

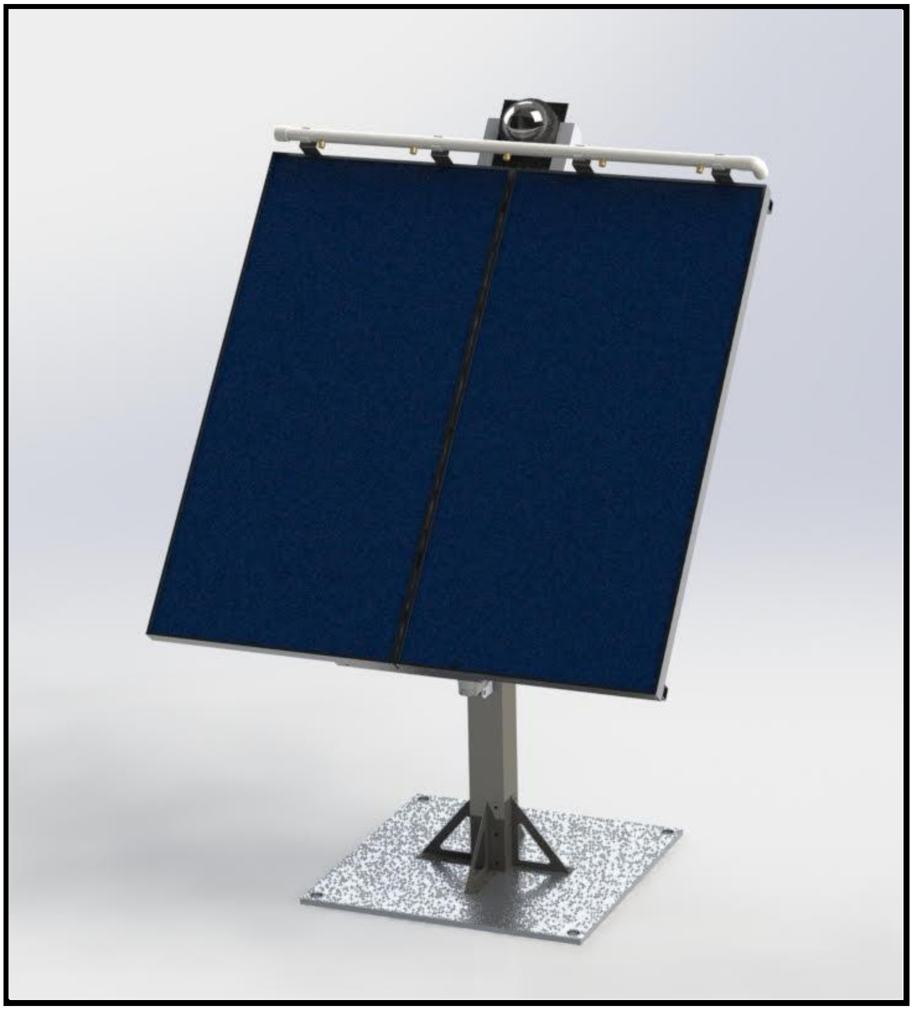


Figure 1: Detailed CAD drawing of solar tracking and automated cleaning photovoltaic panel. The system relies on two separate linear actuators to rotate the panel. In addition, a nozzle-based water cleaning system is shown at the top end of the frame and will sit close to the surface of the panel.

1.2 Concept of Operations

To best grasp the general concept of operations (CONOPS), Figures 2 and 3 below demonstrate the CONOPS for both the tracking and cleaning systems. The panel will tilt using the two linear actuators to point perpendicular to the oncoming solar rays. An automated cleaning system will clean the panels of dust, dirt, and debris on a regular schedule to maintain the maximum efficiency of the panels.

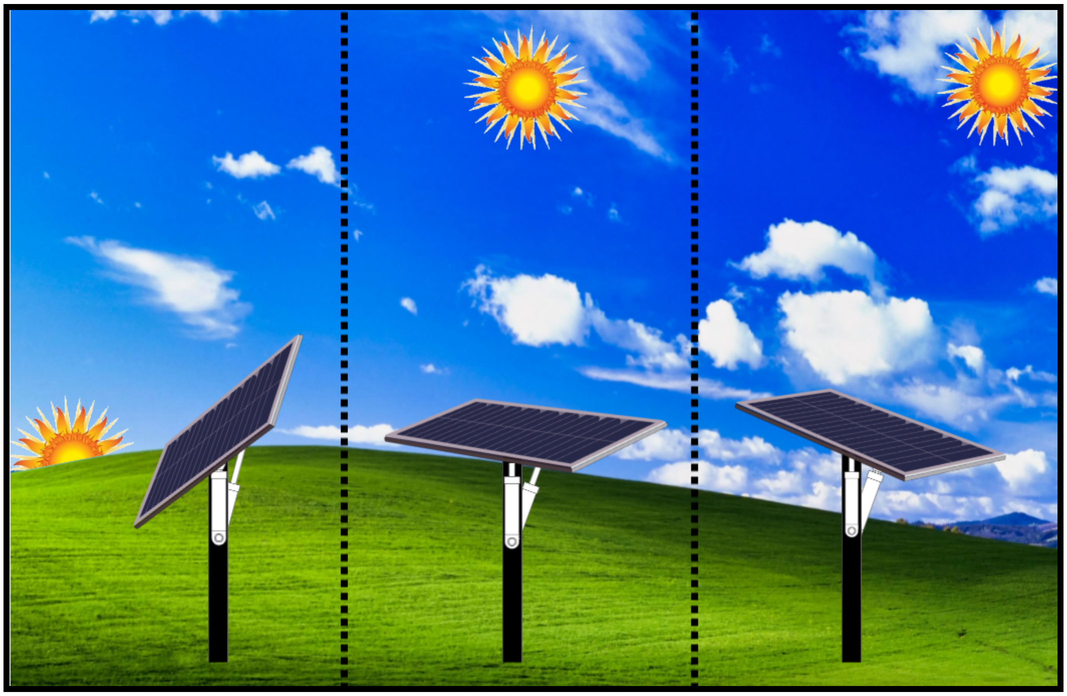


Figure 2: Concept of Operations for tracking system. The panel is shown following the location of the sun in order to maximize energy capture.

Figure 3: Concept of Operations for cleaning system. The panel is shown in a fixed position for demonstration purposes.

Chapter 2: Systems Level Analysis

2.1 Customer Needs

In order to best determine the needs of our potential customers, we conducted interviews with stakeholders. By translating customer interviews to technical terms, we were able to set target specifications for the project. We included Santa Clara University faculty members, engineering industry professionals, and local homeowners in our group of stakeholders. The interviews resulted in an unprocessed raw set of needs, often not in technical terms. This raw set of customer needs was converted into a technical hierarchy of needs as seen in Table A1 in Appendix A. Furthermore, we then developed the five most relevant customer needs (CN 1-5). The interviews with faculty and an engineering professional resulted in the development of CN 1-2. The most important feedback from homeowners included CN 3-5. See Appendix B for full interview information.

Table 1: Highest importance customer needs. For additional details and supporting needs, see Appendix C for full hierarchy of customer needs. These customer needs were determined through interviews with relevant stakeholders.

Customer Need	Description	Notes/Measure of Effectiveness
CN 1	Easy to integrate with current infrastructure	Usage of standard water hookup, 110V standard home power.
CN 2	Little hands-on maintenance is required	Components are well protected from the elements.
CN 3	Easily Programmable by consumer	Cleaning system can be set on the desired schedule.
CN 4	System is a good investment	Tracking + Cleaning yields a net positive boost to solar efficiency.
CN 5	System is easy to understand	Feedback to the user should be concise, measurable, and comparable to a reference value.

2.2 Product Specifications

Based on the aforementioned research, certain product specifications have been deemed viable as expectations for our product. Below in Table 2, the initial target product specifications are shown, each ranked with importance. The most important targets have been highlighted in green.

Table 2: Comparative table displays ranges and target values for product comparison. Importance is as follows: 1 is most important, 5 is least important.

Importance	Metric	Units	Target	ECO-WORTHY Solar Tracking	PST-2AL Dual Axis Tracker
3	Apparatus height	ft	5	6	N/A
2	Power output	W	Any panel	Any panel	85m^2 panels
1	Efficiency gain	%	20	10-25	40-45
1	Manufacturing cost	USD	Subj.	Subj.	Subj.
1	Sale price	USD	2000	590	N/A
4	Customizability	Subj.	Battery, 4 panels/100W-400W	4 panels/100W - 400W	N/A
3	Wind speed resistance	ft/s	30	N/A	154
4	Weight capacity	lb	300	N/A	N/A
3	Material corrosion resistance	Subj.	Paint/Aluminum	Powder coat/galvanize	MAC Steel
4	Installation time	min	60	60	Professional
4	Time for maintenance	min	20	N/A	N/A
4	ROM	degree	-60 - 60	270	0-60
5	Actuation Type	Subj.	Actuator	Actuator	DC motor
5	Control System	Subj.	Raspberry Pi	Proprietary	Proprietary
2	# of axes	Subj.	2	2	2

Table 2 above shows the target aspects for our proposed solar tracker as well as specifications from two other companies that produce similar concepts. The basic importance of each metric was also recorded in the left column on a scale from one to five, with one being most important. We compared our proposed design to the two researched solar trackers expanded upon above: the ECO-WORTHY Solar Tracking, a consumer-grade product, and the PST-2AL Dual Axis Tracker, a commercial-grade product. Using information gathered from these two designs, we were able to pinpoint certain aspects that we had originally overlooked in our initial design, such as wind speed resistance and customizability. Furthermore, this comparative table helped us consider changing certain aspects of our proposed project to better fit what is needed in the existing market. During design considerations, a design matrix was also employed to further assess the viability of the features on our system. More consideration of each subsystem will be presented in the following chapters

2.3 Comparing 1 Axis of Rotation, 2 Axis of Rotation, & Benefits of Cleaning System

In order to finalize the direction and design of our project, more research was conducted to analyze the efficiency gains of single-axis rotation, double-axis rotation, and cleaning systems. Five different designs for 2-axis solar trackers were researched. One such tracker is the ST-2AL Dual Axis Tracker from Sun Action Trackers, which features both wide vertical and azimuthal angles [1]. Two of which are products currently available on the market, the remaining 3 designs are from scholarly articles that give an overview and analysis of the proposed design. These five designs are listed as references [1]-[5]. It should be noted that none of these designs include automated cleaning, possible designs for this will be discussed later. The research was then organized in tables and then an informed decision was made by the team on the direction of the project. A summarization of the research conducted is presented in Table 3 below and the full list of articles read can be found in Appendix D.

Based on our research, a system using two axes of rotation and an automated cleaning system was chosen. This combination maximizes the efficiency of a solar panel which is our main project goal. Dual-axis rotation systems see an efficiency increase of 25% - 40% and cleaning systems limit the losses by .005% per day or an average efficiency increase of 17.5% over time.

Based on these criteria of dual-axis rotation and automated cleaning the subsystems of structure and actuation, automated cleaning, and electrical and solar array were created. The design and selection process is outlined for each of these subsystems.

Table 3: Existing research pertaining to current market offerings, as well as research conducted with various tracking methods. This research drove the initial concept generation phase of our product.

	Energy and Efficiency	Tracking Methodology	Takeaways
ST-2AL Dual Axis Tracker from Sun Action Trackers [1]	- Energy generation up to 40% - 45% more than fixed-tilt systems and has more than 40,000 units across the country.	Uses magnesium alloy-coated (MAC) steel for the frame as well as a screw drive and a linear actuator to control the rotation of the axis. The linear actuator allows 0° - 60° of tilt around the horizontal axis and the screw drive allows 0° - 270° of rotation around the vertical axis.	- This product has many design attributes that could be beneficial to us. - The general components are a good starting point for us. Steel or aluminum tubing for the overall structure as well as either actuators or motors to control the direction of the axis.
ECO-WORTHY Solar Tracker [2]	- The site claims a 10% - 25% increase in energy capture compared to a fixed panel.	This design uses two linear actuators to control the axis of rotation. The system tracks the sun by using four smaller solar cells positioned in each quadrant. The product has a maximum load of 330lbs, rated power of 8-25V, max load current of 6A, and operating temperature of -40 ~ +85℃.	- Linear actuators are cheap, durable, and can withstand high loads. This will likely limit the vertical axis rotation, however. The way this product approaches the problem of tracking the sun is interesting but can be approved upon.
Effective and Low-Cost Arduino based Dual-Axis Solar Tracker [3]	- Uses light-dependent resistors (LDR) in a closed loop system to track the sun. This in conjunction with geographical data and	Small scale solar tracker controlled by an Arduino Uno. Tracking utilizes equations and functions based on geographical data	- Inner workings and control systems needed for a tracker but much improvement could be made to the physical design. - This could be of use with an

	equations could be an effective and cheap method to track the sun.		active tracker to have redundancies and methods to check the accuracy of the tracker.
Primary-Secondary Configuration for Dual-Axis Solar Tracker [4]	- This is an example of an active solar tracking system. Article discusses a type of configuration called primary-secondary configuration.	- This method includes one “primary” device that has a microcontroller and actively tracks the sun. There is then one or more “secondary” device(s) that have no controller but only mimic the movements of the primary device.	- Flow charts for a proposed tracking system may be helpful in understanding what is necessary to construct such a system. The proposed method of primary and secondary devices is also something we may consider as a possible option for our project. If our product was to be implemented on a large scale a system like this would be beneficial to the end user.
Design and Performance Analysis of a Dual Axis Solar Tracker [5]	- This article tested a 20W solar panel and found a 37.76% increase in power and used LDR’s to actively track the sun.	This design used gears and servo motors to control the axis of rotation. The paper also included a detailed circuit diagram.	- The design uses few parts which is helpful when considering cost and manufacturing ability but has aspects such as the axis control that could be improved upon.

2.4 Description of Finished Product

The completed solar tracking project will mechanically track the position of the sun and autonomously clean a 200W photovoltaic panel area. Tracking the sun will maximize the panel efficiency while following a set cleaning schedule will reduce energy lost to debris build up on each 42.4” x 40” x 1.4” panel. The main frame of the tracker will be constructed with 6061 aluminum and 1020 steel. Aluminum is implemented for the members in motion to reduce mass and minimize the force required to move. Steel is used for the main upright and hinges to maximize strength and rigidity. The connections between members will be bolted using various fasteners.

Linear actuators will maneuver the panel with two axes of rotation to track the movement of the sun. The maximum loading of the purchased actuators is 1320 lbf and a stroke length of 200 mm. Using these actuators, a range of motion of 35° - 102.5° (measured from the vertical plane) is possible for the North-South axis and 35° - 290° (measured from the vertical plane) is possible for the East-West axis.

This autonomous cleaning system is composed of ¾” standard PVC piping, spray nozzles, as well as various standard connections and tubing. The nozzles are spaced every 12’’ across the panel. The system will be pressurized by a 12V water pump such as the Thermomate 12V DC Diaphragm Water Pressure Pump, purchasable from Amazon. This configuration should be able to sufficiently clean the panels.

The solar tracker will utilize a series of four photo resistors to maneuver the panel and follow the sun. A module with four photoresistors located on a plane separated by perpendicular barriers will execute this process. The panel will first orient itself with solar and geographic information. This photoresistor solution was devised to fine tune panel position and maximize efficiency. As the sun shifts the barriers will cast a shadow on the photoresistors. This will initiate a control system to reposition the panel to remain perpendicular to the sun.

The electrical system is composed of photoresistors, actuators, water pump, relays, and energy conversion hardware. The two solar panels will feed a 700W DC/AC inverter and a charge controller which will charge a 12V battery. Users will be able to monitor the status of the charge controller and the inverter through the Renogy app for live-feedback. The battery is to represent the typical home-use case where a battery bank stores charge during solar hours, later to be used during the night. The photoresistors work in conjunction with the linear actuators and Raspberry Pi 4 to correctly position the system such that it is always facing the sun for maximum power generation. The Raspberry Pi is to be programmed such that it periodically checks the voltages of pairs of photoresistors and adjusts the system such that it moves towards the side with least resistance (stronger sunlight). The program will utilize flags to activate the cleaning system if the required criteria are met, and will aim to return the solar panel to a base position at the end of each day.

2.5 Project Budget and Return on Investment

Table 4 below details the cost breakdown of our project. Out of the total $3,000 allocated, approximately $1,400 was spent towards manufacturing the project. Extraneous items and tools have pushed the total expenditure to $2,300. Much of the remaining funds were used for testing subsystem configurations and also extra material in the event of mishap. To put the manufacturing cost into perspective, our sale cost was set to $2000, which equates to roughly 42.8% profit per unit.

Table 4: Breakdown of budgeting for sourced parts.

Part	Source	Qty.	Quantified Cost
CanaKit Raspberry Pi 4 Starter PRO Kit	Variable	1	$130.00
Renogy 100W 12V Compact Panel	Renogy	2	$196.00
Renogy 700W Inverter	Renogy	1	$146.00
Renogy Rover Elite 20A Charge Controller	Renogy	1	$130.00
Mighty Max Battery Mighty Max SLA Rechargeable Sealed Lead Acid 12180 Backup Power Batteries	Lowe's	1	$69.00
200mm Linear Actuators	Amazon	2	$110.00
Wiring Kit	Amazon	1	$19.00
Battery Cables	Amazon	1	$18.00
Nuts/Bolts	McMaster	4	$130.00
Max 31855 Thermocouple amplifier/signal converter	Adafruit	1	$15.00
Water Pump	Amazon	1	$60.00
Thermocouple	HGSI	2	$88.00
Thermal Adhesive Tape	Amazon	1	$16.97
JBtek 4 Channel DC 5V Relay Module	Amazon	2	$16.00
Monitor	Best Buy	1	$145.00
Aluminum Tubing	McMaster	1	$157.50
Acrylic Dome	McMaster	1	$15.59
Flat Spray Nozzle	McMaster	6	$107.08
Photo resistors	Adafruit	4	$3.80
Solar Panel Y Splitter/Extensions	Amazon	1	$41.97
Pipe Fittings	Home Depot	1	$202.75
Solar Shield Coating	DK Hardware	1	$36.48
CanaKit 3.5A Raspberry Pi 4 Power Supply	Amazon	1	$9.99
Rosin Core Solder	Amazon	1	$17.99
Adjustable Elbow	Home Depot	1	$5.97
Double Sided Tape	Home Depot	1	$6.88
3D printer filament	Dynamism	1	$44.99
SD Cards	Amazon	1	$17.99
Shipping/Tax		1	$344.80
			Total Cost
			$2,302.75

Chapter 3: Actuation and Structure

3.1 System Overview

The actuation and structures system encompasses the mainframe, linear actuators, and serves as the mounting structure for the rest of the solar tracker and the ground. Responsible for the reliable and accurate movement of the solar panels, it must be strong enough to support the weight of the panel, resist wind load, endure time exposed to the elements, and house the components of the other subsystems. The actuators must be able to respond to input from the tracking system in order to follow the sun, as well as communicate with the raspberry pi system for easy systems integration.

The decision matrix shown in Table A1 in Appendix A used a scale from 1-5 in a range of categories and a weighted version of the ranking system. Cost, simplicity/maintenance, manufacturability/project integration, integration with existing PV systems, durability, and ground footprint were all considered. These criteria were derived from information gathered from customer interviews, scholarly research articles, and intuition on the overall project integration. The end result showed that a dual linear actuator system was the optimal solution. This solution resulted in the highest score for both the weighted and unweighted decision matrix results.

3.2 Final Design

To best meet the needs of our system, a dual linear actuator combination was selected. The movement is driven by two 12V, 200mm stroke length linear actuators, with one for each axis of movement. The decision to use actuators as opposed to other forms of movement was made based on the fact they are widely available, can provide highly accurate and repeatable movement, and eliminate the need for more complex mechanisms. Simplicity can often be the best path forward. One drawback of the linear actuators is their limited range of motion, particularly in the E-W directions. Figures 4, 5, and 6 below show the final CAD rendering, as well as a close-up view of the E-W hinge, and N-S linear actuator.

Figure 4: CAD rendering of the final actuation and structure subsystem. The actuation and structure subsystem is responsible for movement of the panel, as well as supporting the weight of the panel and system components in addition to serving as a mounting point for these system components.

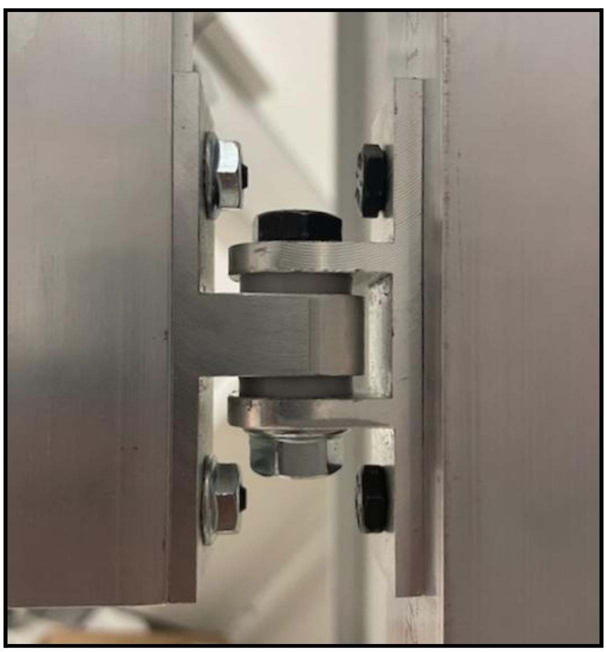


Figure 5: Close-up view of the E-W hinges connecting N-S frame to the solar panel mount. Hinges were manufactured in the SCU Machine shop under the supervision and guidance of Rodney Broome.

Figure 6: Close-up view of the N-S linear actuator attached directly to the upright post. This linear actuator is responsible for movement along the N-S axis of rotation.

The linear actuators were designed to articulate the panel in each axis independently. This allows for the panel to move along the North-South (N-S) axis separately from moving along the East-West (E-W) axis. One linear actuator is connected directly to the upright post, allowing for movement in the N-S directions, and the other actuator is connected to an offset L-bracket allowing for movement in the E-W directions. The linear actuators provide a range of motion of 35° - 102.5° (measured from the vertical plane) for the North-South axis and +47° - -47° (also measured from the vertical plane) for the East-West axis. In summary, the linear actuators provide the necessary articulation based on directions from the Raspberry Pi4 system and the upright post provides necessary structural support and mounting opportunities for the electrical and other system components.

Chapter 4: Automated Cleaning System

4.1 System Overview

This subsystem's goal is to provide effective cleaning of the PV panel in order to mitigate the losses due to dust and dirt accumulation. Components of this subsystem could include pumps, hoses, fittings, brushes, motors, as well as a frame and associated hardware to mount all the components. This subsystem will need to be integrated with the electrical subsystems as pumps and motors will need power to run as desired. A control system will be needed to control when and for how long this cleaning system will operate. This subsystem may also have to be integrated with the structures and actuations subsystem. One of the major problems associated with this subsystem will be the challenging integration of the designed components with the rest of the subsystems. For example, if a water-based cleaning system is to be used – the electrical system will need to be designed to resist contact with water. Nominally, this system should be able to clean the PV panel effectively to 95% of its rated power and be able to be operational without maintenance for 1 year.

4.1.1 System Design Selection

Brush System - This system uses a rotating brush as the main mechanism to remove dirt and debris from the PV panel. Aluminum L-channels provide a frame and a surface for rollers to register in order for the brush to move along the surface of the panel. Motors and belts control the movement and rotation of the brush

Wiper System - This system uses the same L-chanel and roller design as the brush system but utilizes a squeegee as the means of cleaning. This system is designed to not need water for cleaning purposes

Sprinkler System - This cleaning system intends to utilize the force of gravity to clean the panel. By rotating the panel with the sprinkler side up water is evenly applied to that side of the panel. Due to the angle the water will naturally cover the entire panel as it flows across the panel.

The Sprinkler System will be attached onto the frame structure securing the panel to the rest of the device.

Moving Sprinkler System - The Moving Sprinkler System will incorporate two rails with rollers mounted on them powered by servo motors. The System will begin at one edge of the PV panel and slowly roll to the other edge as it applies water cleaning the panel.

4.1.2 Decision Matrix

Assembling a decision matrix allows the group to make an analytical comparison between the four cleaning subsystem design sketches. The four systems were judged on a scale from 1-5 in six criteria selected specifically for this subsystem. The Decision matrix and Criteria descriptions can be found in Appendix A as Table A2. Overall, the Sprinkler System arose as the optimal solution based on this decision matrix and will be the design we continue with.

4.2 Final Design

The cleaning system is responsible for reducing the accumulation of settled debris on the panel from long term environmental exposure. One of the major priorities for this subsystem was to reduce the associated costs as much as possible so the overall product cost does not exceed the level that customers would be willing to pay. Thus, the selected design was chosen to be simple utilizing relatively inexpensive components that are easy to work with. The water-based nozzle cleaning system was selected to best meet the needs of the system. Figure 7 shows the overall design when it was initially assembled and attached to the rest of the system.

Figure 7: Cleaning system attached to the final system prototype during testing.

The main run of tubing that runs along the top edge of the panel is constructed out of PVC pipe and necessary fittings to equally space nozzles across the panel. PVC piping was selected as it is widely available, easy to work with, and has numerous fittings to allow for the necessary customization. Pressurized water is pumped through five equally spaced nozzles along the top of the panel at various angles to maximize coverage. These nozzles are attached using PVC T-joints with brass reducers allowing for rapid exchange of different nozzles for testing and maintenance purposes. Figure 8 shows the system components and the attachment method for the nozzles.

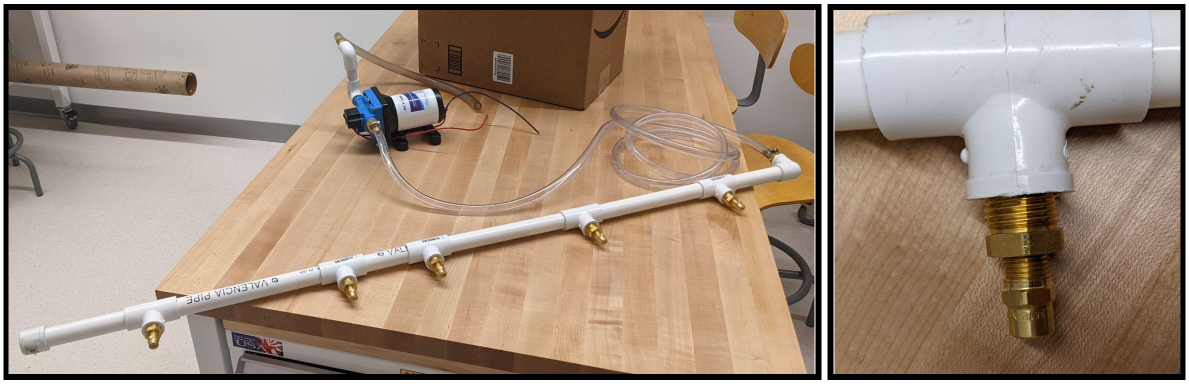


Figure 8: Cleaning system components (left) and nozzle attachment method (right). These include SFDP 1/2-30-55-42 pump, five brass nozzles, and various forms of tubing. Not pictured is the reservoir used for the system testing.

All of these nozzles are brass flat spray nozzles specified to 0.5 gallons per minute at 55 PSI or 0.3 gallons per minute at 20 psi. On each of the panel edges, 80° nozzles are used to minimize the amount of water wasted by spraying off the panel. The other three nozzles spray at a 120° angle to ensure that the whole panel is by a spray of water. Figure 9 shows the spray pattern of this suite of nozzles. To improve the effectiveness of the water spray system, a ceramic coating is applied to the panel to limit debris from sticking strongly to the panel's surface. This coating allows for water to flow more readily across the panels and release the stuck debris.

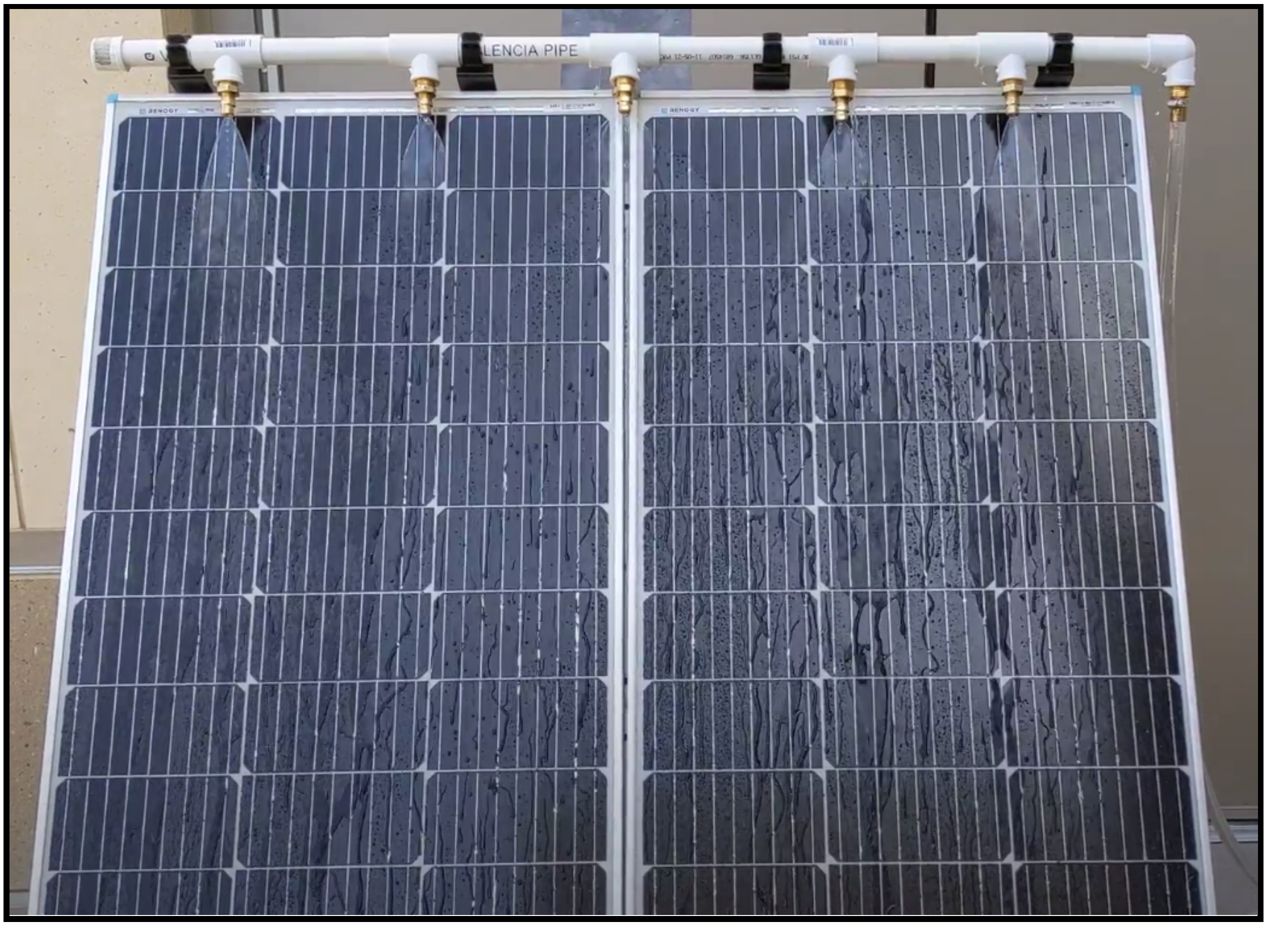


Figure 9: Cleaning system nozzle spray pattern. This was conducted during an initial testing run to observe the real-world spray pattern.

To carry the water that the nozzles will spray, flexible tubing is used to maintain the moving functionality of the rest of the system. Connected to this flexible tubing is a 3 gallon per minute pump rated for 55 psi with 9.8 feet of head. This pump is explicitly chosen to provide moderately high pressure while maintaining the 12-volt restriction of the rest of the system. With this configuration, the system is targeted to run at 1.6 gallons per minute at 35 psi. The pump performance curve is shown in Figure 10. This pump is chosen because it provides a sufficient head for the numerous fittings required for the rest of the system, in addition to providing the required flow rate at a pressure that the nozzles are designed to work best at. Regardless though, the pump is not a significant design element as in a final product connected to existing infrastructure, the cleaning system would be connected to the existing water system on-site. The pump was chosen to imitate city water systems while providing the flexibility needed for mobile testing. To carry water for this test, simply a five-gallon bucket is used as a reservoir.

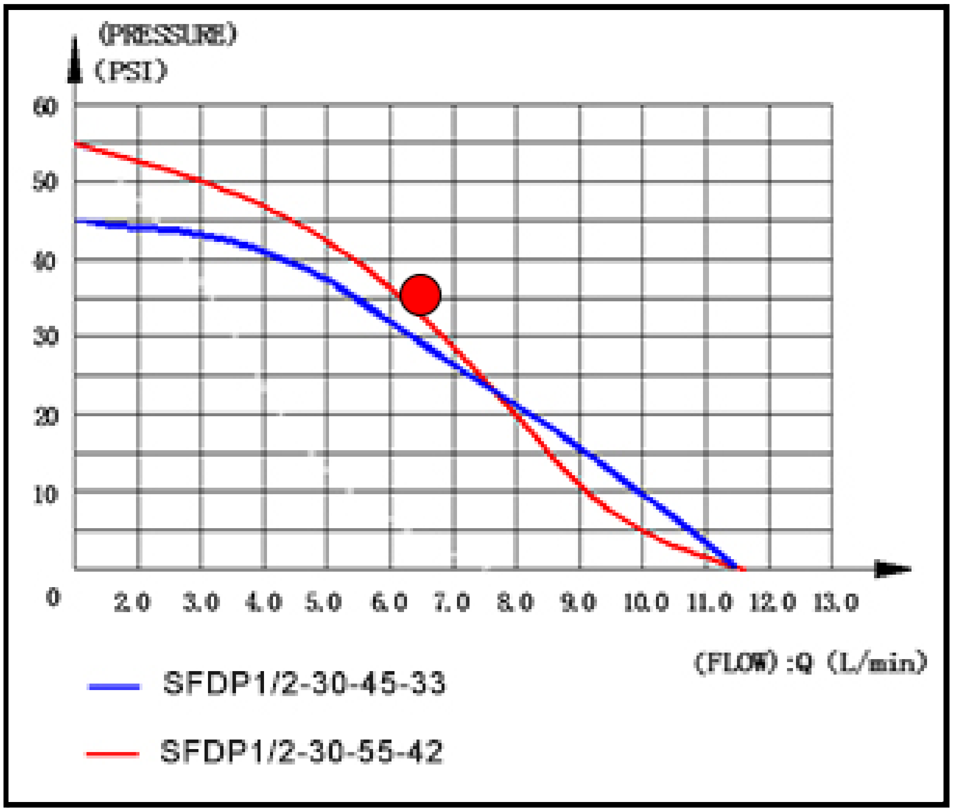


Figure 10: Pump performance curve for selected SFDP 1/2-30-55-42. The relevant curve is the red curve showing the specified pump performance. The pump is operating at the red point at 1.6 gallons per minute at approximately 35 psi.

One drawback about this subsystem design using these nozzles is that there is a section where no water is sprayed on the panel. Due to an overarching product goal to mitigate the additional space required for the system, the necessary design change to move the nozzles further from the top of the panel is not possible in this current configuration. Despite this, only a small portion of the panel receives no cleaning spray — therefore, there should still be a significant gain in panel performance when the cleaning system is run at a regular interval.

Chapter 5: Electrical and Solar Array System

5.1 System Overview

The goal of this subsystem is to identify and plot out the required electronic components in creating a closed feedback loop control system for the entire project. This control system must be able to communicate with both motors utilizing capacitor charging time and photoresistors to aid in tracking the sun. It must also be able to autonomously run the cleaning system cyclically based on consumer needs. The entire electrical system must fulfill certain safety requirements, and remotely provide information to the customer on how their solar panels are performing. A diagram of the electrical system is shown in Figure 11, and the control feedback system is outlined in dotted blue lines.

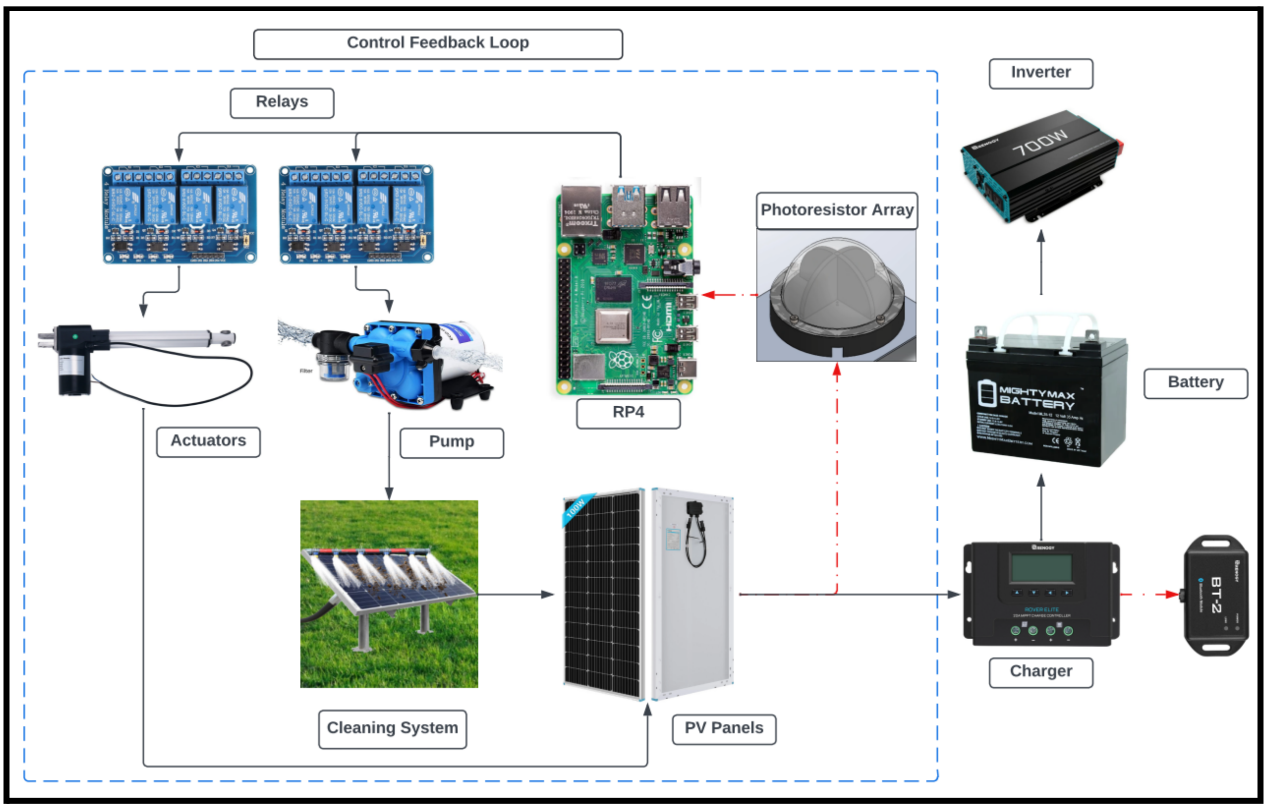


Figure 11: Electrical diagram of the Raspberry Pi control system.

Our electrical system consists of numerous parts working in tandem. It is crucial that all parts are working correctly, are compatible, and are calibrated. Beginning with the Raspberry Pi 4 (RP4), this computer is used to control all parts of the system. The RP4 receives data from the photoresistor array and adjusts the linear actuators accordingly in order to follow the sun. The photoresistor array is composed of four photoresistors that work in series with capacitors, from which the RP4 measures charging time. The more light that a photoresistor receives, the less resistance it has, resulting in a faster charging time. The system will then move in the corresponding direction based on the received information. The linear actuators and water pump are enabled by two 5V DC relays, which receive low-current signals in order to permit 12V DC power. As for the solar system, two 20V 100W solar panels are connected in parallel to the charge controller, which subsequently charges and monitors the battery's condition in order to prevent over and undercharging. The charge controller is enabled with Maximum Power Point Tracking in order to record total power data at specific time intervals. This data is then transmitted to a homeowner via the BT-2 module, which is a Bluetooth device that relays all information stored on the charge controller. An inverter equipped with onboard safety trips, 700W in this case, is used to convert the battery's 12V DC to a more usable 110V AC. This allows us to run the RP4, self-sufficiently. A full table of each electrical component and description can be found below in Table 5.

Table 5: Comprehensive table of electrical components shown in the electrical diagram.

Part	**Description**
Photoresistors (x4)	Four photoresistors arranged in quadrants to measure light intensity across the system
Raspberry Pi 4	Single board computer to be the main controller of the entire subsystem.
5V Relays (x2)	Takes a low-current control signal to engage connected components (pump & linear actuators)
12V Water Pump	Pumps water from the reservoir for the cleaning system.
Linear Actuators (x2)	One actuator for each axis of movement.
PV Panels (x2)	100W panels for solar energy collection.
Charge Controller w/ MPPT	Intakes solar power, monitors, and charges the 12V battery.

Inverter	Converts 12V to 110V in order to power Raspberry Pi 4 and other appliances.
BT-2 Module	Provides and records power data for the end-user.
12V Battery	Stores collected solar energy.

5.2 Controls (Tracking)

In order to properly track the sun throughout the day, we utilized a Raspberry Pi as the main microcontroller which was wired to capacitors and photoresistors arranged in a module with four different quadrants (Figure 12). Photoresistors were chosen for their cost-effectiveness, as well as their easy integration with our microcontroller. With each photoresistor linked in series to its own capacitor, charging time could be read as data by the microcontroller. As stated previously, this is how we measured light intensity across the array. As the sun moves across the sky, the separated quadrants in the photoresistor array module would become shaded, as seen in the leftmost graphic in Figure 13. The logic, which is simplified down to a simple loop, is showcased in Figure 14.

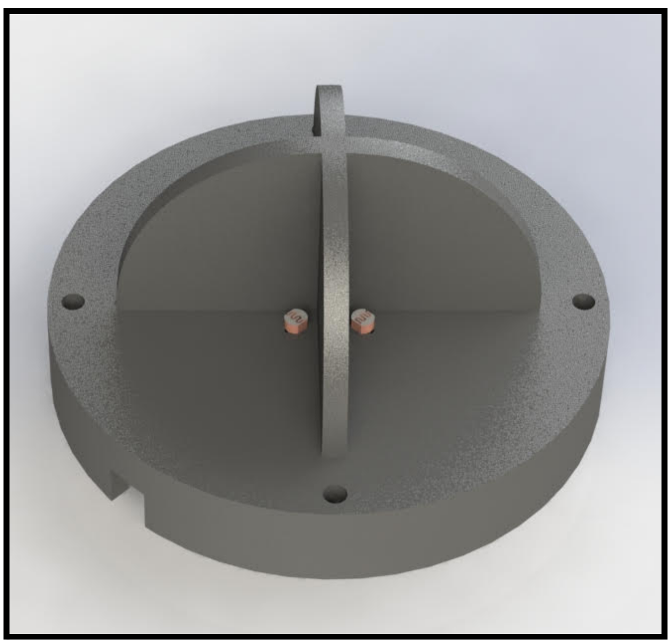


Figure 12: Rendered image of photoresistor array module.

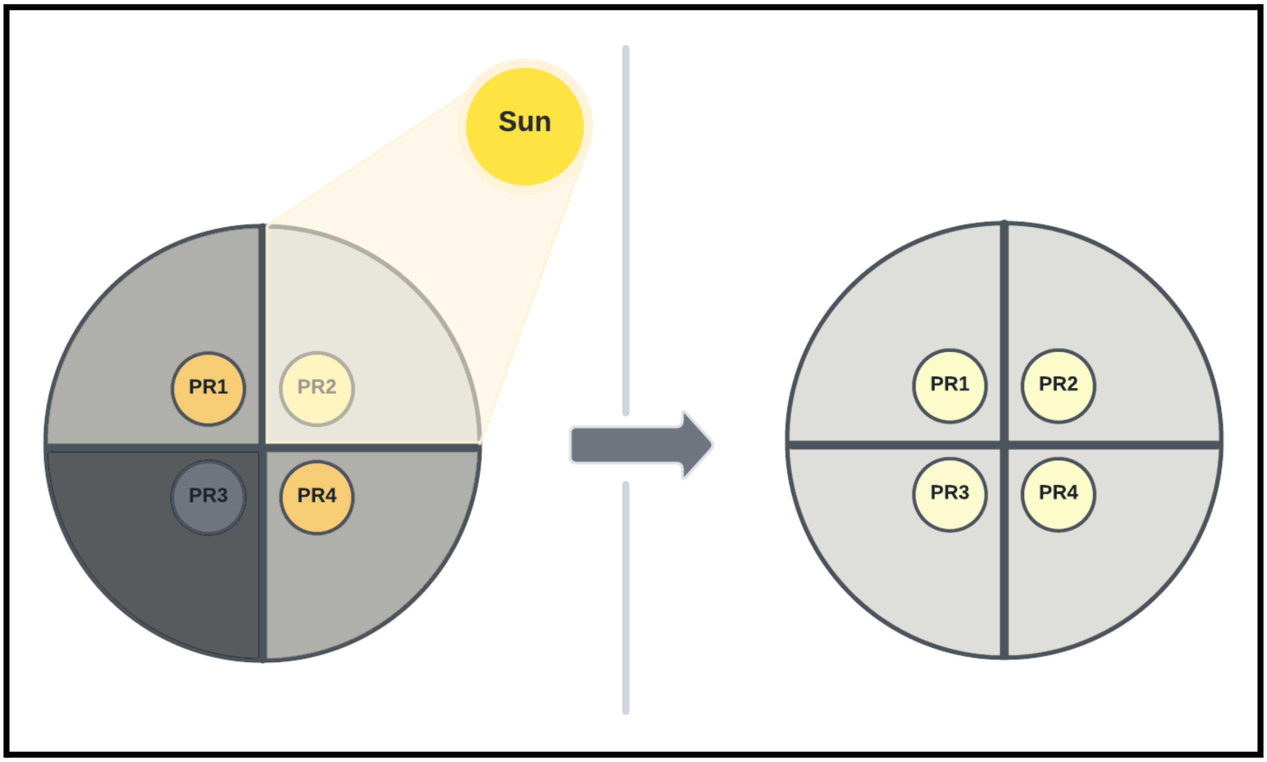


Figure 13: Imagery of how shadows would be cast on the photoresistor array. Rightmost image showcases a photoresistor array in-line with the sun.

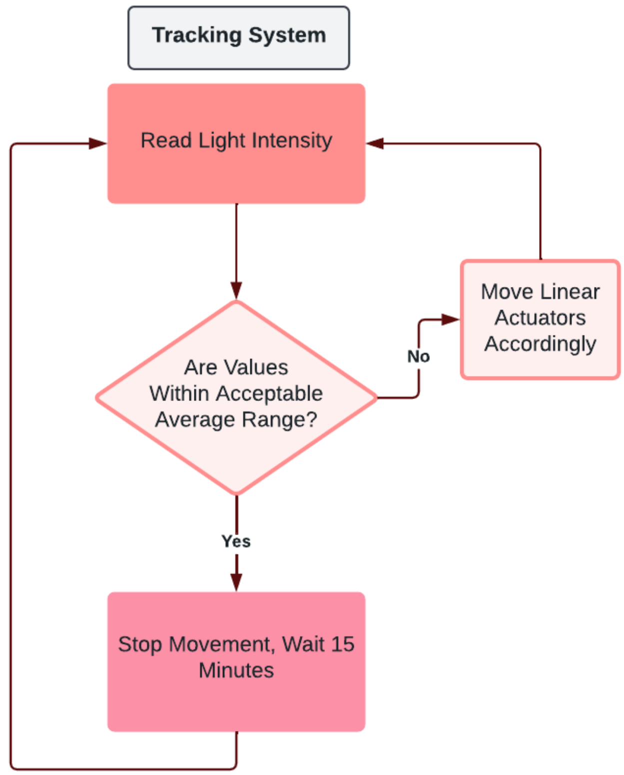


Figure 14: Simplified logic flow diagram of the tracking system.

The control feedback loop works by continuously checking light intensity across the photoresistor array and relaying that data to the Raspberry Pi. A separate function was put in place to constantly monitor the recorded values against each other to determine if the photoresistors were all in line with the sun to an acceptable degree. A tolerancing value was added, as testing revealed that although the photoresistors were quite accurate, small discrepancies were observed between each photoresistor. Should each photoresistor not be within the acceptable range of each other, the Raspberry Pi would then turn on the corresponding relay to activate the linear actuators to reposition the panel accordingly. For example, if the photoresistor array were to be in the situation shown in the left side of Figure 13, the panel would reorient itself upwards and towards the right until each photoresistor is perpendicular to the sun as can be seen in the rightmost graphic. This would mean that the solar panel itself would be perpendicular to the solar rays, leading to maximum energy generation. Should the correct orientation be found, the cycle would halt for 15 minutes before restarting to check where the sun had moved during the stall time. The linear actuators are coded to only move for 0.64

seconds per interval. This is due to the sun moving 15 degrees across the sky on average per hour. With our stall time of 15 minutes, the sun should only move 3.75 degrees (Equation 1), and based on our linear actuator's calculated 2.93 degree angle change per second, it would need 1.28 seconds of actuation to realign itself to the sun (see Equation 2) . We decided to cut this actuation time in half so that the panel would need to run through at least two intervals of actuation to reach the desired angle before halting movement, as to provide greater accuracy should the sun have moved a greater or lesser distance across the sky as the seasons change. The entire system itself is only set to run between sunrise and sunset to further save on energy consumption. In order to properly account for daylight savings, changing seasons, and geography, two python libraries; sunTime and geocoders were utilized. These two libraries were used in tandem such that a user could input their current geographical location in the script, and find the local sunrise and sunset times. These times would then be compared constantly to the current time using the internal clock to allow or deny system activity. At the end of the day, the panel will be reoriented back to a neutral base position of 45 degrees. The variable Θ [°/hour] represents the rate at which the sun moves across the sky. The variable $\Delta\beta$ [°/second] represents the rate at which the actuators can rotate the panel. The degrees covered by the sun can be found mathematically by multiplying Θ by 0.25 hour, as seen in Equation 1 below. Then, this amount covered by the sun per quarter hour, can be divided by the rate at which the panel articulates, $\Delta\beta$, in order to calculate t, the time needed to articulate the panel in line the sun. This time needed to cover the sun's change in location can be seen in Equation 2 below.

$$\Theta * 0.25\text{hr} = \mathbf{3.75°} \tag{1}$$

$$t = (\Theta * 0.25\text{hr}) / \Delta\beta = 3.75°/2.93° = \mathbf{1.279s} \tag{2}$$

5.3 Controls (Cleaning)

The cleaning control system (Figure 15) is contained within the microcontroller itself and exists purely in code. Utilizing the sunTime and datetime python libraries, a check is continuously performed for both date and time. The system itself will only run once per week at sunrise, on a set specific day of the week based on user preference. Should the date and timing be correct, the microcontroller will first reorient the panel to a base neutral position of 45 degrees in order for maximum cleaning efficacy. The microcontroller will then send signals to the corresponding pump relay, which will then activate the pump to run for 20 seconds. From testing, 20 seconds is enough time for the system to fully clean off heavy debris build up. Once this cleaning cycle is complete, the code will then flag the entire cleaning loop as “off”, utilizing a counter, which would be reset at the start of the next week. This flag is put in place to prevent the cleaning system from misfiring at any other time than what was scheduled.

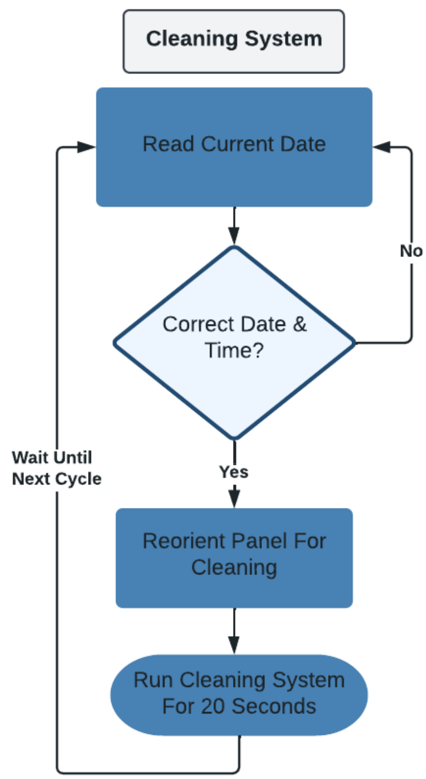


Figure 15: Simplified logic flow diagram of the cleaning subsystem.

Chapter 6 Finite Element Analysis and Thermal System Simulations

6.1 Finite Element Analysis Introduction

The goal of our finite element analysis (FEA) is to model the frame subsystem in order to determine the Factor of Safety (FOS) for critical points. Critical points identified include but are not limited to: the connection between frame and ground, the connection between the north-south hinge and upper frame structure, and connections between the East-West hinges and PV panel support structure, shown in Figure 16 in red, blue, and green respectively. Validation of the connection between frame and ground will be conducted through hand calculations. These hand calculations will treat the upright frame as a fixed-free beam subjected to a point load at the tip of the beam. This calculation will validate the model and allow for FEA analysis of the aforementioned critical points.

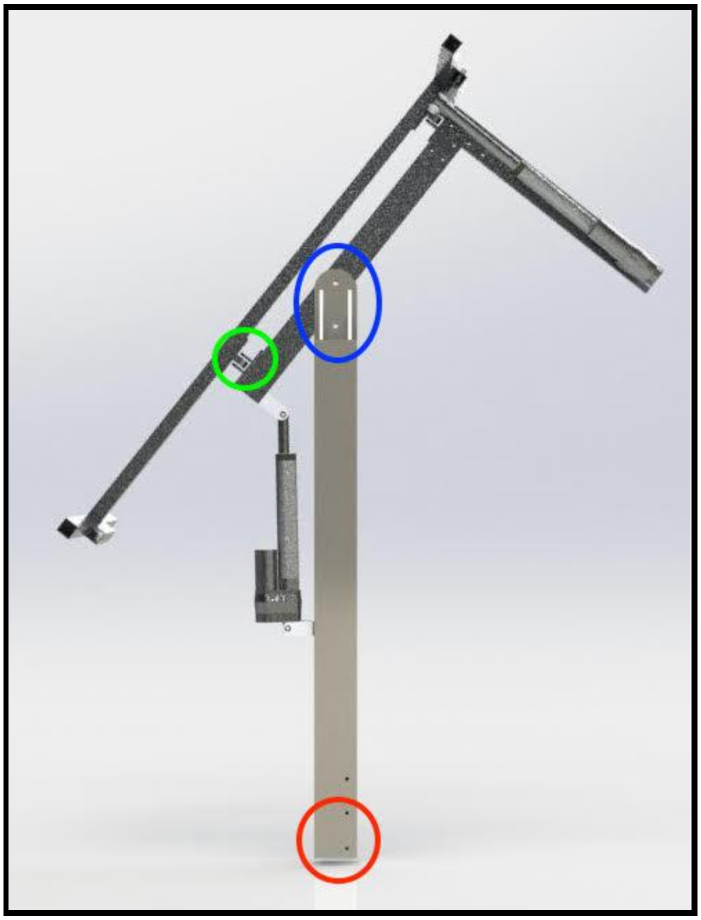


Figure 16: Location of identified critical failure points on the frame. Locations identified are the connection between frame and ground (red), connection between the north-south hinge and upper frame structure (blue), and connections between the East-West hinges and PV panel support structure (green).

Additionally, thermal loading will also be conducted in order to better understand final thermocouple placement. Since the thermocouple is planned to be placed on the backside of the solar panel, a thermal relationship will need to be found through thermal simulations. This thermal loading was used in conjunction with prior thermocouple research conducted during Fall 2021.

The north-south hinge is the main connector between the vertical upright post. This hinge is to be made from 1020 steel as is the upright post. The north-south hinge is shown in Figure 17 below. The east-west hinges serve as rotating mechanisms for the east-west tracking. The east-west hinge is shown in Figure 18 below. Both east-west hinges are made of 6061 aluminum.

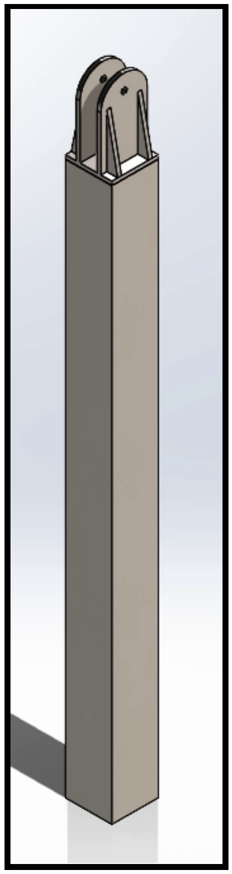
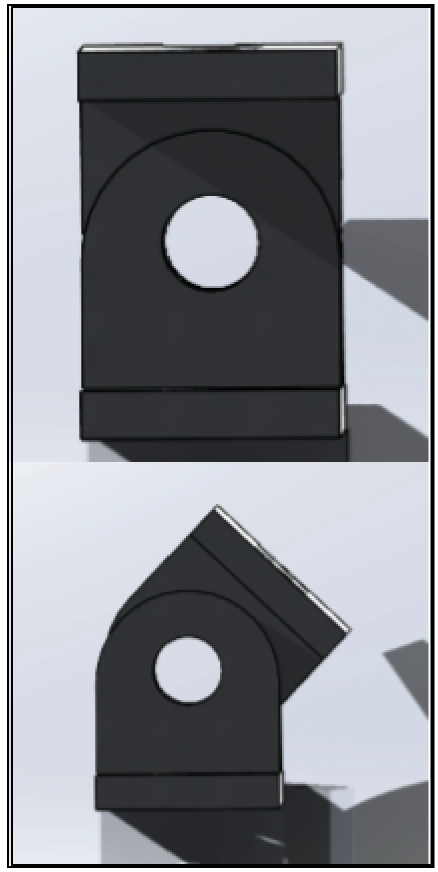



Figure 17 (left) and Figure 18 (right): North-south and east-west hinges respectively. These hinges have been identified from preliminary FEA as critical points. Through specified loading cases, their structural integrity will be verified.

6.2 Finite Element Analysis Validation

The FEA was validated through modeling the upright post of the tracking system as a cantilever beam with an applied load at the free end. Figure 19 below shows the assumed model for FEA validation. Some assumptions used for this validation include: 40” beam length, 3”x3” square tubing with 1/8 “ wall thickness, and reduction of forces such that the wind load acts perpendicular to the face of the panel (inclined to an angle of 37° with the vertical. Equation 3 below details the stress calculation used. The detailed wind load calculated using the ASCE Standard 7 can be seen in Appendix C. The X direction force creates an axial stress $\frac{P}{A}$ and the Y direction force creates a bending stress $\frac{My}{I}$. The calculated value of stress was found to be 17 MPa (Equation 3). As discussed later, the CAD simulation under the same force conditions yielded a result of approximately 19 MPa. These two values will be considered as being sufficient in validation of the FEA simulation. Differences between the hand-calculated stress and Finite Element derived force can be attributed to stress concentrations created by the mesh used in FEA solution as a result of approximations made near the edge of bodies in FEA solutions. It is then the conclusion of this report that the FEA simulation is valid, and can be used for other modeling applications other than the one demonstrated in this section. The following variables are necessary for calculating bending stress σ: *P* as the force applied (lbf), A is the cross sectional area of the beam (in^2), M as the applied moment (lbf-in.), y as the distance from the neutral axis (in), and I as the moment of inertia for the chosen cross section (in^4).

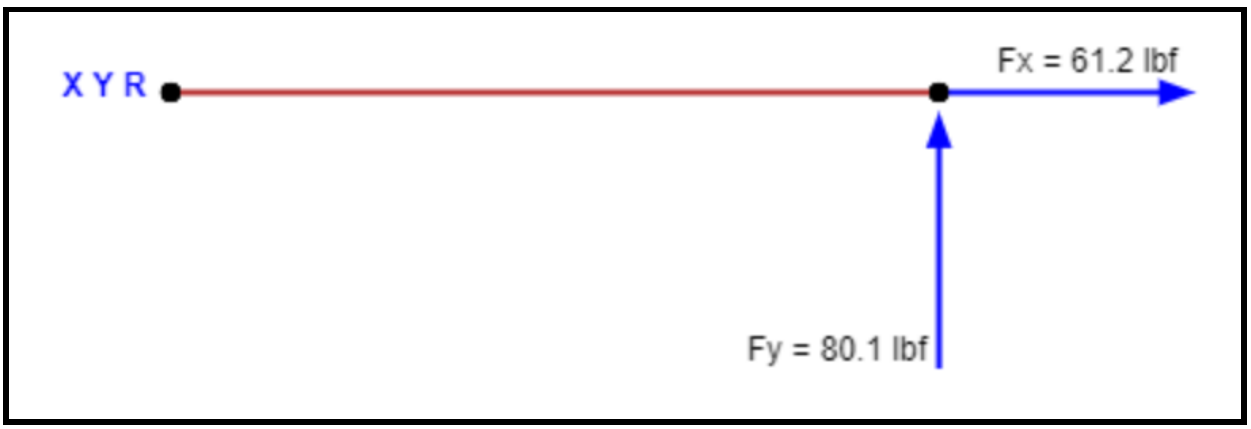


Figure 19: Cantilever beam FBD for hand calculations. with translational constraints in the X and Y directions and a rotational constraint on the left end. This setup is used to model the FEA simulation run on our CAD model. The applied load of 100.8 lbf (acting at an angle of 53* with respect to the horizon) was split into force vectors of 61.2 lbf in the X direction and 80.1 lbf in the Y direction.

$$\sigma = \frac{P}{A} + \frac{M \cdot y}{I} = \frac{61.2 lbf}{1.4375 in^2} + \frac{3205.2\, lbf \cdot in * 1.5 in}{1.984\, in^4} = 2465.82\, psi = 17.00\, MPa \quad (3)$$

Comparing this to the FEA simulation in Figure 20 below, it can be seen that the load case is similar, and this report considers the model to be validated as such.

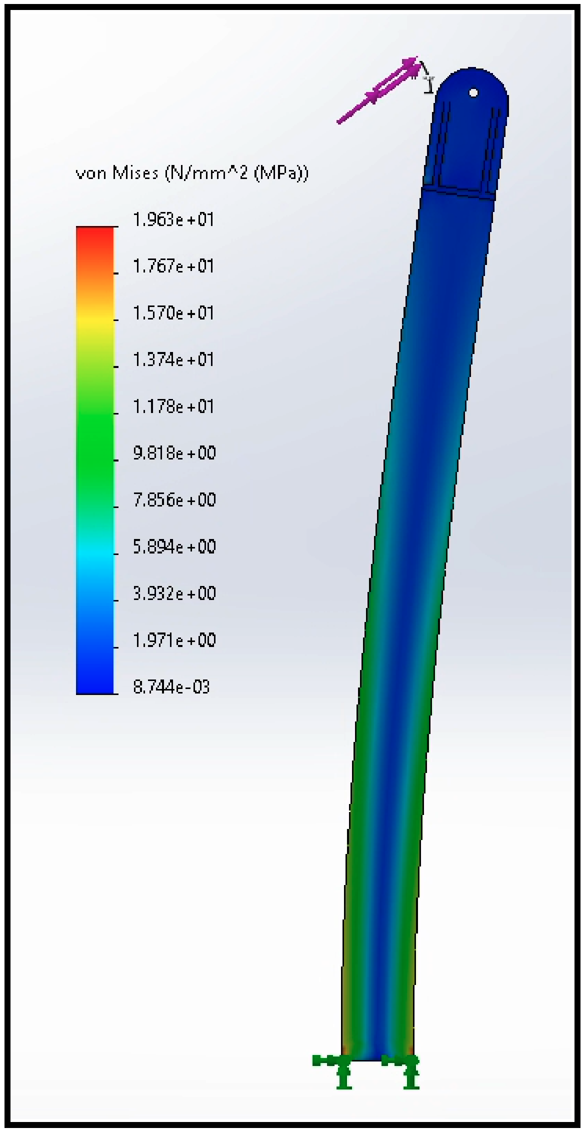


Figure 20: FEA model of primary post, referred to as primarily load condition. This model is based on the wind load calculations taken from ASCE Standard #7. The assumptions for wind load include: located on the U.S. Western Seaboard, at a height of fifteen feet above sea level, and treating the panel as a rooftop stationary object.

6.3 Results of Finite Element Analysis and Usage in Design

6.3.1 Main Post and North-South Hinge Member Bending From Wind

Experimental Loading Conditions

This member was tested under two loading conditions for this analysis. Using the known wind loading from previous calculations, a point load of 100.8 lbf will be placed on the hinge axis. For the first case, the load is applied at an angle of 37.35° from the vertical in the plane of rotation.

This is to simulate the position at which the member will experience the maximum possible front loading condition. For the second case, the point load is applied on the hinge perpendicular to the plane of motion and at an angle of 47.23° from the horizontal. This is to simulate the maximum side-load that the member will experience. For both cases, the upright member will be fixed simulating a rigid connection with the ground.

Results

From the Finite Element solution of the two loading conditions, neither case yielded or had large displacements. The output from the Solidworks simulations can be seen in Figures 21 and 22.

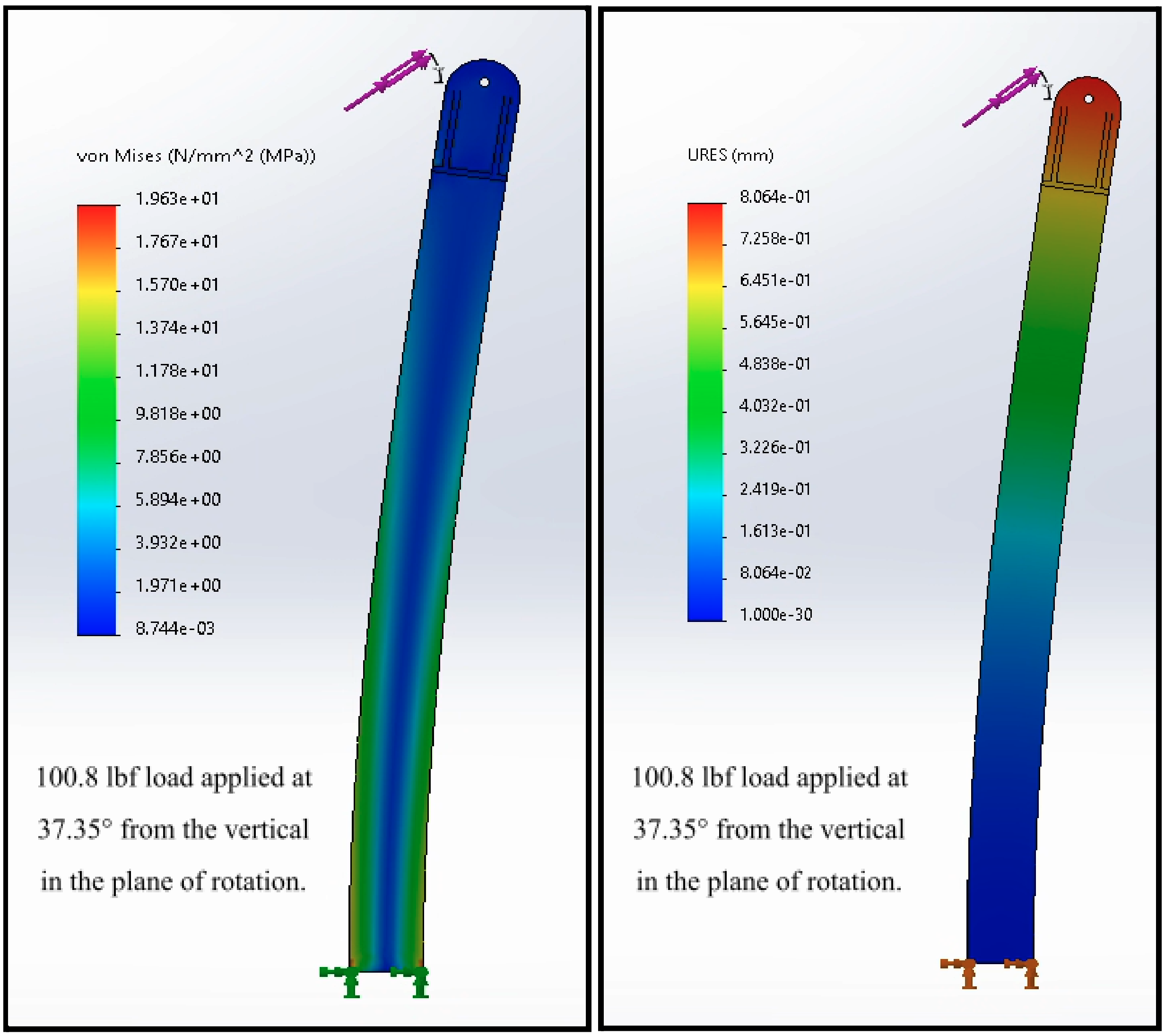


Figure 21: Von Mises stress and deflection for the upright post first loading condition. 100.8 lbf load applied at 37.35° from the vertical in the plane of rotation.

For the first loading case, there was a maximum stress of 19.63 MPa at the base near the fixed boundary condition. At the top of the member, there was a maximum deflection of 0.8mm.

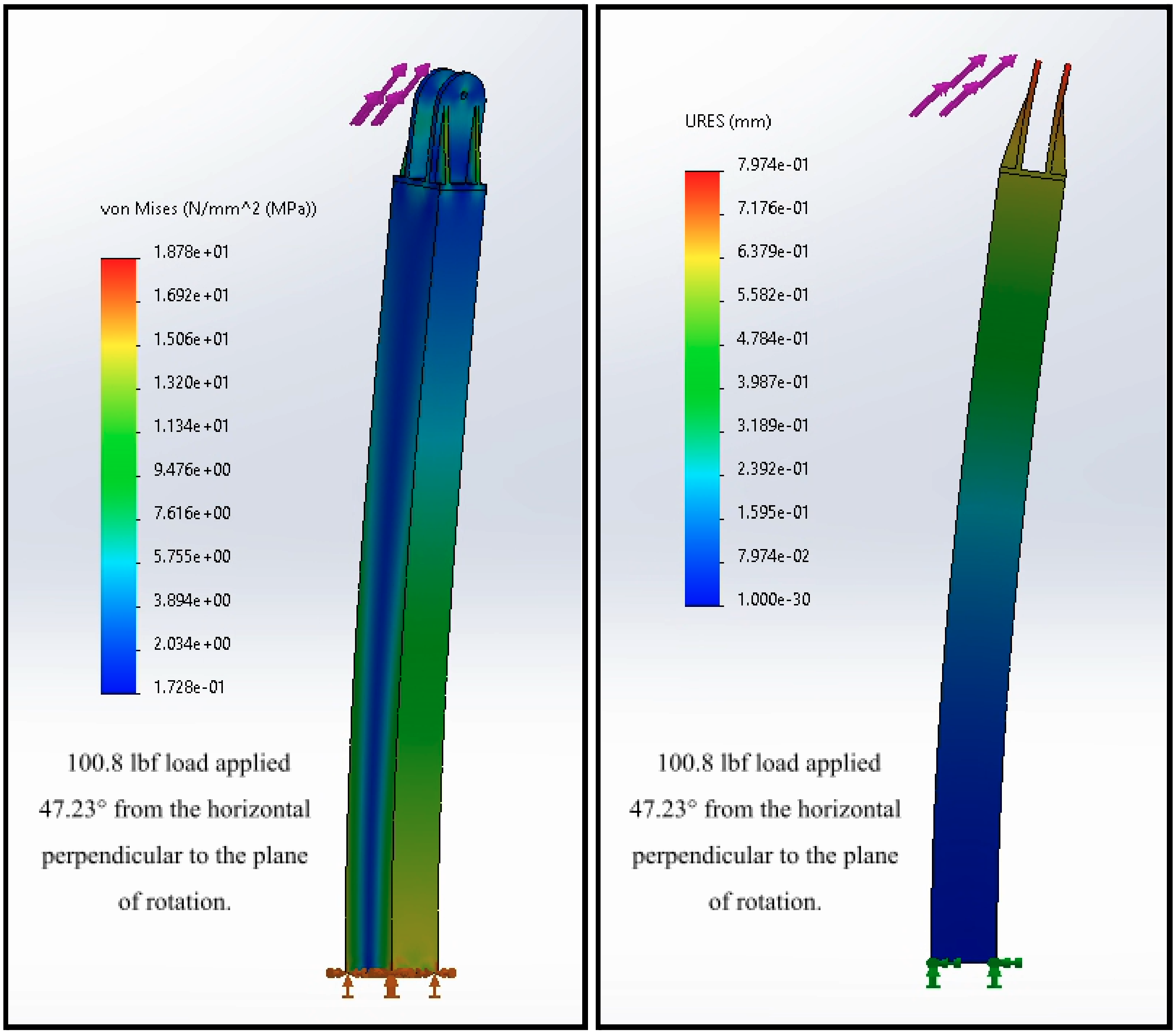


Figure 22: Von Mises stress and deflection for the upright post second loading condition in MPa and mm. 100.8 lbf load applied 47.23° from the horizontal perpendicular to the plane of rotation.

The maximum stress experienced in the second loading case was 18.78 MPa with a maximum displacement of 0.79 mm. As expected for fixed-geometry simulations, the maximum stress is located near the fixed boundary condition – further proving that the simulated member is overbuilt for this loading condition. From the initial view during the design process for the hinge on the top of this member, there was some concern about the stresses and deflection that would be experienced that could cause some binding issues on rotation. From this simulation, the maximum stress on the hinge panels was found to be 10 MPa, well below the yield strength of 1020 steel.

Based on the result of the FEA done on the main post and the aforementioned hand calculations, it was concluded that with FOS of 17.8 and 20.59 respectively (Equations 3 & 4), both material and geometric properties of the designed post required no secondary design iteration. While the thickness of the square tubing could be decreased to save on weight, material, and cost while maintaining an acceptable factor of safety, the dimensions were taken from existing spare tubing found in the machine lab. Weight is not a driving factor in the design of this post, as it is the acting anchor to the ground, and would not need to be moved in any way by the linear actuators. The extra bulk and weight of the steel post will also help dampen vibrations and increase rigidity. To further the decision on not redesigning the main post, a maximum deflection of only 0.8mm was observed at the top of the hinge. The sideloading analysis resulted in an observed deflection of 0.79mm at the same location. Both of these deflections are minimal enough to be considered as negligible. Based on the fact that the material is currently accessible and that it well exceeds the structural rigidity requirements, the conclusion is that the main post requires no design change. In Equations 4 and 5 below, σ and σ_{ult} are the calculated stress from FEA and ultimate stress of the material, respectively.

$$FOS\ (FEA) = \frac{\sigma_{ult}}{\sigma} = \frac{350\ MPa}{19.63\ MPa} = 17.8 \tag{4}$$

$$FOS\ (Hand\ Calc) = \frac{\sigma_{ult}}{\sigma} = \frac{350\ MPa}{17\ MPa} = 20.59 \tag{5}$$

6.3.2 East-West Hinge

Experimental Loading Conditions

A stress analysis of the east-west hinges was conducted to verify if the designed hinges can withstand a maximum potential loading condition. To test the east-west hinge, two loading cases were applied. For the first loading case, a load of 50.4 lbf (the 100.8 lbf maximum wind load split between two hinges) will be placed perpendicular to the flat face of the male east-west hinge component. The faces of the hinge components will be made parallel to simulate the case of the panel parallel to the ground. The flat face of the female hinge will be fixed. For the second loading case, the same loading and fixed criteria will be used as case one. The faces of the hinge components will be at an angle of 47.23° to one another measured from the vertical around the axis of rotation. This will simulate the case of when the panel is at its maximum angle in the east-west axis.

Results

For each of these test cases, the von Mises stress and deformation displacement was recorded. Figure 23 shows the results from the Solidworks simulation for the first test case and Figure 24 shows the results for the second testing case. For both cases 6061 Aluminum was used.

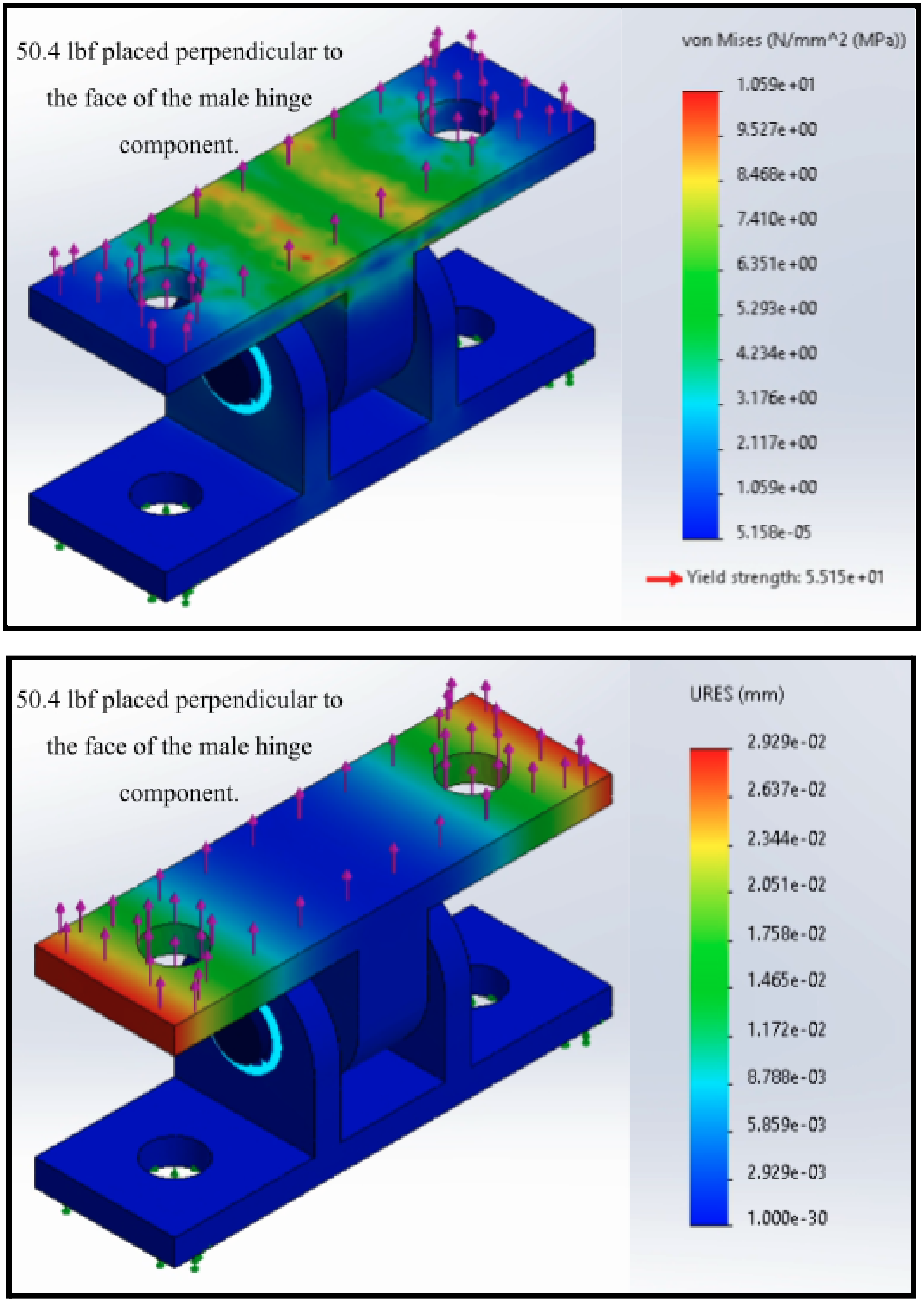


Figure 23: Von Mises stress and deflection for east-west hing first loading condition. Maximum stress is 10.59 MPa located at the underside corners of the hinge. Maximum deflection is 0.029 mm at the edges of the hinge.

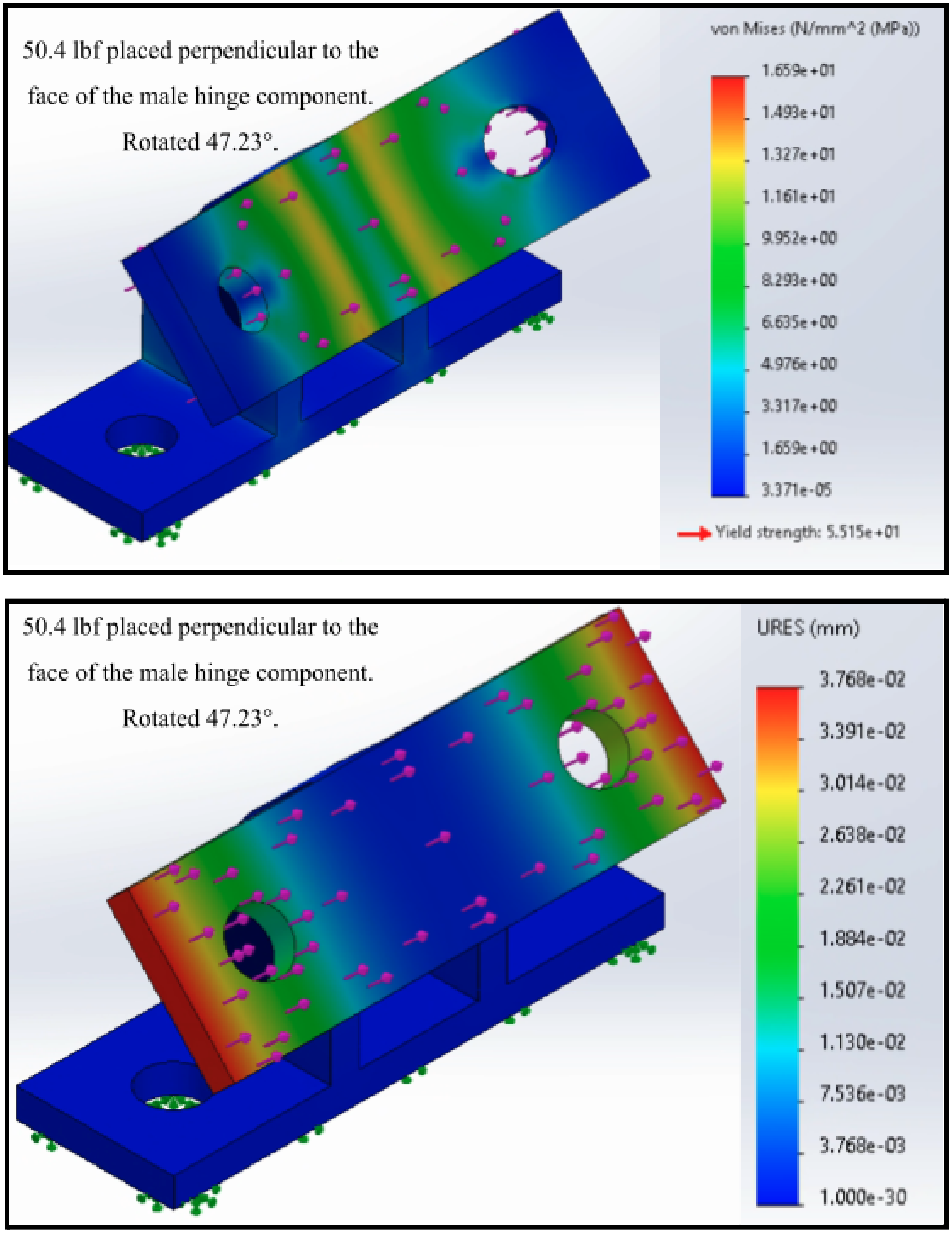


Figure 24: Von Mises stress and deflection for the east-west hinge second loading condition in MPa and mm. Maximum stress is 16.59 MPa located at the underside corners of the hinge. Maximum deflection is 0.038 mm at the edges of the hinge.

From test case one, the maximum recorded stress was 10.6 MPa with a maximum deflection of 0.029 mm. The maximum stress is located on the underside of the hinge where the horizontal plate turns into a vertical plate. For this location, the factor of safety can be calculated when taking the yield strength of 6061 Aluminum as 55.15 MPa. Therefore, the yielding factor of safety for this part is 5.2. Such a small displacement is negligible for this testing case so its effects can be ignored.

From test case two, the maximum recorded stress was 16.6 MPa and a maximum deflection of 0.38 mm. Like case one, the maximum stress is also located on the intersection of the horizontal and vertical members of the hinge bracket. For this loading case, the factor of safety is 3.32 – lower than case one but still within a safety margin. Like case one, the maximum displacement is so small that it is negligible.

To solve the problems from the stress concentrations on the brackets, two things could be changed about the design. The first of which can be redesigning the hinges with a lesser stress concentration. This can be done by adding a filet or some chamfer buttresses so the stress has a way to "flow" easier between sections. Alternatively, simply adding more of these existing hinge designs will reduce the amount of stress each hinge will be required to handle. Manufacturability will have to be considered when choosing which design solution to use. If adding the filet or buttress will make the manufacturing process much more extensive, then adding more of the hinges may be more cost effective. Further investigation into the manufacturability of this part is needed before any finalized design decision can be made.

6.4 Thermal Analysis

A thermal analysis of the solar panel system was also conducted in order to determine the best place to place the thermocouple to monitor the temperature of the panel. This thermocouple will monitor the temperature of the panel, reporting whether or not the panel has reached the critical temperature threshold for the coating to release dirt and grime. Due to physical limitations, the thermocouple is to be placed on the back-side of the panel to avoid impeding PV operation. To model the solar panels, a combination of layers of glass, silicon, and PVC were used, along with an aluminum frame. Glass was ¼" thick, silicon was ⅛" thick, and a 1/8" layer of PVC was used as a backing. This was followed by connections to the aluminum frame members of the system. In order to model the expected thermal loads on the system, 1000W/m^2 of heat flux was placed across the solar panel's surface, with a natural convection load of 15W/m^2 to all other exposed faces. A revised average 1000W/m^2 was calculated from our latitude of 37° linand time frame of tests, approximately May - June. The heat transfer coefficient for natural convection varies from 5-25 W/m^2; therefore, an average of 15 W/m^2 was used. Figure 25 below shows the proposed location of the thermocouple temperature measuring device.

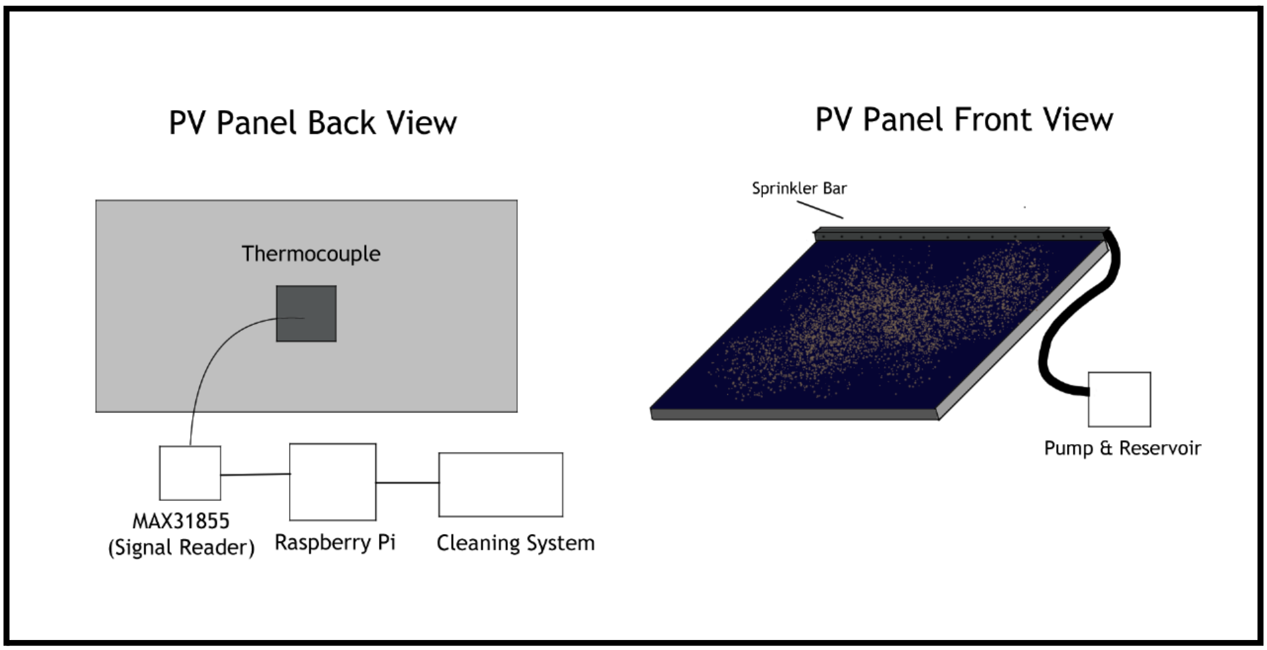


Figure 25: Proposed position of the thermocouple, the center of each panel. Thermocouple to be placed such that an accurate reading of the panel may be taken.

During the initial runs of thermal analysis, the heat load from the sun was calculated using the top of the atmosphere as a reference point. We realized that the heat flux values from the top of the atmosphere were not representative of where and when our system would be tested, thus revising it to 1000 W/m^2. We learned that the placement of the thermocouple was more crucial than obtaining temperatures, since the solar panels do not conduct heat very well. Once the thermocouple is placed, we can then determine the relationship between the temperatures on the front of the panel and the back. Below in Figures 26 and 27, the thermal simulations along with temperatures can be seen. The best placement for a thermocouple or two would be near the middle of the solar panel array.

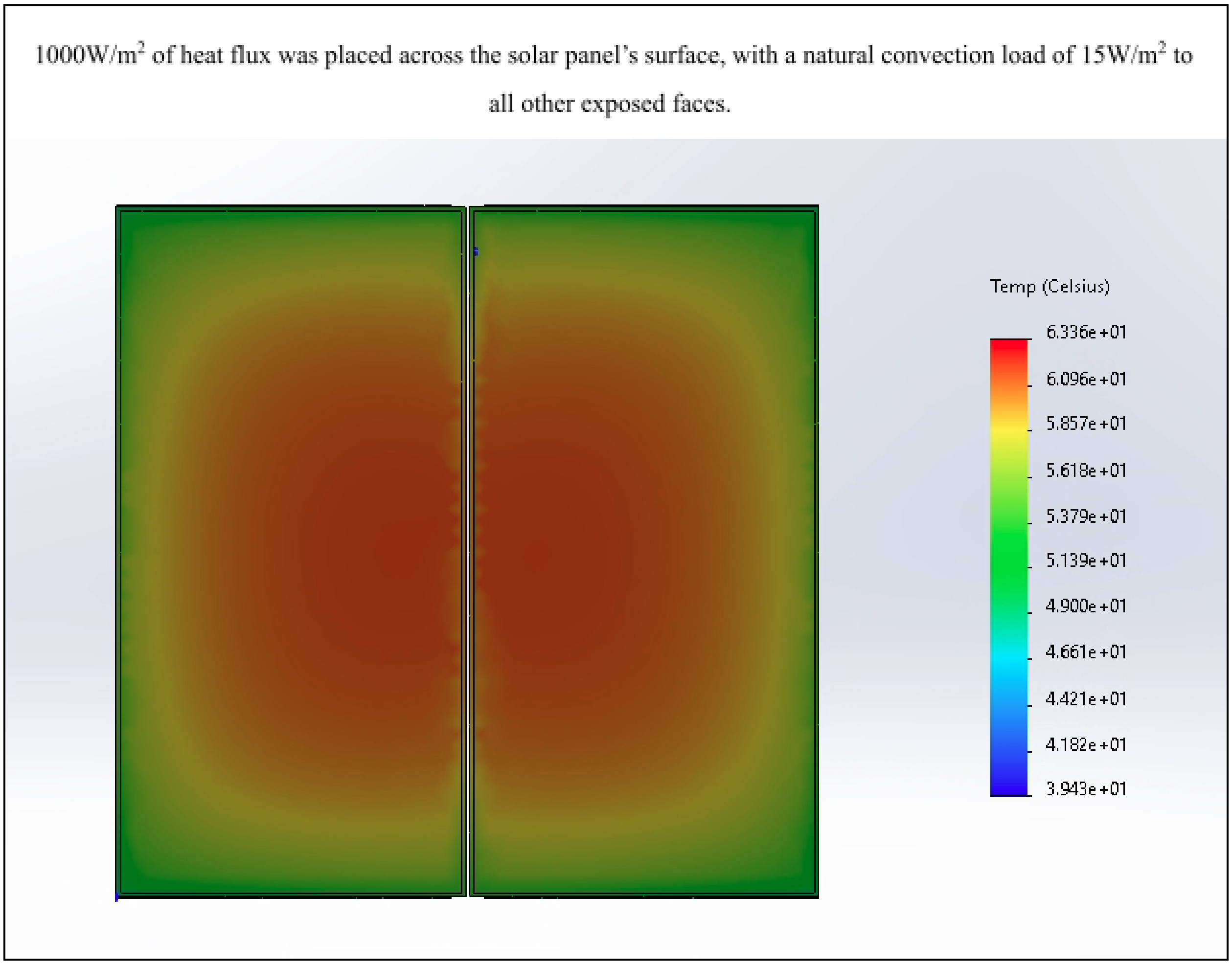


Figure 26: Thermal simulation of the front side of the panel. This side is exposed to 1000 W/m^2 of radiation energy calculated based on Santa Clara county geographical location.

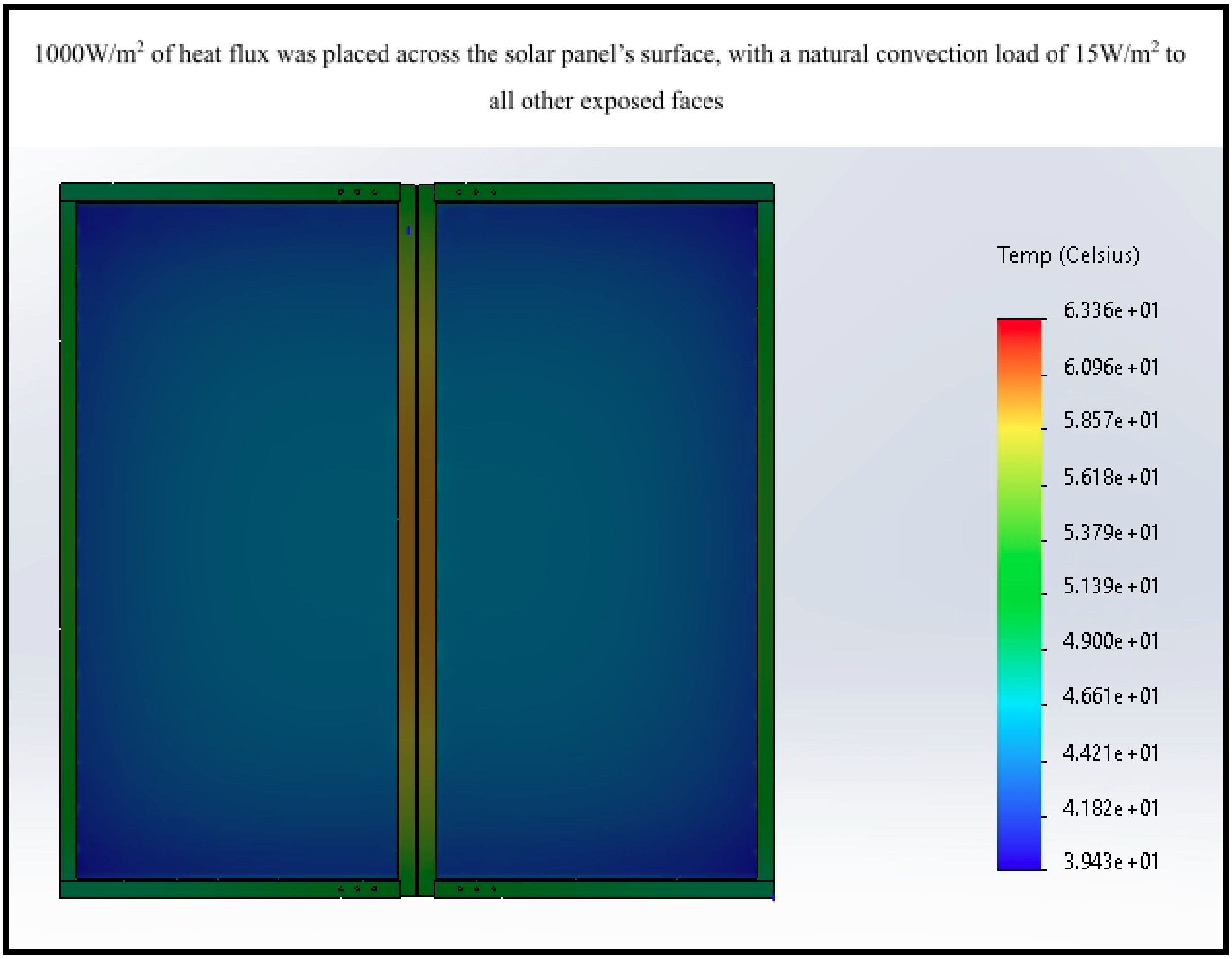


Figure 27: Thermal simulation of the back side of the panel. Front side is exposed to 1000 W/m^2 of radiation energy calculated based on Santa Clara county geographical location.

6.5 Thermocouple Analysis

To complement the thermal model, we needed to determine an appropriate thermocouple for the solar panels, since we planned to clean the solar panels when a certain temperature threshold was reached. The selection of a thermocouple was done via analyzing the accuracy of three selected thermocouples: the TL0225, WPTC-ST, and CS240DM, seen in Table 6 below. The design stage uncertainty was calculated using the RMS of the zeroth-order uncertainty and each of the manufacturer's measuring accuracy. The final selection was the WPTC-ST thermocouple probe, with a measuring uncertainty of $\pm$ 1.51 °C, seen below in Equations 6-8. The WPTC-ST thermocouple was selected due to its affordability ($45) and had uncertainty that was well within acceptable ranges for our specific application. In Equations 5-7 below, U_o , $U_{manufacturer}$, and

U_d are the resolution error, manufacturing uncertainty, and design stage uncertainty respectively. In Equation 6, the acronym LSD represents the phrase, "least significant digit," and refers to the smallest significant digit output by the thermocouple.

Table 6: Selected temperature sensor specifications

Sensor	Price	Sensor Type	Operating Range	Accuracy	Response Time
TL0225	$26	K-Type Thermocouple	0°C – 200°C	±1.1°C	No Exact Spec "2-3 Seconds"
WPTC-ST	$45	K-Type Thermocouple	-100°C – 1200°C	Greater of ±0.4% reading or ±1.1°C	300 ms
CS240DM	$140	Class A RTD	-40°C – 135°C	±(0.15 + 0.002T)°C	No Spec Given But Generally Slow

Uncertainty Calculation

$$U_o = 1LSD = [1^2 + .25^2]^{1/2} = \pm 1.03\,°C \tag{6}$$

$$U_{manufacturer} = \pm 1.1°C \tag{7}$$

$$U_d = \left[1.03^2 + 1.1^2\right]^{1/2} = \pm 1.51\,°C \tag{8}$$

Chapter 7 Manufacturing and End Product

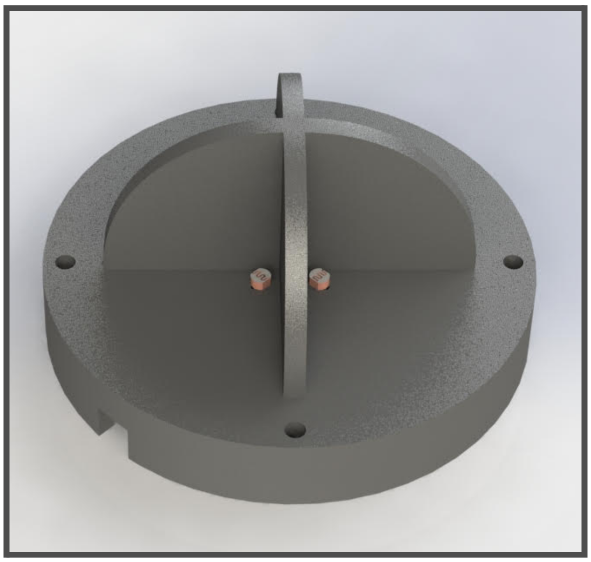
After careful consideration of each individual subsystem, safety and thermal simulations, and economic considerations, the final design can be manufactured. Integrating 3D Printed parts into our design allowed for quick manufacturing time, and maximum flexibility with our ability to make changes to the components. Section 9.1 details our usage of 3D printed parts. Furthermore, Section 9.2 discusses assembly of our product and contains sample images of the end product. An image of our final product is seen below in Figure 28. After manufacturing the product, and validating the tracking code worked as intended through manual configuration, the system is ready for testing.

Figure 28: End product after being manufactured in SCU Machine Shop. System shown in picture built using project specifications and required components.

7.1 Use of 3D Printed Parts

Given that this solar system was manufactured from scratch, 3D printing was incorporated into the end product for manufacturing efficiency. Parts such as the electrical shrouds and holding fixtures were printed out of non-conductive Tough PLA.

3D printing allowed us to circumvent more complex geometries that would be otherwise difficult to machine by ourselves, and it allowed for fast prototyping, as we had numerous iterations of designs. Seen below in Figures 29 and 30, we were able to create multiple design iterations within a few days, expediting the complete product.



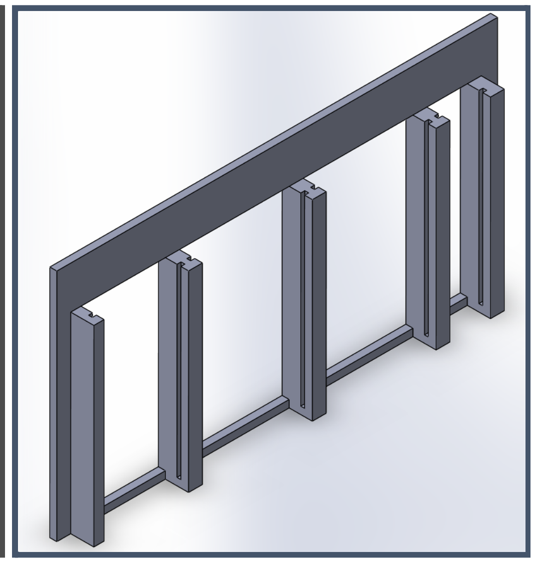


Figure 29 (left) and 30 (right): On the left, the 3D printed photoresistor hub. On the right, the PCB holder for the circuits.

The photoresistor hub was specifically printed in a matte black color to reduce reflection back onto the acrylic dome. All other parts were printed in matte black for consistency. For the future, we intend to either use more weather-resistant materials.

7.2 End Product

Our finished prototype solar system demonstrates a fully functioning project, combining each of the aforementioned subsystems: structure and articulation, solar and electrical, and cleaning. Each of these subsystems, while validated on an individual basis, had not been validated as an entire system before project assembly. As such, the system shown in Figure 31 below validates that our solar system is fully operational as per initial system designs.

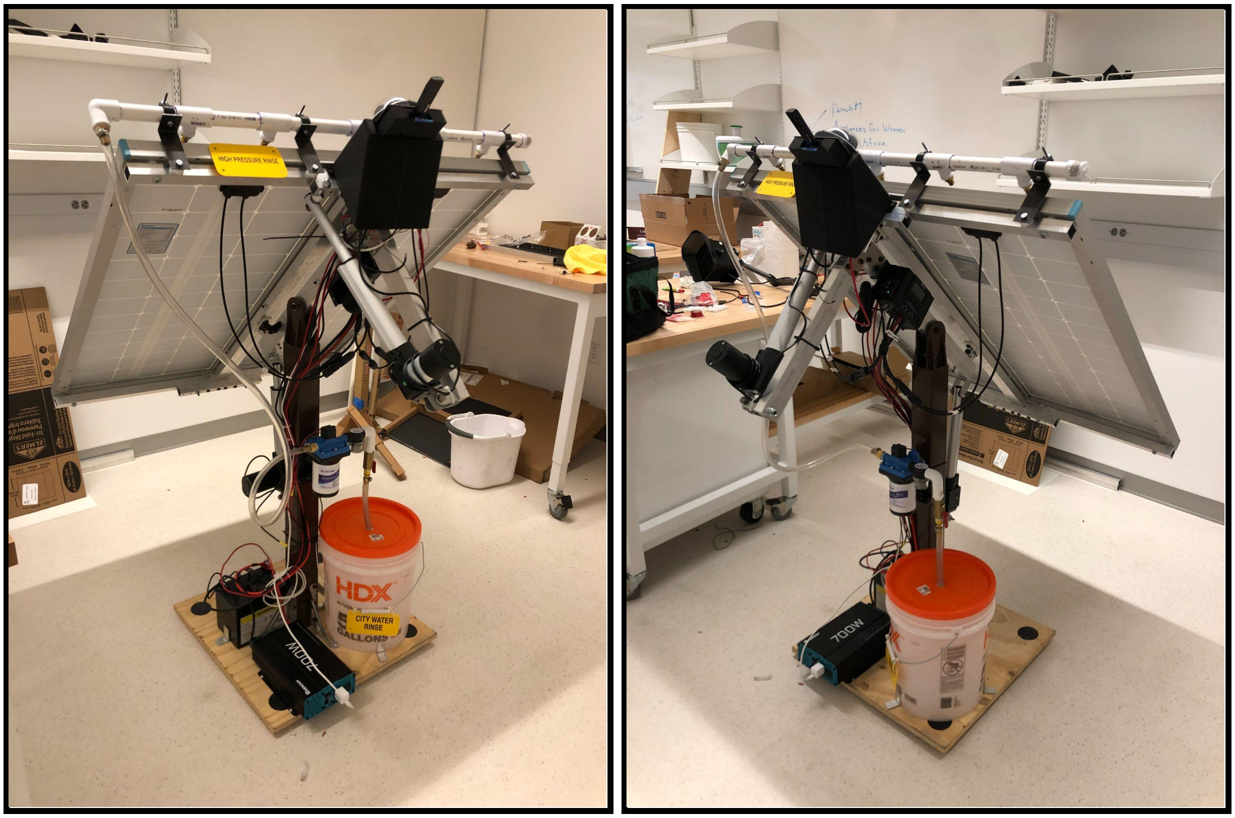


Figure 31: Completed system images from rear left and rear right. Shown are 700W battery storage, bucket and pump system, tracking dome, and cleaning system all attached to plywood base and caster frame.

Chapter 8 Testing and Results

8.1 Cleaning Testing Methodology

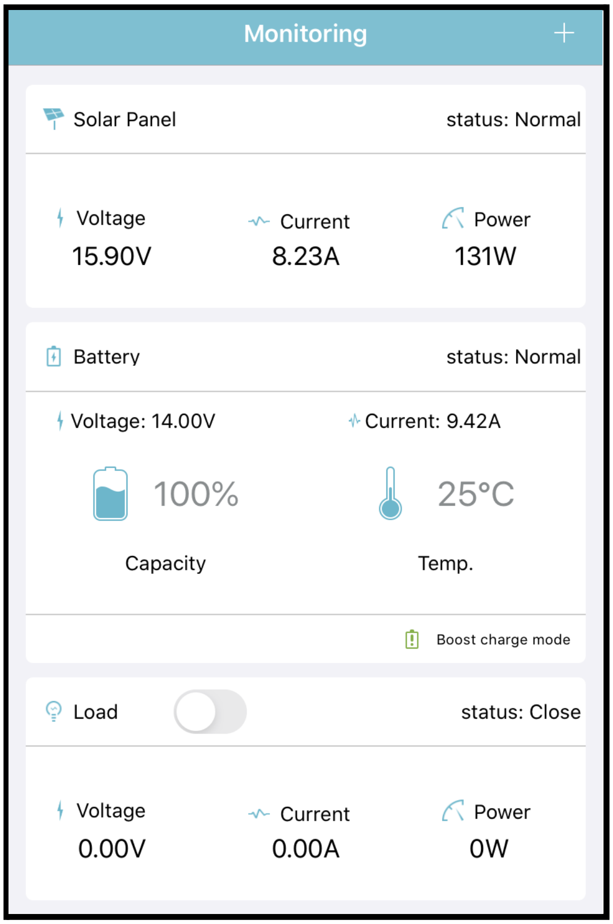
In order to test the effectiveness of the cleaning system, the solar panels were covered in fine dust and sand to simulate the worst case scenario of neglect, seen below in Figure 32. An anti-soiling coating was applied to panels to aid in dirt removal and for maintaining efficiency. The solar panels were then angled at 45 degrees from the horizontal axis to allow water runoff to avoid pooling and draining onto the electronics below. The cleaning system was turned on for 20 seconds, cleaning the panels. Through a trial of several tests, the total time for the cleaning system on time was determined to be the optimum time to clear debris from the panels.

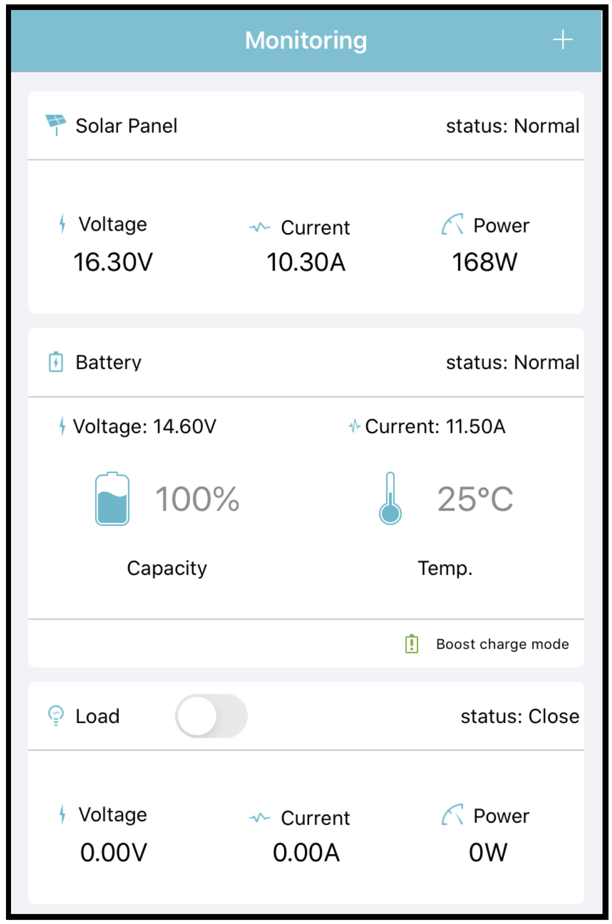
The panels were also allowed to dry until some of the dirt and sand had hardened on the surface of the panels. In order to gather more substantial data, furthered testing over the course of multiple weeks would need to be conducted.

Figure 32: Depicted scenario of a dirtied panel in the worst possible conditions.

8.2 Cleaning Testing Results

A top section of the panels was missed by the spray pattern due to a design flaw, where the nozzles are positioned too far forward over the panels. This uncovered section is very minimal, and we still see sizable gains from cleaning. Seen below in Figures 33 and 34, is a before and after comparison of our cleaning system. The severely dirtied panels had a power output of 131W, whereas the subsequently cleaned panels had a power output of 168W, a 28% improvement. To put this in perspective, we expected to see around a 17% improvement; however, our testing was only conducted over the course of one day, as opposed to a multi-week test in our conducted research. The method of adding dirt was also to simulate the worst possible scenario of neglect and is not entirely representative of a typical solar panel system.





Figures 33 and 34: On the left is the power generated from the dirtied panel array. On the right is the power generated from the cleaned panel array. A cleaned panel has a 28% power output improvement.

8.3 Tracking Testing Considerations

In order to ensure the best results possible given a small time frame of testing, multiple variables were considered in order to minimize errors in our results. These variables included the location of our testing, the duration and time of the testing, and the weather conditions during the test. In the literature studied, summarized in section 1.3, the duration of tests varied from weeks to months. Given the nature of our project schedule, a test duration similar to what was studied would not be possible. Precautions and variables were considered to minimize error however more accurate results will only be possible from long-term testing. Safety was also considered while testing, and OSHA 1910.212 - General Requirements for all Machines standard was followed in order to ensure safety for project members and bystanders. Safety tape allowing a "safety zone" of five feet from all directions of the project as well as signage was used to accomplish this. See Figure 35 for depiction of testing setup.

Figure 35: Solar tracker test setup for two 24 hour tests. Tests conducted on 5/8/2022 and 5/9/2022 on Santa Clara University campus.

8.4 Tracking Testing Methodology

Two 24-hour tests were conducted on the 3rd-floor balcony of Santa Clara's Sobrato Campus For Innovation and Discovery building, located in Santa Clara California. These tests were run from 10 am - 10 am the following day in order to ensure all possible sunlight available through the day could be collected. The first test was conducted on 5/8/2022 without the tracking system activated to obtain a baseline value to compare against. The panel was oriented at a position of 45° from the vertical in the north-south direction and positioned flat (0°) in the east-west direction. The following day, 5/9/2022, the tracking system was activated and allowed to run for another 24-hour period. The days of testing were chosen for the similar weather conditions. Both days were partly cloudy in the mornings with scattered clouds throughout the day. However, slightly more clouds were noticed on 5/8/2022 during the static test. Total power generation data recorded by the charge controller were taken before and after each test. Results from the tests can be seen in Table 7.

8.5 Tracking Testing Results

From these tests it was found the dual-axis tracking system increased power generated by 0.451 kWh compared to a fixed panel. This is a result of a 52.61% increase in power generation. The additional power generated is enough to power a mid-sized, 10,000 BTU window AC unit consuming 900 Watts of power for an additional 30 minutes per day. Table 7 below summarizes the static and active tracking tests.

Table 7: Results of static and active tracking tests. Tests conducted on 5/8/2022 and 5/9/2022 respectively.

Test	Power Generated [kWh]
Static	0.861
Tracking	1.31

These results are substantially higher than the 25% - 40% increase expected from the literature read. This is likely due to the changes in weather conditions during the tests. As previously mentioned a long-term test for both static and tracking would eliminate errors and provide more accurate results.

8.6 Return on Investment

After conducting all tests and consolidating our research, we have calculated a basic return on investment for a typical customer. Many assumptions were taken into consideration in order to create a universal ROI analysis.

Table 8: ROI Comparison between experimental and theoretical systems. Systems included are 2-Axis Tracking with Cleaning Systems and a Fixed Solar panel systems.

	Theoretical 2-Axis + Cleaning	Experimental 2-Axis + Cleaning	Fixed
Base System Power Output (W)	6000	6000	6000
Efficiency Gain	32.5%	52%	0%
Total Power Output (W)	7950	9157	6000
Manufacturing Cost ($)	41,220.00	41,220.00	22,500.00
Electricity Cost (c/kWh)	0.39	0.39	0.39
Yearly Power Generation (kWh)	23214	26737	17520
Yearly Power Consumption (kWh)	10950	10950	10950
Net Yearly Power Generation (kWh)	12264	15787	6570
Potential Yearly Savings ($)	4,782.96	6,157.04	2,562.30
Installation Cost ($)	9000	9000	3000
Cleaning Cost ($/yr)	100	100	3000
Potential ROI (years)	10.5	8.2	11.1
1-Year Cost Savings ($)	-45537.04	-44162.96	-25937.70
10-Year Cost Savings ($)	-2490.4	8739.60	-2877.00

Seen above in Table 8, a basic return on investment comparison was conducted between different configurations of solar systems. The fixed system was based on our current system configuration, sans certain parts. All manufacturing costs were based on our current system configuration of 200W, upscaled to an average 6kW system that a typical homeowner would purchase. This translates to 30 systems of our current configuration. The manufacturing cost for our system was $1374 each, and the manufacturing cost for the fixed system was $750 each. Yearly power consumption was based on an average U.S. homeowner consumption of 11kWh, priced at .39 cents per kWh from PG&E [9]. Selling energy back to the grid as well as all tax incentives and solar fees were disregarded from this ROI for simplicity. Should energy sellback be included, our ROI would be sooner than calculated; however, this is dependent on owner usage. Additionally, the cleaning costs, based on current hourly rates, estimated labor hours, and Santa Clara water rates, were included as recurring yearly costs rather than efficiency improvements to keep variables consistent with a fixed system.

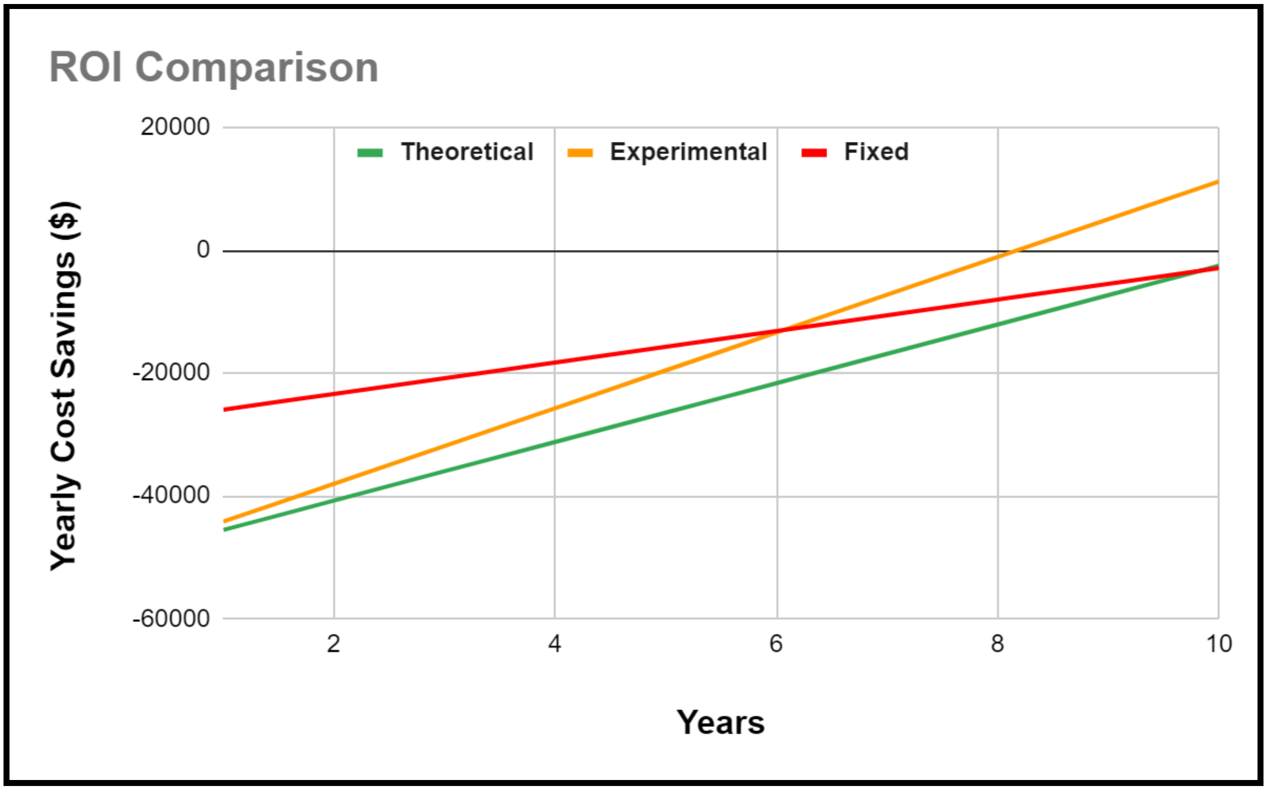


Figure 36: Plot of the ROI Comparison. Costs of 2-Axis Tracking and Cleaning system, 1-Axis Tracking system, and Fixed solar system over time.

Figure 36: is a graphical representation of the ROI comparison. As the graph indicates, the upfront costs of a 2-axis solar system are nearly double that of a fixed system. Despite initial drawbacks, the estimated breakeven point of the system configuration based on our testing is 8.2 years, as opposed to 11.1 years for a fixed system. To put this in perspective, an average fixed solar system will take approximately 8-10 years for homeowners to start seeing returns.

Chapter 9 Realistic Constraints and Engineering Standards

9.1 Realistic Constraints

Our solar tracking system seeks to push the boundaries of current limits on renewable energy technologies. It serves as a proof of concept for individual consumer solar generation systems or as a component in a large utility scale system. The health and safety component involves ensuring that any end user as well as anyone maintaining the system will be guaranteed safety. The system must also make an economic impact in the form of energy savings providing a return on investment over the long term. Sustainability can be demonstrated through long term energy gains compared to a fixed panel system. Our system can be manufactured with relatively standard materials, but the design does leave room for improvement with regards to ease of manufacturing. To ensure consideration of social impacts, the design makes use of no proprietary components or designs.

9.1.1 Health and Safety

To address health and safety issues within our design, the most paramount concern is user safety. If the end user is not guaranteed safety around our design, then as engineers, the design is not one worthy of production. Our design consists of moving parts, sharp corners, and live electricity. Part of our end goal was to create a set of assembly instructions. Included within these instructions are several safety guidelines including but limited to: do not touch the system while moving, ensure that power to the system is off before touching or moving the system, and to ensure children are not left unsupervised in the area of the system.

One safety issue encountered along the way is roof construction and integrity. As part of our design, we have mounted the system on a vertical upright post, and all documentation references the system as being mounted on the ground or industrial flat roof. One issue with residential homes, specifically those built before 1980, is the method of construction: simple nails and a 2x6 beam. As part of our customer interviews, we discovered that most homes, especially those built before 1980 cannot withstand the forces required to place a solar tracking system on the roof.

This is chiefly due to the wind load on the panel, which is then transmitted to the beams in the roof. In homes built before 1980, a single 2x6 support beam and nails cannot withstand the forces ripping the nails from the support beam. As such, our design is targeted solely towards ground or flat roofed industrial installations. Safety is paramount, and nothing, even the pursuit of sustainable and renewable energy, should trump the safety of the end user, the general populous, and structural integrity of an individual's home.

9.1.2 Economic

An economic analysis of a solar system should include not only system component costs, but also upfront set-up costs as well. In order to examine the economic impact of our solar system within the lens of realistic constraints, some values must be considered. These values include our component cost of $1,373.94 and our additional initial set-up cost of $928.81 for a total cost of $2,302.75.

With these figures in mind, and based on the ROI conducted in Section 2.5, our product successfully delivers a solar system to an end user with a better return on investment compared to a traditional fixed photovoltaic system. This falls into line with our initial goal of providing the end user with a return on investment in the same order of magnitude as traditional solar.

If this proof of concept was to be delivered as a complete system to a typical household consumer with little to no experience in solar systems, manufacturing considerations would most definitely alter the price point at which the system could be offered. Large orders of third party components, as well as decrease in cost of parts manufactured would almost certainly yield a net reduction in end price point.

9.1.3 Sustainability and Environmental Impact

Our solar tracking system addresses a problem directly related to sustainability. By seeking to push the boundaries of renewable energy technologies, our design looks to address issues of global sustainability. How can we as a society continue to lessen the impact of climate pollution?

One way to address climate pollution is through the integration of more renewable energy into our current power grid. Our design seeks to maximize solar energy flowing into the power grid, thus reducing the amount of energy generated by fossil fuels. Additionally, for environmental reasons, our design makes use of a water based cleaning system. While a chemical based solution may provide for larger energy gains due to more efficient cleaning, our design uses only tap water in order to reduce risk of pollutants being discharged into the local environment. It is important to note that all of the metal on our frame is recyclable, and able to be used in other projects should the end user decide to do so. It is even more important to note that our design does make use of some high impact materials: battery, inverter, Raspberry Pi, keyboard, and monitor. However, the specific models selected were chosen based on lifespan and repurposing ability for after the span of the tracking system. Regarding the photovoltaic panel itself, the panel is rated for a thirty year lifespan, much longer than the rest of the system components.

To address sustainability relating to product lifespan, our design includes weather resistant parts, and is constructed solely of parts available off the internet, at the local hardware store, or 3D printed parts. The product uses any standard size photovoltaic panel, and if one wanted to switch panels, the only change required would be modifying the mounting holes on the frame railing. If one wanted to switch linear actuators, that could also be done through simply switching mounting hardware on the L shaped frame brackets.

9.1.4 Manufacturability

Our paramount concern in manufacturability was to ensure that all parts could be sourced from the internet, local hardware stores, or manufactured in-house using mills, lathes, and 3D printing technology. Many of the aluminum and steel members of the frame, for example, required machine shop work. While these machined parts are not “off the shelf” ready to go, they are however able to be machined locally. Other components such as the Raspberry Pi microcontroller are commercially available on Amazon or other international suppliers. 3D printing was used to create smaller, more complex parts such as limit switch holders and the photoresistor housing. Having been able to locally source our materials, the solar system is capable of achieving quick-turn manufacturability.

In comparison to other existing solar tracking systems, our design uses a combination of existing technologies and new ideas. One example is our cleaning system, which is entirely designed, tested, and manufactured ourselves. Design changes such as new and more robust hinges, and flexibility in panel size, make our product more effective and viable for long-term use. These two examples demonstrate how if a user wanted to manufacture our design, they could make use of various resources, engineering knowledge, and experiences in order to manufacture the solar tracking and cleaning system.

Throughout the design process, manufacturability was a paramount consideration. Using standard machine shop tools and common electrical and mechanical components our project was able to be constructed in a reasonable amount of time. The components needed to construct this design cost $1,373.94. Our system was designed to be an all-in-one, complete solution from battery to solar panels, thus justifying the cost. For these reasons, it is reasonable to assume this project would be viable to produce commercially.

9.1.5 Social Considerations and Usability

In the process of designing our solar tracking system, the end user was consistently a primary consideration. From our customer interviews and market research, the end user is particularly interested in ease of use, programmability, and return on investment.

In addition to providing a return on investment, our design also seeks to be customizable for various environments, social conditions, and user preferences. These considerations fall under the umbrella of usability. One example of an environmental condition which played a role in shaping the final design was the 2018 California wildfires. From our customer interviews, solar panels face diminishing energy capture with the accumulation of ash and soot. This ash and soot is sent airborne during the wildfire season, and lands on the end user's solar system. Our design seeks to provide the user the ability to customize their cleaning system, as in the case of the California wildfires the end user would desire a more frequent cleaning schedule to offset the ash accumulation. This design, which allows for end user customization, provides for maximized usability within the given constraints of the system.

Furthermore, the design for the system is a modular design. One individual panel and cleaning system could be integrated into an existing system. Even greater than serving as an add-on to existing systems would be the installation of multiple new solar tracking and cleaning systems. There exist endless possibilities for end user usage of our design.

9.2 Engineering Standards

The following section covers relevant industry standards necessary to the successful design, manufacturing, and assembly of our solar system. Without these standards as guiding principles, we would not be able to stand proudly by our design as mechanical engineers. These six standards are listed as references [6]-[8] & [10]-[12].

OSHA 1910.133 - Eye and Face Protection [6]

Our project was conducted with the careful consideration of several safety-related OSHA standards. All fabrication during the winter and spring quarters of the 2022 academic year took place in the teaching and machine shop located at 1122 in the Sobrato Campus for Discovery and Innovation (SCDI). During the manufacturing of all parts in the system all team members always wore appropriate eye and face protection. OSHA standard 1910.133 describes how to appropriately utilize eye and face protection when working in an environment with potential flying particles in the air. The standard states eye and face protection must provide sufficient side protection from debris in the air. Every member of the team utilized eye protection at all periods while in the machine lab environment. Furthermore, when performing work at heavy machinery such as the milling machines or observing faculty of the university weld a full-face shield aided in protecting the team members.

OSHA 1910.95 - Occupational Noise Exposure [7]

This OSHA standard ensures safe working conditions by providing protection against noise exposure for any environment deemed unsafe. The only environment where this standard applied is the faculty machine shop located in room 1123 in the Sobrato Campus for Discovery and Innovation. Gary Sloan, the manager of the machine and electronics shop, aided the group in the machining work for the pump bracket constructed out of sheet metal. Gary further helped the group by welding the north-south hinge. During the time spent in SCDI 1123 the group members were provided and utilized ear protection against heavy noise exposure.

OSHA 1910.212 - General Requirements for all Machines [8]

Over the course of manufacturing the project the team utilized the milling machines and lathes located in SCDI 1122. The machines utilize two-axis computer numerically controlled (CNC) capacity. The CNC capacity allows for a safer environment in the lab. OSHA 1901.212 states that, "One or more methods of machine guarding shall be provided to protect the operator and other employees in the machine area from hazards such as those created by point of operation, ingoing nip points, rotating parts, flying chips and sparks." Both the lathe and milling machines in the lab environment are complete with barrier guards and electronic safety devices. These systems do not allow for the heavy machinery to run unless the guard is engaged.

ASME Y14.100-2017 - Engineering Drawing Practices [10]

To display and communicate the engineering drawings through the help of computer aided design software SolidWorks the group incorporated ASME drawing- related standards. Each part machined in the lab had a drawing made in order to ensure safety and a laid out plan that would allow for maximum safety and organization. There were also subassembly drawings and a complete assembly drawing. These drawings can be found in Appendix G. We adhered to the ASME standard Y14.100-2017 in conjunction with ASME Y14.5. These standards outline the requirements and expectations of a completed set of professional drawings. The drawings seen in Appendix G allow for another engineer or machinist to complete the part without having a discussion with our CAD engineers. There are sufficient measurements, labels, and material expectations in these drawings. The drawings provide a clear set of views that permit the parts to be completed by anyone familiar with this engineering standard.

ASME Y14.5 - Dimensioning and Tolerancing [11]

This standard for dimensioning and tolerancing was vital during the process of creating the part drawings and assembly drawing. It specifies the requirements for symbols, datums, along with other aspects of dimensioning and tolerancing. By identifying the tolerancing options in the drawings packet provided in Appendix G, the ASME standard was applied to allow for another engineer to be familiar with the expectations for each part. Along with the policies taught in MECH 10/L at Santa Clara University the group inserted dimensioning information in the drawings to follow this engineering standard. As seen in the drawing labeled “North-South Bracket” in the drawing packet located in Appendix G. The location of the holes in relation to the top right corner of the sheet metal was deemed the most critical measurement. Therefore, all measurements were dimensioned from this point. The same logic was applied to all the parts and drawing in this packet.

6.5.15 ASCE 7 - Minimum Design Loads and Associated Criteria for Buildings and Other Structures [12]

Specifically, 6.5.15 within ASCE 7 refers to Design Wind Loads on Other Structures. This standard was used to provide wind load values for our solar tracking system. By using this standard, we were able to mathematically provide a theoretical value for force acting upon the panel. By making use of this standard, we then were able to turn information about our system such as panel size, geographic location, and height off the ground into a wind load force value. This force value was then used in our initial FEA simulations. These FEA simulations provided a secondary measure of checking safety of components such as hinges, posts, and frame members.

Chapter 10 Project Evaluation and Conclusions

10.1 Suggested Improvements to Current Build

Through the course of researching, designing, manufacturing and testing, there were key moments in which team members were able to reflect on our progress. It was from these moments that these suggested improvements were born. There are four main areas we would have done differently, had we known what we know now. These areas are: frame weight, plywood and caster selection, cable and electronics management, and mistakes with fine details. Each of these areas provided a time setback, minor inconvenience, or potential safety risk, all of which we lacked the foresight to see in advance.

10.1.1 Overbuilt Frame and Resulting Weight

While the decision to keep the upright post as ⅛” steel was driven out of concern for linear actuator performance and fear of deflection impacting system performance, it became apparent that the weight of the system made it challenging to move. Many of our other decisions were driven by portability, such as the decision to not integrate home outdoor hose bibs and standard 110V power. With better foresight, our recommendation is to use a lighter or thinner upright post. If this is not an option, then the recommendation is to select more robust components for the base. The next section will detail issues we ran into with the plywood base and casters.

10.1.2 Plywood Base & Caster Selection

During systems development, we continue to add more and more weight to the plywood base and casters. While the initial casters held steady through our manufacturing efforts and up until the system was ready to undergo validation testing. It was at this point just before our first set of tests, the first set of casters broke.

In order to overcome this setback, we purchased a new set of casters and attached them to the plywood base. However, once this new set of casters was installed, the center of the plywood base began to sag slightly inwards. While not a cause for immediate safety concern, a long term system would need to address this problem.

Not only did the casters break initially, but the casters also failed while moving the system into the presentation room during the annual Senior Design Conference. In the Sobrato Campus for Discovery and Innovation courtyard, one caster broke, resulting in the team carrying the system to the presentation and back to the shop afterwards.

10.1.3 Cable and Electronics Management

While less of an issue compared to the casters, the cable and electronics management became a nuisance while repeatedly moving the system for testing and presenting. The loose wires and cables were easily snagged on a passing object or by a team member moving the system. In order to minimize risk to system components, it is recommended that more care and attention be placed on the placement of electronic devices on the frame. Additionally, it is recommended that velcro cable ties be used to ensure there is no danger to system wiring and system movement.

10.1.4 Attention to Detail and Finishing Touches

In end reflection, some of the smaller details were overlooked throughout the process. During the process of cutting frame pieces to length, the corners became jagged and sharp. While at the time the jagged edges did not seem sharp, it became clear the edges were a slight safety hazard once assembled as part of the larger system. It is recommended for all future endeavors to round corners, sand all edges once assembled, and cover any sharp bolt edges with caps or other 3D printed safety measures. In addition to the sharp edges, there were also open ended tubes as part of the frame assembly. It is recommended that for future usage, the tube ends be capped with either store bought plastic caps or manufactured 3D printed caps.

10.2 Future Considerations

For future expansion, there are clear areas within which the system could be developed further. Whether concepts originating from our customer needs, or concepts developed during the project life cycle, there are a few key areas with room left for evolution. These areas include: home integration, user experience (UX) creation, and long-term data acquisition (DAQ).

For the scope of this project, it was determined that integrating home water tap and connection to 110V power would be detrimental to our ability to move, test, and adapt the system to the various locations around campus. For example when conducting testing, we were not forced to consider testing locations with a home water tap and 110V power, as our system drew power from the onboard battery and ran the cleaning system using the onboard pump and bucket. In order to develop the concept further, it would be necessary to consider adding a home water tap and 110V power integration. These integrations would allow for more rigorous testing, as well as be an initial first step into turning our system into a product worthy of delivery to a home consumer.

Additionally, the creation of a proprietary user interface or mobile or web application was determined to be outside the scope of this project. Due to our ability to use the bluetooth app to collect power generation, and our limited time to conduct testing, the decision was made to not invest many hours into the development of our own application. For a product to be delivered to an end consumer, a user experience that combines power generation data with cleaning programming would be of utmost importance. From our initial customer interviews, it was apparent that users value easy to understand feedback and easy programming of their cleaning system. An ideal user experience, tailored to fit the needs of our system, would be instrumental in ensuring end user satisfaction.

Finally, in order to measure the performance of our system in the long term, it is highly important to consider durability, robustness, and repeatability of results. An ideal long term testing plan would need to consider the following, and possibly even more variables:panel location, weather conditions, fixed panels in control group, and different panel manufacturers and models. For the limited time after completed systems integration and testing, our focus was placed into gathering initial sets of data. For an end consumer to truly understand the value of such a system, a complete demonstration of our system capabilities and long term success would be absolutely necessary.

A complete drawing packet and instructions manual for panel assembly can be found in Appendix G. In order to recreate this proof of concept, the drawing packet can be used as a reference guide, and is instrumental in repeating the process undertaken in this experiment.

10.3 Evaluation of Final Design and Build

Evaluation of our final design and build will be based on our initial five customer needs. Customer needs (CN) 1-5, as shown in Table 1, can be used as a self-created method of evaluation. Sections 10.3.1-10.3.5 will discuss how our final design and build executes our initially identified customer needs.

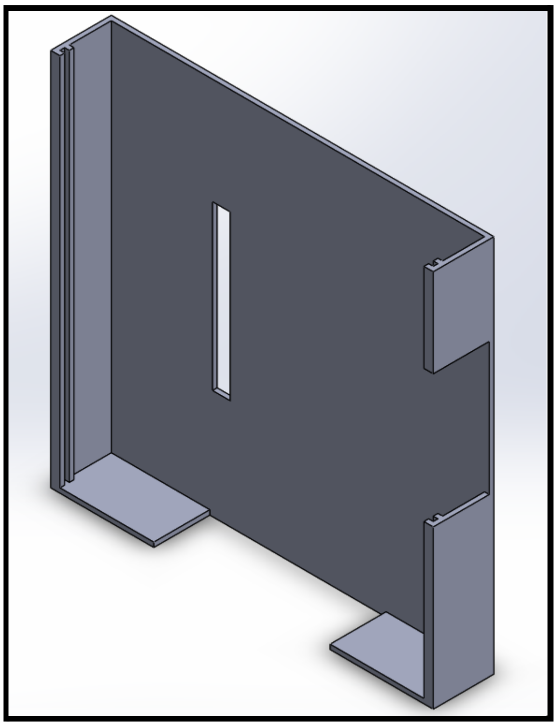
10.3.1 Customer Need 1: Easy to Integrate with Current Infrastructure

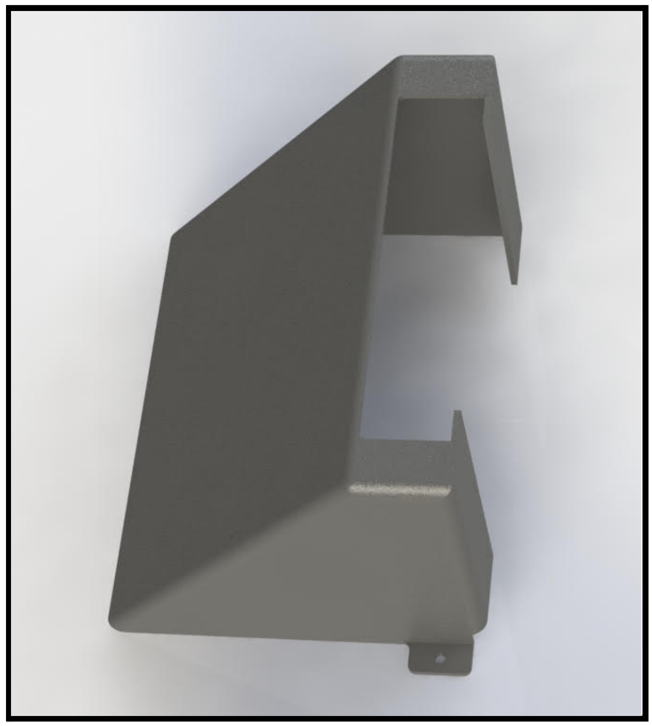
With the need to move the system frequently from various locations around Santa Clara University, the decision was made to not integrate an outdoor faucet connection. During manufacturing and testing, the system was moved at least once daily between the machine shop, first-floor patio (cleaning and systems validation testing), and third-floor patio (fixed and tracking testing).

Additionally, for mobility purposes, the system was designed to draw power from the mobile battery attached to the system. This allowed us to test the system in places without a standard 110V outlet nearby. A full concept delivered to an end user outside the scope of an academic setting would require 110V power, or other additional electrical configurations necessary to power the onboard electrical systems.

10.3.2 Customer Need 2: Little Hands-on Maintenance is Required

The onboard electronic components are shielded from the elements using 3D printed shrouds, seen below in Figures 37(a) and 37(b), designed to resist light water spray, either from the environment or from the cleaning system. The cleaning system is designed to only run when the panel is at a certain optimal angle for cleaning, thus avoiding pooling water and indirect water spray to electronics. With this in mind, the cleaning system runoff does not come into contact with the electronic components housed at the base of the system.





Figures 37(a), left, and 37(b), right: Shrouds used for the Raspberry Pi and the PCB holder.

10.3.3 Customer Need 3: Easily Programmable by Consumer

For the system to truly be effective, the cleaning system must be able to operate from a distance, and programmable such that the user is able to set a recurring schedule in addition to manually triggering the cleaning cycle. With the integration of the Raspberry Pi, the user is able to set their desired cleaning schedule as discussed in Section 5.3.

For future development, a user experience (app or web portal based) would provide the user with power generation values as well as cleaning system control.

10.3.4 Customer Need 4: System is a Good Investment

In order for the system to make economic sense, our energy returns need to be high enough to justify the upfront cost of a dual axis and water cleaning solar system. Based on our own ROI, the breakeven time for a fixed system is 11.1 years, while the breakeven time for our system is 8.2 years. Further details can be found in Section 8.6, and provide full information for the ROI and budget. Based on our system providing a better breakeven time compared to a fixed panel as well as our initial set of testing data, our system does accomplish the original goal of a combined tracking and cleaning system being a better investment than a fixed panel system.

10.3.5 Customer Need 5: System is Easy to Understand

Aiming for ease of end use, the system should provide measurable feedback. In order to complete testing in a timely manner, the decision was made to use the mobile app from the Renogy module as an interim solution. For future development and delivery as a full product to an end consumer, the system should be incorporated into a user experience as discussed in Section 10.2.

10.4 Lessons Learned

Throughout the entire lifecycle of the project, each stumbling block led to a new solution. Each time our team ran into an issue or something that would potentially hold us back, we pushed past it through team collaboration and fundamental engineering knowledge. The ability to hold in person or remote meetings was advantageous. In person meetings for six individuals were often challenging to schedule, so the ability to fall back on remote meetings was key in our ability to push past technical roadblocks. Each subsystem was developed by two lead team members. Early on, we structured our team so that only two members looked at each subsystem, but we learned to implement routine checks of other subsystems to maximize the engineering knowledge and ability channeled into each subsystem. The hard work from each team member culminated in presenting our work at the annual end of year Santa Clara University Senior Design conference. The slides for this presentation are shown in appendix H. We identified some team values early on, even before we had chosen a project. These values included accountability within the team, clear written communication and expectations for deadlines and quality of work, as well as focusing on discussing the concepts rather than the individual presenting the idea. Each team member provided a unique perspective, and we held each other to the highest standards. Through balancing personal and professional struggles, applications for graduate school, career aspirations, and our rigorous academic curriculum, the team values we identified at the beginning of the project were the driving force in accomplishing goals we initially deemed impossible.

References

[1] Sun Action Trackers. "Dual Axis Solar Trackers by Sun Action Trackers: PST-2AL." *Sun Action Trackers*, Sun Action Trackers, 13 Oct. 2020, http://www.sat-energy.com/pst-2al-dual-axis-solar-tracker/.

[2] Ray, S., & Tripathi, A. K. (2016). Design and development of tilted single axis and azimuth-altitude dual axis solar tracking systems. *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*. https://doi.org/10.1109/icpeices.2016.7853190

[3] Faculty of Mechanical Engineering University Malaysia Pahang, 2020, "An Experimental comparison study between Single-Axis Tracking and Fixed Photovoltaic Solar Panel Efficiency and Power Output: Case Study in East Coast Malaysia," Faculty of Mechanical Engineering, University Malaysia Pahang.

[4] Liu, Y., Zhang, Y., Zhao, Y., Yue, H., Gao, D., Zhang, H., & Chen, H. (2021). Performance comparison of solar single-axis tracking low-concentrating photovoltaic/thermal system with different axes. *IEEE Access*, *9*, 28632–28645. https://doi.org/10.1109/access.2021.3058283

[5] Kar, S. K., Akhtar, A., Gambhir, A. S., Vignesh, J., & Nair, R. (2020). Design and development of waterless solar panel cleaning system. *IOP Conference Series: Materials Science and Engineering*, *912*(3), 032005. https://doi.org/10.1088/1757-899x/912/3/032005

[6] "Occupational Safety and Health Administration 1910.133 - Eye and Face Protection." *1910.133 - Eye and Face Protection. | Occupational Safety and Health Administration*, www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.133.

[7] "Occupational Safety and Health Administration 1910.95 - Occupational Noise Exposure." *1910.95 - Occupational Noise Exposure. | Occupational Safety and Health Administration*, https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.95AppA.

[8] "Occupational Safety and Health Administration 1910.212 - Occupational Noise Exposure." *1910.95 - General Requirements for all Machines. | Occupational Safety and Health Administration*, https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.212.

[9] "*Use of energy explained-Energy use in homes*". (2019, May 9). U.S. Energy Information Administration. Retrieved May 31, 2022, from https://www.eia.gov/energyexplained/use-of-energy/electricity-use-in-homes.php

[10] "Y14.100 - Engineering Drawing Practices: ASME." *ASME*, www.asme.org/codes-standards/find-codes-standards/y14-100-engineering-drawing-practices.

[11] "Y14.5 - Dimensioning and Tolerancing." *ASME*, www.asme.org/codes-standards/find-codes-standards/y14-5-dimensioning-tolerancing.

[12] *"ASCE 7 - Minimum Design Loads and Associated Criteria for Buildings and Other Structures." ASCE,* https://www.asce.org/publications-and-news/asce-7.

Appendix A: Subsystem Iterations

Table A1: Decision matrix for the structure and actuation subsystem. After a weighted decision, a system utilizing two linear actuators rose as the best design choice.

	Criteria (Out of 5)						Total (Unweighted)	Total (Weighted)
	Cost	Simplicity & Maintenance	Manufacturability/ Project Integration	Integration with Current PV Systems	Durability	Ground Footprint		
Weights	23%	18%	13%	17%	14%	15%		100%
Cable Pulley System	4	1	2	1	2	2	12	2.11
2 Linear Actuators	3	4	4	4	4	5	24	3.92
1 Linear Actuator & Rotary Actuator	2	2	3	5	3	4	19	3.08

Cost - Total we expect the subsystem to cost after completion. A higher score corresponds to a lower cost.
Simplicity & Maintenance - Less moving parts corresponds to less risk of breaking, or maintenance required. The simplicity of a solution is valued more compared to its complicated counterpart.
Manufacturability/Project Integration - How easy a system is to manufacture given our capabilities. Additionally, a measure of the ease with which the concept can be integrated with the rest of our system.
Integration with Current PV Systems - A measure of how well a solution meshes with existing systems on the market and corresponds to the scalability of the system. A one-off solution does not provide value, whereas a scalable solution provides immense value.
Durability - How long we expect a system to work without any human interaction. A higher score corresponds to a longer time.
Ground Footprint - How much space the solution takes up. Less space the better.

Table A2: Decision matrix for automated cleaning subsystem. After a weighted decision, a stationary sprinkler system arose as the best design choice

	Cost	**Manufacturability**	**Project Integration**	**Durability**	**Weather Resistance**	**Cleaning Efficiency**	**Total (Unweighted)**	**Total (Weighted)**
Weights	19%	18%	20%	15%	13%	15%		100%
Wiper System	2	4	2	3	4	4	19	3.07
Brush System	1	2	2	1	4	5	15	2.37
Sprinkler System	4	5	4	4	2	2	21	3.62
Moving Sprinkler System	3	3	2	3	2	3	18	2.67

Cost - Total we expect the subsystem to cost after completion. A higher score corresponds to a lower cost.
Manufacturability - Our projected ability to manufacture design without major complications. A higher score corresponds to easy manufacturing
Project Integration - How easy subsystem design could be integrated with other subsystems of the tracker. A higher score corresponds to easier integration.
Durability - How long we expect a system to work without any human interaction. A higher score corresponds to a longer time.
Weather Resistance - How well we expect a system to hold up to natural conditions. High/low temperatures, rain, snow, dust accumulation, etc. A higher score relates to higher resistance.
Cleaning Efficiency - How well we expect a system to clean the PV panel in a given cycle. A higher score relates to a cleaner panel.

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Table A3: Technical hierarchy of needs from customer interviews. These needs were derived from interviews with key stakeholders.

Need	**Product**	**Needs To**	**Importance**
1.1	Integration	Require standard water hookup	9
1.2	Integration	Draw from 110V power	9
1.3	Integration	System weight should not require additional rooftop or ground construction	3
2.1	Maintenance	Require less maintenance than existing systems	9
2.2	Maintenance	Motor components resist exposure to elements	3
2.3	Maintenance	Cleaning components resist exposure to elements	3
3.1	Programmability	Able to set desired cleaning schedule	9
3.2	Programmability	User can select weather conditions to impact cleaning schedule	1
4.1	Return on Investment	Tracking + Cleaning provides savings compared to fixed panel	9
4.2	Return on Investment	Upfront cost is competitive with fixed panel costs	1
4.3	Return on Investment	Proportional relationship between increased upfront cost and energy savings	1
5.1	Ease of Understanding	User understands feedback from system	9
5.2	Ease of Understanding	Real time feedback provided	3
5.3	Ease of Understanding	Feedback provided comparable to set reference frame	1
5.4	Ease of Understanding	Remote access to feedback provided	1

Appendix B: Summary of Interviews Conducted with Stakeholders

MG Mungal is an SCU Faculty member and homeowner. While he does not currently own solar, he has undergone the bidding process and plans to install solar in the near future. MG highlighted the most important needs as cleaning and ease of feedback for the end-user. One interesting point from the interview with MG was the notion of introducing an easy-to-use measure of performance for the reader. For example, if the panels are supposed to operate at X Watts, and are currently at 0.5X Watts, then the user can understand their panels are working at a fraction of their potential. MG identified this feedback should be instantaneous and presented in an easy-to-understand form.

Stephanie Mason is a current employee at Cupertino Electric Inc. and a local homeowner. Stephanie does not currently own solar panels, but recently underwent the bidding process in order to investigate upfront costs and potential ROI. The interview highlighted the possibility of alleviating confusion in the consumer about system sizing, system performance, and maintenance. Stephanie shared that as someone with little experience with solar, she would most likely pay someone to clean her panels. This exchange highlighted the need for a built-in maintenance system to save costs on periodic cleaning.

Wayne Johnson is a homeowner and owner of SEG Inc. He currently oversees twenty-five employees and works on back-end infrastructure systems for semiconductor fabrication, aerospace. SEG Inc. completed the renovation of the Alumni Science building at SCU. Speaking to Wayne was an enlightening experience, as he is experienced in technical matters and well versed in power transmission and distribution. The largest outcome from the interview with Wayne was a deeper understanding of how residential homes are unfit to support a solar system with a high wind load. Another key takeaway from the interview was the ease with which Wayne is able to clean his panels. With Wayne’s Panasonic panels, he is able to hose them off from the ground floor, and have minimal water pressure.

Aaron Lung is a homeowner and created his own DIY solar array. He maintains and makes upgrades to his system on a periodic basis. One important takeaway from the interview with

Aaron is that in his piecemeal setup (part professionally installed and part self-installed), he is able to monitor his output in real-time. This was not something originally included in the professional installation, so when he installed his own batch of supplementary panels, he also installed a system to be able to monitor his panels in real-time from his phone. To Aaron, cleaning is not a major concern since his current system is relatively low-effort to maintain.

Appendix C: Wind Load Calculations

Wind load calculations take the form of “other structure” as defined by the American Society of Civil Engineers [11]. Standard 7 as published by the ASCE, allows for use of Equation C2 as an estimation for the wind load experienced at a height z. For our purposes, the wind load for the western coast of California was calculated at a height of 15 ft, and assumed to be classified as a non important building per the ASCE guidelines. Equations C1 and C2 below were used to calculate a final wind load of 100.8lbs. In Equation 2, q_z is defined as the velocity pressure evaluated at the centroid of A_f, G is defined as the the gust effect factor and taken to be 0.85, C_f is defined as the force coefficient and taken to be 1.3, and A_f is defined as the surface area of the object in ft^2, taken to be $9ft^2$. Equation C1 details the velocity pressure calculation used later in Equation C2. In Equation C1, K_d = wind directionality factor, taken to be 0.9, K_z is defined as the velocity pressure exposure coefficient and is taken to be 0.7, K_{zt} is defined as the topographic factor and taken to be 1, V is defined as the regional basic wind speed and is taken to be 85 mph or 38m/s and, I is defined as the importance factor and taken to be 0.87. The result of Equation C1 yields a velocity pressure of 10.14. This velocity pressure is then used in Equation C2.

$$q_z = 0.00256 K_z K_{zt} K_d V^2 I = 10.14 \quad \text{(C1)}$$

$$F = q_z G C_f A_f (lb) = 100.8 lbs \quad \text{(C2)}$$

Appendix D: List of Additional References

Additional References vital to the initial research portion of the project, but not directly referenced in this thesis document are listed below:

Coulbourne, William, and Eric Stafford. *Wind Loads: Guide to the Wind Load Provisions of Asce 7–16 (Asce Press)*. Amer Society of Civil Engineers, 2020.

Faculty of Mechanical Engineering University Malaysia Pahang, 2020, "An Experimental comparison study between Single-Axis Tracking and Fixed Photovoltaic Solar Panel Efficiency and Power Output: Case Study in East Coast Malaysia," Faculty of Mechanical Engineering, University Malaysia Pahang.

Habib, M. R., Tanvir, M. S., Suhan, A. Y., Vadher, A., Alam, S., Shawmee, T. T., Ahmed, K., & Alrashed, A. (2021). Automatic solar panel cleaning system based on Arduino for dust removal. *2021 International Conference on Artificial Intelligence and Smart Systems (ICAIS)*. https://doi.org/10.1109/icais50930.2021.9395937

Katrandzhiev, N., & Karnobatev, N. (2019). Energy costs reduce in energy-efficient buildings by applying single Axis Solar Tracker. *2019 Second Balkan Junior Conference on Lighting (Balkan Light Junior)*. https://doi.org/10.1109/blj.2019.8883440

Kuttybay, N., Saymbetov, A., Mekhilef, S., Nurgaliyev, M., Tukymbekov, D., Dosymbetova, G., Meiirkhanov, A., & Svanbayev, Y. (2020). Optimized single-axis schedule solar tracker in different weather conditions. *Energies*, *13*(19), 5226. https://doi.org/10.3390/en13195226

Mejia, F. A., & Kleissl, J. (2013). Soiling losses for solar photovoltaic systems in California. *Solar Energy*, *95*, 357–363. https://doi.org/10.1016/j.solener.2013.06.028

Othman, N., Manan, M. I. A., Othman, Z., & Al Junid, S. A. M. (2013). Performance analysis of dual-axis solar tracking system. *2013 IEEE International Conference on Control System, Computing and Engineering*. https://doi.org/10.1109/iccsce.2013.6719992

Pratama, Aditia Yoga, July 2019, "Performance Enhancement of Solar Panel Using Dual Axis Solar Tracker," International Conference on Electrical Engineering and Informatics (ICEEI).

Rani, P., Singh, O., & Pandey, S. (2018). An analysis on Arduino based single Axis Solar Tracker. *2018 5th IEEE Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON)*. https://doi.org/10.1109/upcon.2018.8596874

Rengasamy, Dr. Dhanabal & Bharathi, Venuturla & Ranjitha, R. & Ponni, A. & Deepthi, S. & Mageshkannan, P.. (2013). Comparison of efficiencies of solar tracker systems with static panel single-axis tracking system and dual-axis tracking system with fixed mount. Intern. J. Eng. Technol.. 5. 1925-1933.

Rinaldi, R., Aprillia, B. S., Ekaputri, C., & Reza, M. (2020). Design of open loop single axis solar tracker system. *IOP Conference Series: Materials Science and Engineering*, *982*(1), 012016. https://doi.org/10.1088/1757-899x/982/1/012016

Shah, A. H., Hassan, A., Laghari, M. S., & Alraeesi, A. (2020). The influence of cleaning frequency of photovoltaic modules on power losses in the desert climate. *Sustainability*, *12*(22), 9750. https://doi.org/10.3390/su12229750

Smith, Alazone, "Dual Axis Solar Tracker: Trends, Influence & Impact" (2019). *Undergraduate Honors Theses*. 10. https://digitalcommons.cwu.edu/undergrad_hontheses/10

Sugiartha, N., Ardana, I. G., Sugina, I. M., Widiantara, I. B., Suparta, I. N., & Adi, I. K. (2020). Preliminary design and test of a water spray solar panel cleaning system. *Journal of Physics: Conference Series*, *1450*(1), 012108. https://doi.org/10.1088/1742-6596/1450/1/012108

Sugiartha, N., October 2019, "Preliminary design and test of a water spray solar panel cleaning system," Journal of Physics: Conference Series.

Yan, Shengzan., December 2020, "Research on Design of Intelligent Cleaning Robot for Solar Panel," International Conference on Electronic Business

Zolkapli, M., Al-Junid, S. A., Othman, Z., Manut, A., & Mohd Zulkifli, M. A. (2013). High-efficiency dual-axis solar tracking developement using Arduino. *2013 International Conference on Technology, Informatics, Management, Engineering and Environment*. https://doi.org/10.1109/time-e.2013.6611961

Appendix E: Raspberry Pi4 Control Systems Code (Python)

For reference purposes, while the text below may appear as a figure, it is truly text. The text is best displayed with the proper black background, and colored text in order to provide an authentic portrayal of how our system code appears in the software.

```
#Final System Script
from itertools import count
from typing import Counter
import RPi.GPIO as GPIO
import time
from datetime import datetime
from multiprocessing import Process
from suntime import Sun
from geopy.geocoders import Nominatim

#define rPI pinouts w/ colored wire connections
GPIO.setmode(GPIO.BOARD)

#photoresistor pins
rpin1 = 11 #Blue
rpin2 = 13 #Gray
rpin3 = 15 #White
rpin4 = 18 #Purple

#linear actuator pins
lpin1 = 29 #Red
lpin2 = 31 #Orange
lpin3 = 32 #Yellow
lpin4 = 33 #Green

#pump pins
```

```
ppin1 = 36 #IN3 Blue
ppin2 = 37 #IN4 Purple

GPIO.setup(lpin1,GPIO.OUT)
GPIO.setup(lpin2,GPIO.OUT)
GPIO.setup(lpin3,GPIO.OUT)
GPIO.setup(lpin4,GPIO.OUT)
GPIO.setup(ppin1,GPIO.OUT)
GPIO.setup(ppin2,GPIO.OUT)

#initiate start time
starttime = time.time()
counter = 0

#function to confirm day of week
def dayOfWeek():
    WEEKDAYS = ['Monday', 'Tuesday', 'Wednesday', 'Thursday',
'Friday', 'Saturday', 'Sunday']

    now = time.localtime()
    dayOfWeek.weekday_index = now.tm_wday
    dayOfWeek.today = WEEKDAYS[dayOfWeek.weekday_index]

#function fetching sunrise & sunset times based on geographical
location
def sunTime():
    #Nominatim API to get latitude and longitude
    geolocator = Nominatim(user_agent="geoapiExercises")

    #input place
    place = "San Jose"
    location = geolocator.geocode(place)
```

```
    #latitude and longitude fetch
    latitude = location.latitude
    longitude = location.longitude
    sun = Sun(latitude, longitude)

    #fetch time now
    t = time.localtime()
    current_time = time.strftime("%H:%M", t)
    yearNow = int(time.strftime("%Y"))
    dayNow = int(time.strftime("%d"))
    monthNow = int(time.strftime("%m"))

    #date in your machine's local time zone
    time_zone = datetime.date(yearNow,monthNow,dayNow)
    sun_rise = sun.get_local_sunrise_time(time_zone)
    sun_dusk = sun.get_local_sunset_time(time_zone)

    sunRise = sun_rise.strftime('%H:%M')
    sunDusk = sun_dusk.strftime('%H:%M')

    sunTime.sunRise = (int(''.join(filter(str.isdigit,
sunRise))))
    sunTime.sunDusk = (int(''.join(filter(str.isdigit,
sunDusk))))
    sunTime.timeNow = (int(''.join(filter(str.isdigit,
current_time))))

#functions taking photoresistor values based on capacitor
charging time
def rc_time1 (rpin1):
    count = 0
```

```
    #Output on the pin for
    GPIO.setup(rpin1, GPIO.OUT)
    GPIO.output(rpin1, GPIO.LOW)
    time.sleep(0.1)

    #Change the pin back to input
    GPIO.setup(rpin1, GPIO.IN)

    #Count until the pin goes high
    while (GPIO.input(rpin1) == GPIO.LOW):
        count += 1

    return round(count/1000)

def rc_time2 (rpin2):
    count = 0

    #Output on the pin for
    GPIO.setup(rpin2, GPIO.OUT)
    GPIO.output(rpin2, GPIO.LOW)
    time.sleep(0.1)

    #Change the pin back to input
    GPIO.setup(rpin2, GPIO.IN)

    #Count until the pin goes high
    while (GPIO.input(rpin2) == GPIO.LOW):
        count += 1

    return round(count/1000)
```

```
def rc_time3 (rpin3):
    count = 0

    #Output on the pin for
    GPIO.setup(rpin3, GPIO.OUT)
    GPIO.output(rpin3, GPIO.LOW)
    time.sleep(0.1)

    #Change the pin back to input
    GPIO.setup(rpin3, GPIO.IN)

    #Count until the pin goes high
    while (GPIO.input(rpin3) == GPIO.LOW):
        count += 1

    return round(count/1000)

def rc_time4 (rpin4):
    count = 0

    #Output on the pin for
    GPIO.setup(rpin4, GPIO.OUT)
    GPIO.output(rpin4, GPIO.LOW)
    time.sleep(0.1)

    #Change the pin back to input
    GPIO.setup(rpin4, GPIO.IN)

    #Count until the pin goes high
    while (GPIO.input(rpin4) == GPIO.LOW):
        count += 1
```

```
    return round(count/1000)


#function checking if all vList values are within tolerance
range of each other
tol = 6
def chkList(vList, rAvg):
    rAvg = round(sum(vList)/len(vList))
    if all(rAvg - tol <= x <= rAvg + tol for x in vList ):
#allowable range from rAvg
        return True
    else:
        return False


#tracking system feedback loop
delay = 0.64 #calculated actuator movement time for precise
tracking
def photoResLoop():
    sunTime()
    while sunTime.sunRise <= sunTime.timeNow <=sunTime.sunDusk:

        vList =
[rc_time1(rpin1),rc_time2(rpin2),rc_time3(rpin3),rc_time4(rpin4)
]
        rAvg = round(sum(vList)/len(vList))

        #photoresistor orientation:
        #[r1 r2]
        #[r3 r4]

        while chkList(vList, rAvg) != True:
```

```
            if rc_time1(rpin1) + rc_time2(rpin2) <
rc_time3(rpin3) + rc_time4(rpin4):
                GPIO.output(lpin1,GPIO.HIGH)
                GPIO.output(lpin2,GPIO.LOW)
                print('move up')
                time.sleep(delay)
                GPIO.output(lpin2,GPIO.HIGH)
            if rc_time1(rpin1) + rc_time2(rpin2) >
rc_time3(rpin3) + rc_time4(rpin4):
                GPIO.output(lpin1,GPIO.LOW)
                GPIO.output(lpin2,GPIO.HIGH)
                print('move down')
                time.sleep(delay)
                GPIO.output(lpin1,GPIO.HIGH)
            if rc_time1(rpin1) + rc_time3(rpin3) <
rc_time2(rpin2) + rc_time4(rpin4):
                GPIO.output(lpin3,GPIO.HIGH)
                GPIO.output(lpin4,GPIO.LOW)
                print('move left')
                time.sleep(delay)
            else:
                GPIO.output(lpin3,GPIO.LOW)
                GPIO.output(lpin4,GPIO.HIGH)
                print('move right')
                time.sleep(delay)
                GPIO.output(lpin3,GPIO.HIGH)

            vList =
[rc_time1(rpin1),rc_time2(rpin2),rc_time3(rpin3),rc_time4(rpin4)
]
            rAvg = round(sum(vList)/len(vList))
```

```
            if chkList(vList,rAvg) == True:
                print("Correct Orientation, End Movement")
                #stop movement for 15 minutes until next cycle
                time.sleep(900.0)
                sunTime()
            #loops after the above criteria is met in the
function...

def cleaningSystem():
    if counter == 0:
        print("re-orienting panel...")
        time.sleep(1.0)
        #bottom out linear actuators before resetting panel
        GPIO.output(lpin1,GPIO.HIGH)
        GPIO.output(lpin2,GPIO.LOW)
        time.sleep(35.0)
        GPIO.output(lpin2,GPIO.HIGH)

        GPIO.output(lpin3,GPIO.LOW)
        GPIO.output(lpin4,GPIO.HIGH)
        time.sleep(35.0)
        GPIO.output(lpin3,GPIO.HIGH)

        #reset up/down to neutral
        GPIO.output(lpin1,GPIO.LOW)
        GPIO.output(lpin2,GPIO.HIGH)
        time.sleep(5.0)
        GPIO.output(lpin1,GPIO.HIGH)

        #reset left/right to center
        GPIO.output(lpin3,GPIO.HIGH)
```

```
        GPIO.output(lpin4,GPIO.LOW)
        time.sleep(16.0)
        GPIO.output(lpin4,GPIO.HIGH)

        print("cleaning system activated...")
        time.sleep(1.0)
        GPIO.output(ppin1,GPIO.HIGH)
        GPIO.output(ppin2,GPIO.LOW)
        time.sleep(20.0)
        GPIO.output(ppin2,GPIO.HIGH)

#Defined day for cleaning
cleanDay = 1

while True:
    dayOfWeek()
    sunTime()
    print("Sun rise at: ",sunTime.sunRise)
    print("Dusk at: ",sunTime.sunDusk)
    print("The time now is: ",sunTime.timeNow)
    print("Today is: ",dayOfWeek.today)
    #cleaning re-primed day after scheduled testing
    if dayOfWeek.weekday_index == cleanDay + 1:
        counter = 0
    time.sleep(2.0)


    if dayOfWeek.weekday_index == cleanDay:
        cleaningSystem()
        counter = 1
        if counter == 1:
            print('Cleaning disabled until next cycle'+'\n')
```

```
        time.sleep(2.0)

photoResLoop()
print('fin tracking.'+'\n'+'done for the day!')

print('re-orienting panel...'+'\n')

#small buffer delay
time.sleep(1.0)

#bottom out linear actuators before resetting pannel
GPIO.output(lpin1,GPIO.HIGH)
GPIO.output(lpin2,GPIO.LOW)
time.sleep(35.0)
GPIO.output(lpin2,GPIO.HIGH)

GPIO.output(lpin3,GPIO.LOW)
GPIO.output(lpin4,GPIO.HIGH)
time.sleep(35.0)
GPIO.output(lpin3,GPIO.HIGH)

#reset up/down to neutral
GPIO.output(lpin1,GPIO.LOW)
GPIO.output(lpin2,GPIO.HIGH)
time.sleep(5.0)
GPIO.output(lpin1,GPIO.HIGH)

#reset left/right to center
GPIO.output(lpin3,GPIO.HIGH)
GPIO.output(lpin4,GPIO.LOW)
time.sleep(16.0)
GPIO.output(lpin4,GPIO.HIGH)
```

```
#small buffer delay
time.sleep(5.0)
```

Appendix F: Student Hazard Project Assessment

As a reference note, the Student Hazard Project Assessment form does not include table or figure captions. This is due to the assembly Student Hazard Project Assessment form existing outside the thesis environment. The Student Hazard Project Assessment form is intended to be used in order to recreate the project assembly in a safe manner, instead of as a component of this thesis.

Project Title:			
Solar Tracker with Integrated Self Cleaning System			
Project Team Members: Brian Weitzenkamp Matthew Kelley Jonathan Lung Nicholas Gallo Justin Eng Kevin Ehlers			
Project Advisor			
Name:	Department:	Phone:	Email:
Pete Woytowitz	MECH	408-554-4061	pwoytowitz@scu.edu
Proposed Project Location(s) (Department, building, room#): Machine Shop 1st floor SCDI SCDI 3rd floor patio B-E Main parking garage roof			
Anticipated Dates of Project Duration: 10/31/21 to 6/15/22			
Summary of Project Objectives: Our goal is to design a consumer/commercial solar panel system that both tracks the position of the sun and pivots to compensate, while also having a built-in cleaning system to remove debris that settles on the panel. This panel is aimed to replace the static panels that are the current standard for both commercial and residential use.			

Hazard Checklist (check all that apply)

Identify all the tasks that must be completed for your project. Carefully evaluate each task to determine if there are any associated hazards. After identifying the hazards of your project, you will be asked to assess the risk connected to each hazard and to identify control measures that will either eliminate the hazard or reduce the risk to an acceptable level. Safe work procedures for each step involving a known hazard will need to be developed.

HAZARDOUS CONDITIONS/PROCESSES/ACTIVITIES		
Electrical Hazards ☐Electrical parts and assemblies > 50V or high current ☐Batteries ☐Control Panels	**Mechanical Hazards** ☐Power tools and equipment ☐ Machine guarding/power transmission – gears, rotors, wheels, shafts, belt/chain drives, rotating parts, pinch points ☐Robotics ☐Sharp Objects ☐ Stored Energy (springs, gravity, pneumatic, hydraulic, pressure)	**Physical Hazards** ☐ Extreme temps (high temp fluids: water > 160 °F, steam, hot surfaces > 140 °F, cryogenic fluids ☐ Material handling of heavy objects ☐ Elevated heights (scaffolding, ladders, roofs, lifts, etc.) ☐ Overhead falling objects (cranes, hoists, drones, projectiles, etc.) ☐ Confined Spaces ☐Airborne Dusts ☐Bonding / Grounding ☐Electrostatic Discharge
Reaction Hazards ☐Explosive ☐Exothermic, with potential for fire, excessive heat, or runaway reaction ☐Endothermic, with potential for freezing solvents decreased solubility or heterogeneous mixtures ☐Gases Produced ☐Hazardous reaction intermediates/products ☐Hazardous side reactions	**Hazardous Processes** ☐Generation of air contaminants (gases, aerosols, or particulates) ☐Heating Chemicals ☐Large mass or volume ☐Pressure > Atmospheric ☐Pressure < Atmospheric ☐Scale-up of Reaction ☐Metal Fabrication (welding, cutting, drilling, etc.), Soldering, ☐Construction/Assembly, etc.	**Other Hazards** ☐Noise > 80 dBA ☐Vehicle traffic ☐Hazardous waste generation ☐Other (list):

Hazard Checklist (continued)

HAZARDOUS AGENTS			
Physical Hazards Of Chemicals	**Health Hazards of Chemicals**	**Non-Ionizing Radiation**	**Biohazards**
☐Compressed Gases ☐Cryogens ☐Explosives ☐Flammables ☐Oxidizers ☐Peroxides or Peroxides Formers ☐Pyrophorics ☐Water Reactives	☐Acute Toxicity ☐Carcinogens ☐Nanomaterials ☐Reproductive Toxins ☐Respiratory or Skin Sensitization ☐Simple Asphyxiant ☐Skin Corrosion/ Irritation ☐Hazards Not Otherwise Classified	☐Lasers ☐Magnetic Fields (e.g. NMR) ☐RF/Microwaves ☐UV Lamps	☐Bsl-2 Biological Agents ☐rDNA ☐Human Cells, Blood, BBP ☐Animal Work ☐Other (List):

Description of Potential Hazards

Provide a summary of the procedure and describe the risks associated with each hazard that you have identified above or on the previous page. Use one box below per hazard. You may add supplemental pages if needed. Define the hazard control measures that will be employed to minimize the risks based on the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, PPE), and then describe specific control measures you will use (e.g. Work on system de-energized, receive hazard specific training, shield hot surfaces, guard pinch points, relieve stored energy, wear protective equipment, use less hazardous chemical, etc.). Refer to “Hierarchy of Controls” in the instructions sheet for more information to decide which hazard controls measures are most appropriate

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Electrical Parts & Assemblies and Batteries
Summary of Procedure or Tasks: Our project will involve using power output from a PV panel, running it through an inverter, and then using that electricity to power a device such as a 12V Lead-Acid battery.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): This could go wrong if a member of the team touches a part of the live electrical circuit. The risk (hazard x exposure) is the combination of the live electrical circuit, and an individual working on the circuit at the same time. The battery, if handled incorrectly, can leak or otherwise cause electrical shock.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): In order to minimize the risks, we will work on the system while it is de-energized and while power sources are disconnected. There is zero reason for our system to work on an energized circuit. It is feasible that we will be able to assemble all of the parts (another hazard on its own) and then power up the system.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Power Transmission
Summary of Procedure or Tasks: We will be using either servo motors and gear trains (including a chain/belt drive) or a DC actuator to pivot the solar panel.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The risk is pinching a finger, appendage, or being hit by the moving panel, or smaller subsystems in motion. The risk (hazard x exposure) is the pinch point or moving panel being exposed to a group member. In order to remove the exposure portion, we will not work on the panel while it is moving. It is most feasible that the panel can be stationary while we program/ assemble it, and then we can start the panel remotely via computer or connected cables.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): We will minimize the risk by making sure that all motors and drive shaft systems are turned off and disconnected before a group member works on the apparatus in order to minimize risk of pinching or a group member being hit by the moving parts of the panel.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Metal Fabrication and Power Tools
Summary of Procedure or Tasks: We will need to fabricate a stand/frame and assorted parts necessary to hold the panel and motor system together. While doing so, power tools may be used to help fabricate and assemble parts. We will test on the patio in front of SCDI on the 3rd floor. We will now relocate testing on the roof of the B-E Main parking garage.

Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): The risk (hazard x exposure) is the combination of metal fabrication processes, and group members conducting them. There is risk of cuts, flying debris, and much more when conducting work on a lathe, mill, or saw.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): In order to minimize the risk, we are all going through Mech 101L at the end of which we are required to pass a safety exam. In addition, we will work only through approved processes we know how to do. The most important elements of minimizing risk come from: ensuring group members wear safety goggles, long pants, closed toe shoes, and have wrists and arms free and clear at all times in the shop. There are safety mats in the shop such that only one individual can stand near the working machine at a time. This limits the exposure for group members who are not operating the machine. Safety guards will be in place at all times (as the machines do not run without them). We will always use a brush to clear metal chips/scraps. No running or horseplay will be permitted, and no eating or drinking can occur in the shop. No group member will work alone in the shop.

Hazardous Activity, Process, Condition, or Agent (identified from previous page): Construction/Assembly
Summary of Procedure or Tasks: We will need to assemble the parts of the apparatus (PV panel, frame, motor, cleaning system, and electrical inverter). We plan to test the system test on the patio in the fron of SCDI on the 3rd floot. Testing will take place beginning on May 5th. Testing has been rolated to the roof of the B-E Main parking garage.
Describe Hazards (why is the procedure hazardous or what can go wrong – what is the risk): Someone could drop a piece of material on themselves, or a fellow group member.
Hazard Control Measures (what you will do to eliminate the hazard or minimize risks): The most important elements of minimizing risk come from: ensuring group members wear safety goggles, long pants, closed toe shoes, and have wrists and arms free and clear at all times. Team members must have at least one other companion to help ensure safety.

SAFETY EQUIPMENT and PPE

Select the appropriate PPE and safety supplies you will need for the project (Check all that apply)

☐ Appropriate street clothing (long pants, closed-toed shoes)

☐ Gloves; indicate type: ___________________

☐ Safety glasses/ goggles

☐ Face shield and goggles

☐ Lab coat

☐ Hearing protection

☐ Fire extinguisher

☐ Eyewash/safety shower

☐ Spill kit

☐ Other (list):

TRAINING REQUIREMENTS

Identify the appropriate training (check all that apply)

☐ Biology & Bioengineering Lab Safety Camino Course – contact Lab Manager or EHS to enroll

☐ Chemistry & Biochemistry Lab Safety Camino Course – contact Lab Manager or EHS to enroll

☐ Electrical Safety for Engineering Camino Course – contact EHS to enroll

☐ LiPo Battery Safety Training – contact MAKER Lab to enroll

☐ Review of SDS for chemicals involved in project – access SDS library at: rms.unlv.edu/msds/

☐ Laboratory Specific Training – contact Lab/Shop Owner

☐ Project Specific Training – contact Project Advisor

☐ Other (describe below):

ACKNOWLEDGEMENT

By signing, I verify that:

1) I am aware of the hazards and risks of all the tasks associated with the project
2) I have received, or will receive all the necessary safety training and/or have read the safety manual and safety data sheets (SDSs) relevant to the project before performing any hazardous tasks
3) I will follow all required safety precautions while working on this project, including but not limited to use of engineering controls, following safe work practices, and wearing appropriate personal protective equipment

Name of Project Team Member	Signature	Date
Brian Wietzenkamp	BW	10/31/21
Kevin Ehlers	KE	11/03/21
Nick Gallo	NG	10/31/21
Matt Kelley	MK	11/4/21
Jonathan Lung	JL	10/31/21
Justin Eng	JE	11/03/21

APPROVALS		
This document must be reviewed and approved by the people below before any project work can begin. A copy of the approved document must be kept where the work is being conducted		
Faculty Advisor		
Name: Pete Woytowitz		
Department: Mechanical Engineering	Signature	Date 11/5/21
Department Chair		
Name: Hohyun Lee	Signature	Date
Laboratory Director/Manager		
Name: Rod Broome	Signature	Date

EH&S		
Name: Sean Collins	Signature	Date
Other		
Name	Signature	Date

The DC solar panel presents no risks unless both leads are connected. The inverter has a power switch that toggles power output, and so the inverter will always be powered off unless testing the system. The inverter converts 12V DC input from the solar panel to 120V AC output. While AC output is a potential greater hazard than DC, the inverter utilizes two 3-pronged outlets. As such, outlet covers will be in place for added safety. The risk of injury is low unless we intentionally place a conductive object into the outlets. For safety, the solar panel will be covered at all times unless testing the system, ensuring that no power is being generated while the circuit is being worked on. Any potential energy will only be stored in the inverter or battery, in which the inverter has built-in GFCI and voltage protections to prevent hazards. The battery works by the same DC principle as the solar panel. Additional power for other components will work at less than 12V input. If necessary, team members will be grounded to the floor, as well as the system. By recognizing and utilizing in-place safety measures, should any team member forget to de-energize the circuit, they will be protected. That being said, we have all agreed to work in pairs or more, to ensure safety.

Appendix G: Assembly Instructions and Drawing Packet

As a reference note, the assembly instructions do not include table or figure captions. This is due to the assembly instructions existing outside the thesis environment. The instructions are intended to be used in order to recreate the project assembly, not as a component of the thesis.

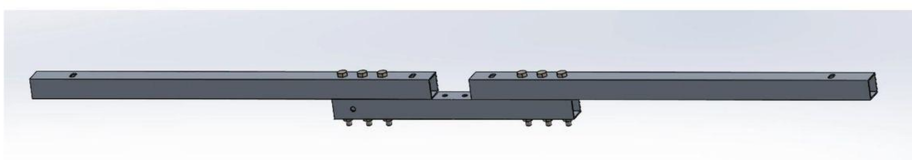
Solar Tracker Assembly Instructions

Main Frame

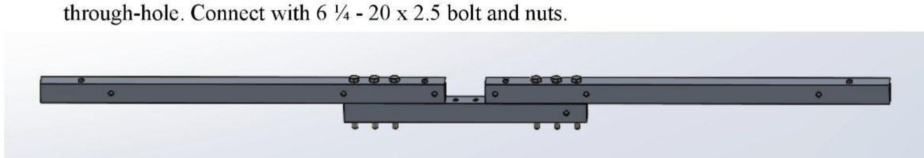
1. Gather all parts

Part	Quantity
Upright post	1
North-south hinge	1
North-south axis member 1	1
North-south axis member 2	1
North-south bracket	2
Hinge female	2
Hinge male	2
East-west member 1	1
East-west member 2	2
Panel mount top	2
Panel mount bottom	2
4-15/16 in. x 6 in. Concrete Form Angle	4
Base	1
East-west washer	4
North-south washer	2

2. Connect the 2 bottom panel mounts with the east-west member 2 that **DOES NOT** have the through-hole on the side. Use 6 ¼ - 20 x 2.5 bolts with nuts.

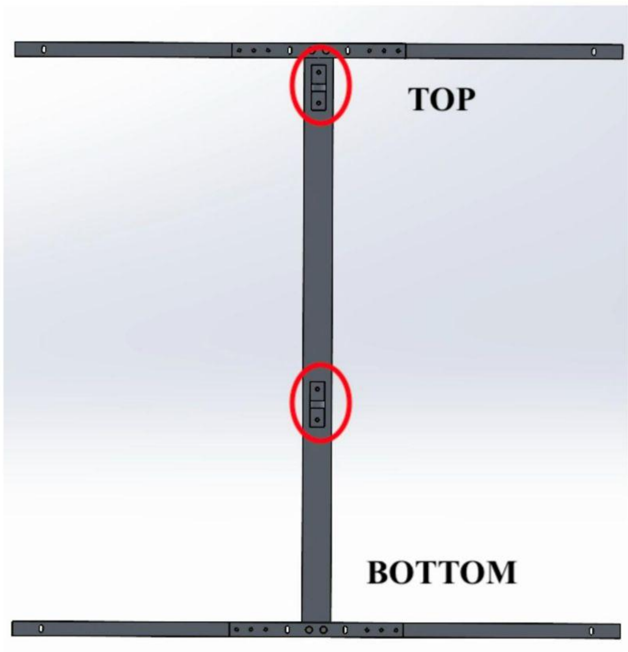


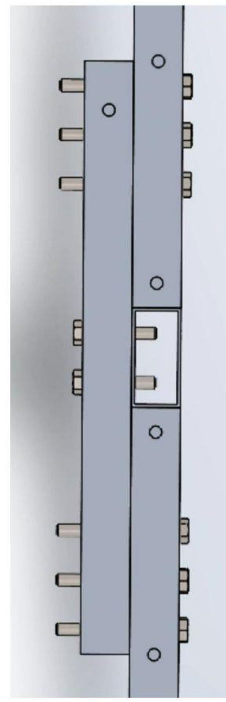
3. Connect the 2 top panel mounts with the east-west member that **DOES** have the side through-hole. Connect with 6 ¼ - 20 x 2.5 bolt and nuts.



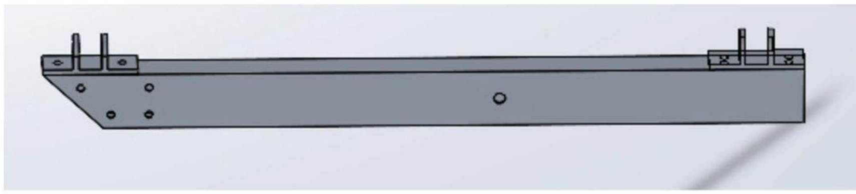
4.

a. Add the male hinges to east-west member 1 using 4 ¼ - 20 x .5 bolts and nuts.
b. Connect assemblies from steps 2 and 3 with east-west member 1. East-west member 1 should be on top of east-west member 2 and between the panel mounts. Assemble with 4 ¼ - 20 x 1.5 bolts and nuts. 2 on top and bottom. Take note of the orientation of the panel mounts and the holes one east-west member 1 as well as the direction of bolts.

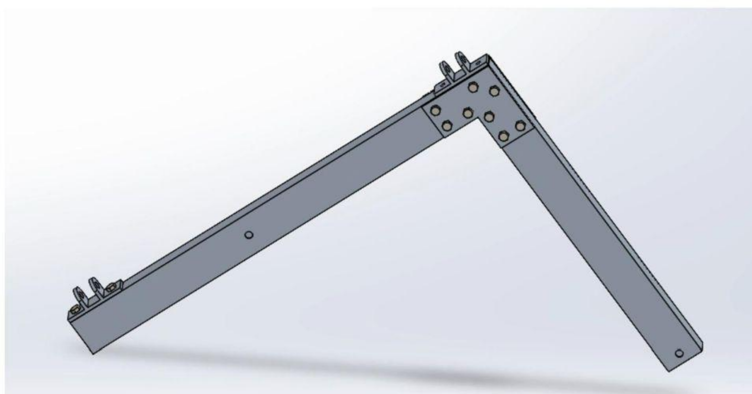




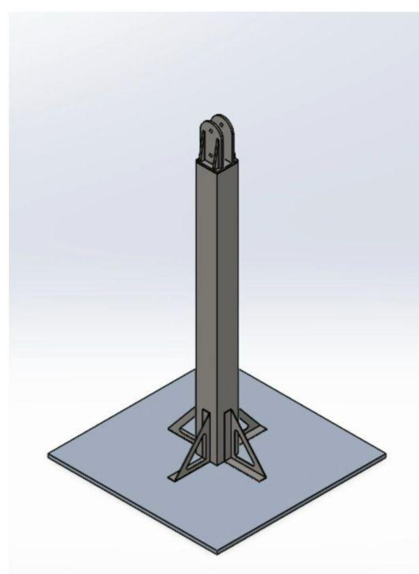
5. Connect the female hinges to north-south member 1 with 4 ¼ - 20 x .5 nuts and bolts



6. Connect North-south member 2 with 8 ¼ - 20 x 1.5 nuts and bolts and the two north-south brackets.

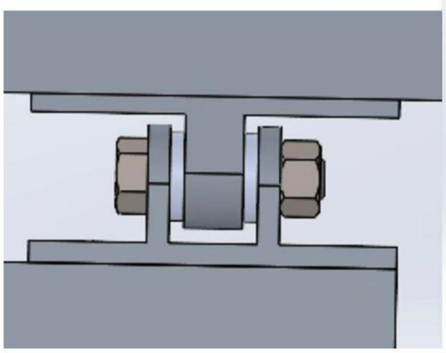


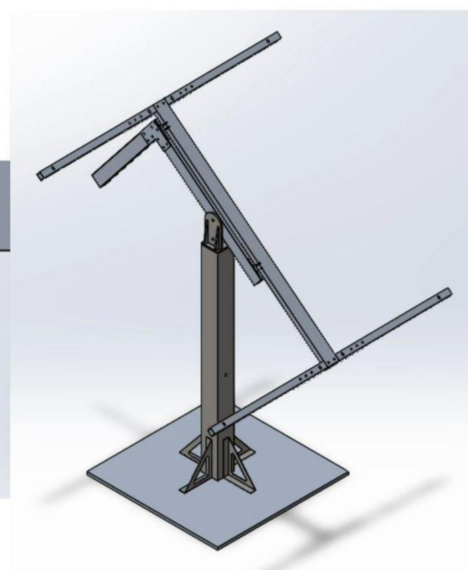
7. Assemble the upright post, north-south hinge (should already be welded together) base, and 4 right angle supports. Using necessary hardware. (I didn't really design these supports so might have drill holes as necessary)



8. Add the north-south axis assembly to the upright post using a ⅜ - 16 x 2.5 bolt and lock nut. Make sure to add the north-south plastic washers between rotating metal components.

9. Add the East-west member/panel mount assembly. Use 2 ⅜ - 16 x 1.5 bolts and locknuts. Make sure to use the 4 east-west plastic washers



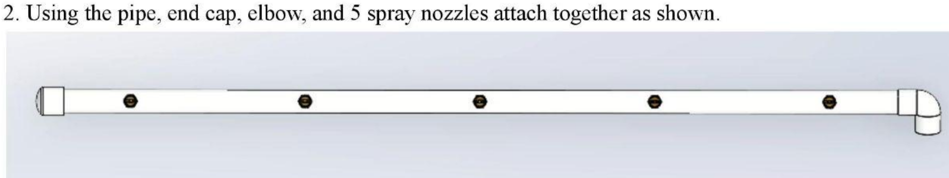


Cleaning System:

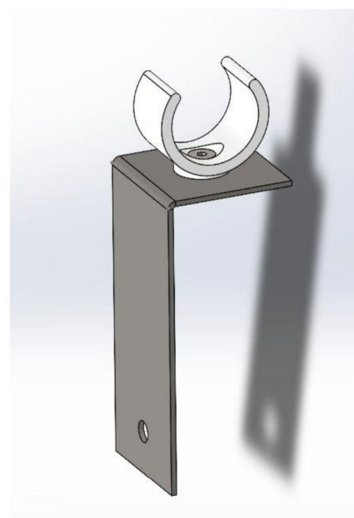
1: Gather/ build all components.

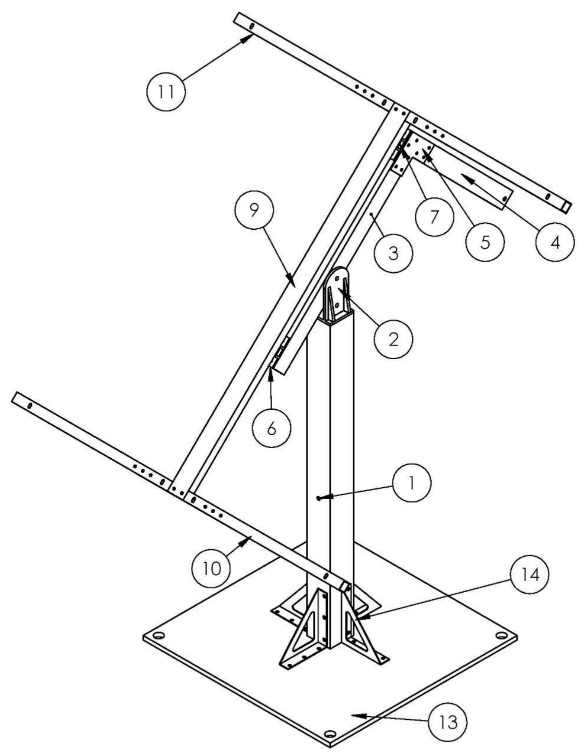
Part name	Quantity
Pipe	1
Pipe clamp	4
Endcap	1
Cleaning system mount	4
Jet flat spray nozzle	5
90 degree elbow	1

2. Using the pipe, end cap, elbow, and 5 spray nozzles attach together as shown.



3. Using a pipe clamp, cleaning system mount, m4-10 bolt, and nut make this assembly. Repeat this a total of 4 times.





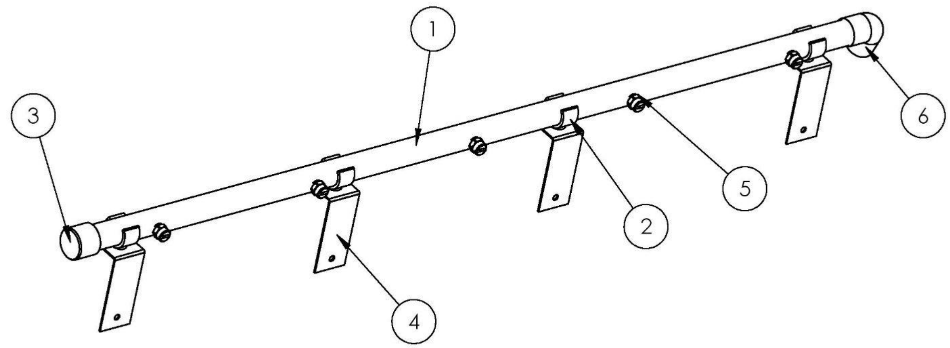
ITEM NO.	PART NUMBER	QTY.
1	upright post	1
2	north south hinge	1
3	north south axis member 1	1
4	north south axis member 2	1
5	north south bracket	2
6	hinge female	2
7	hinge male	2
8	east west member 2	2
9	east west member 1	1
10	panel mount	2
11	panel mount top	2
12	PV panel	2
13	base	1
14	post support	4

TITLE: Frame assembly

SIZE A | DWG. NO. | REV

SCALE: 1:24 | WEIGHT: | SHEET 1 OF 1

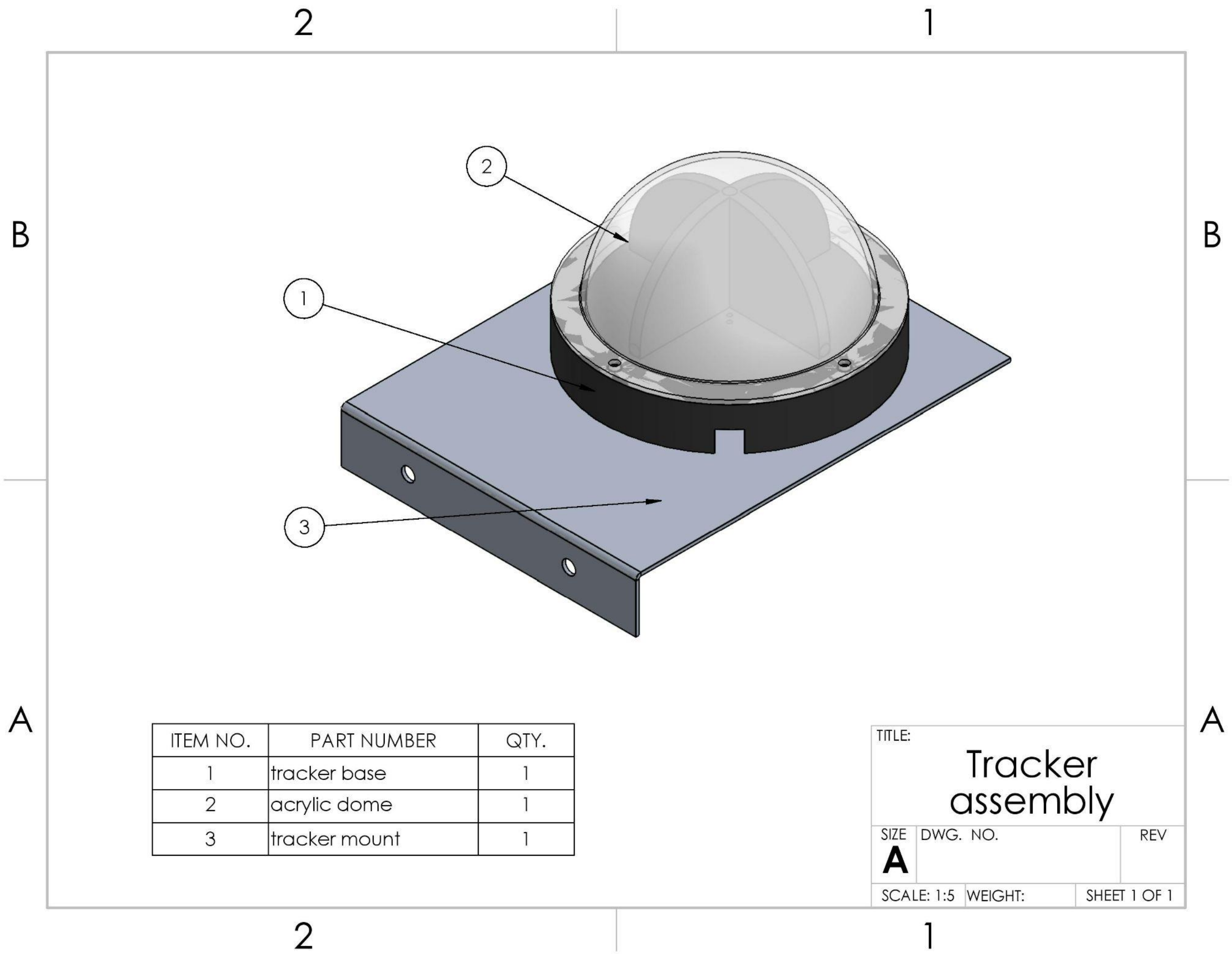
Figure G1: Complete assembly of the solar tracker system



ITEM NO.	PART NUMBER	QTY.
1	pipe	1
2	pipe clamp	4
3	end cap	1
4	cleaning system mount	4
5	Jet Flat Spray 1-4.stp	5
6	0.5 Elbow	1

TITLE: Cleaning system assembly		
SIZE A	DWG. NO.	REV
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

Figure G2: Detailed assembly drawing of cleaning system, including parts one through six as seen above.



ITEM NO.	PART NUMBER	QTY.
1	tracker base	1
2	acrylic dome	1
3	tracker mount	1

Figure G3: Complete assembly of the tracker system

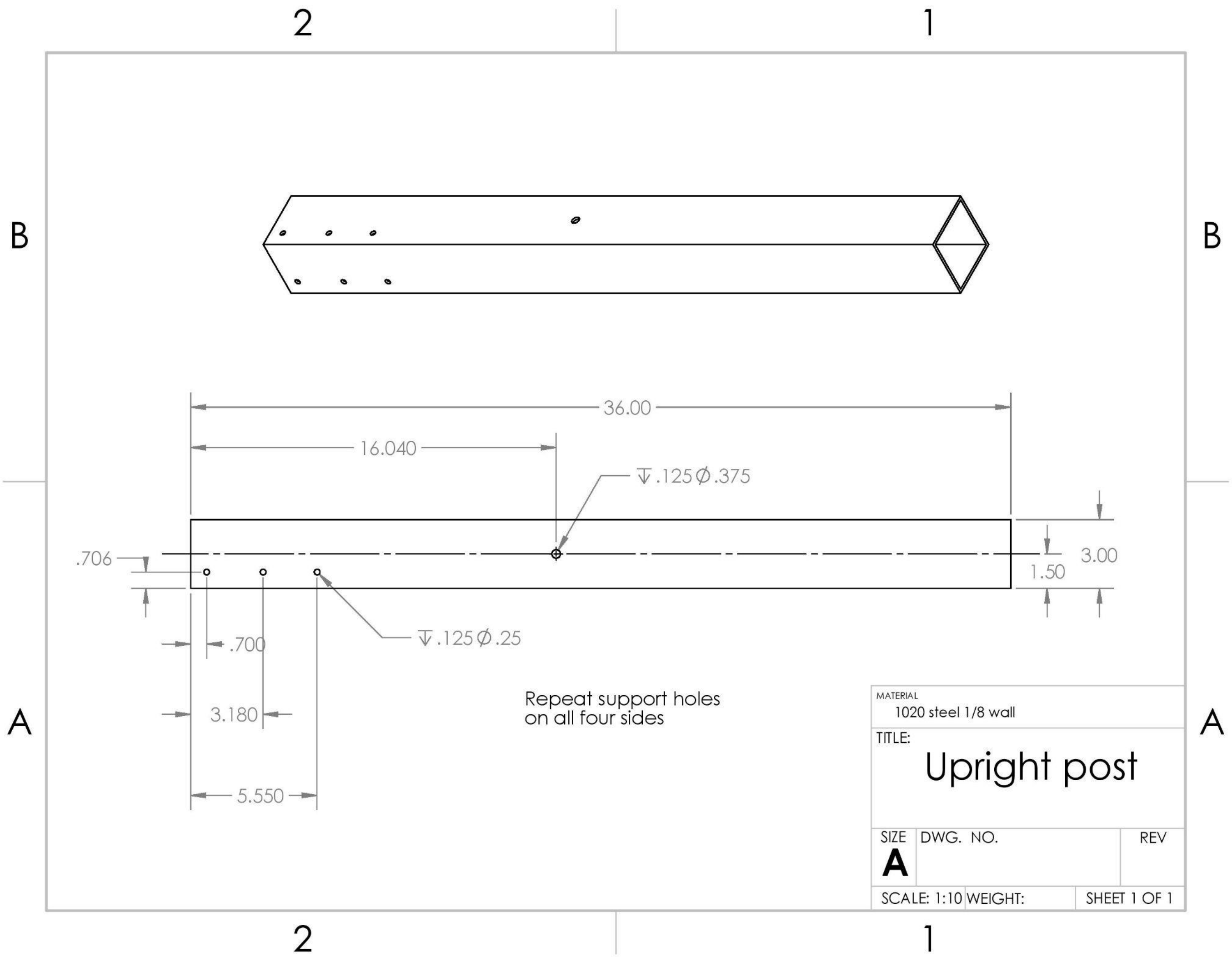


Figure G4: Upright Post detailed drawing and mounting holes.

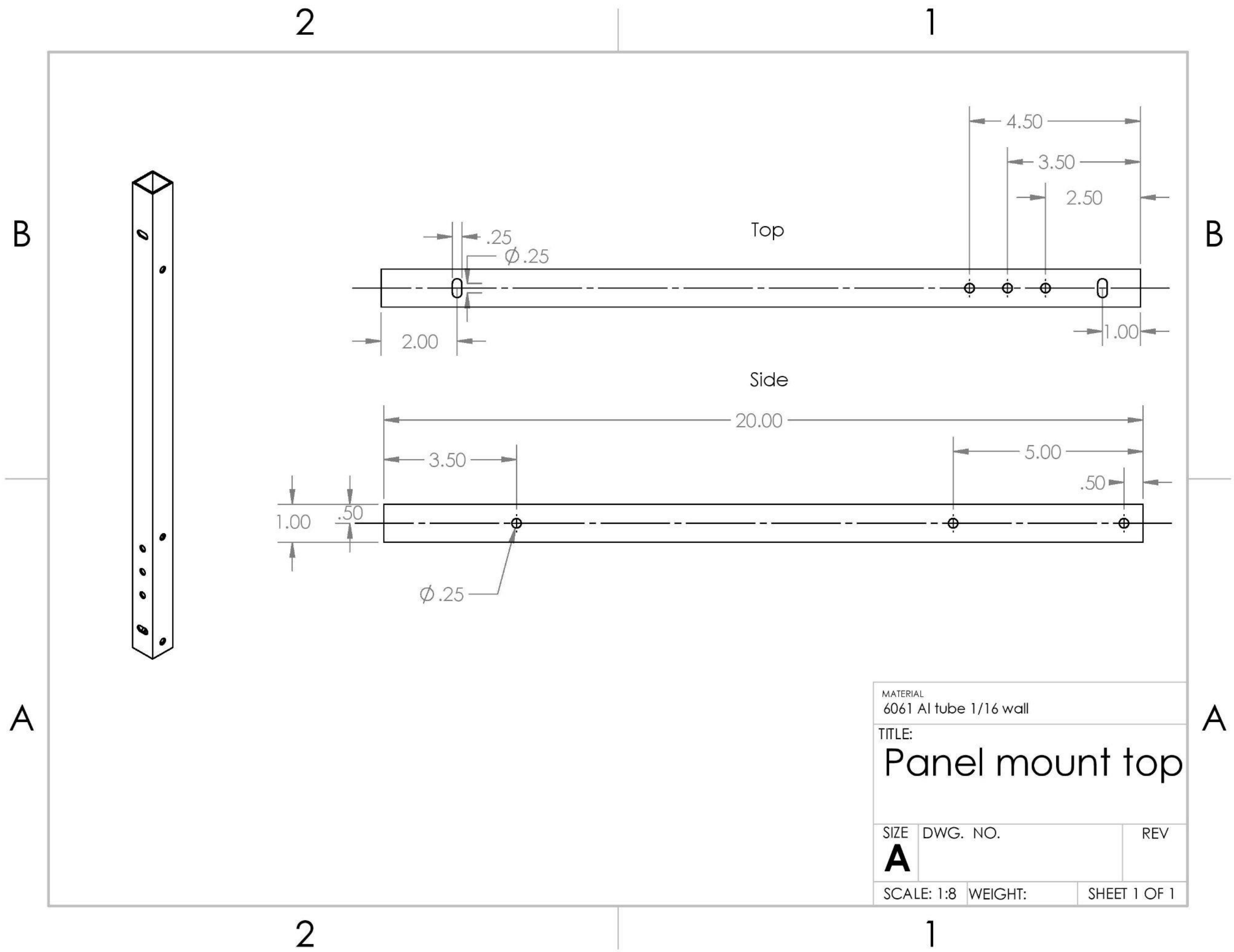


Figure G5: Detailed drawing of panel mount top

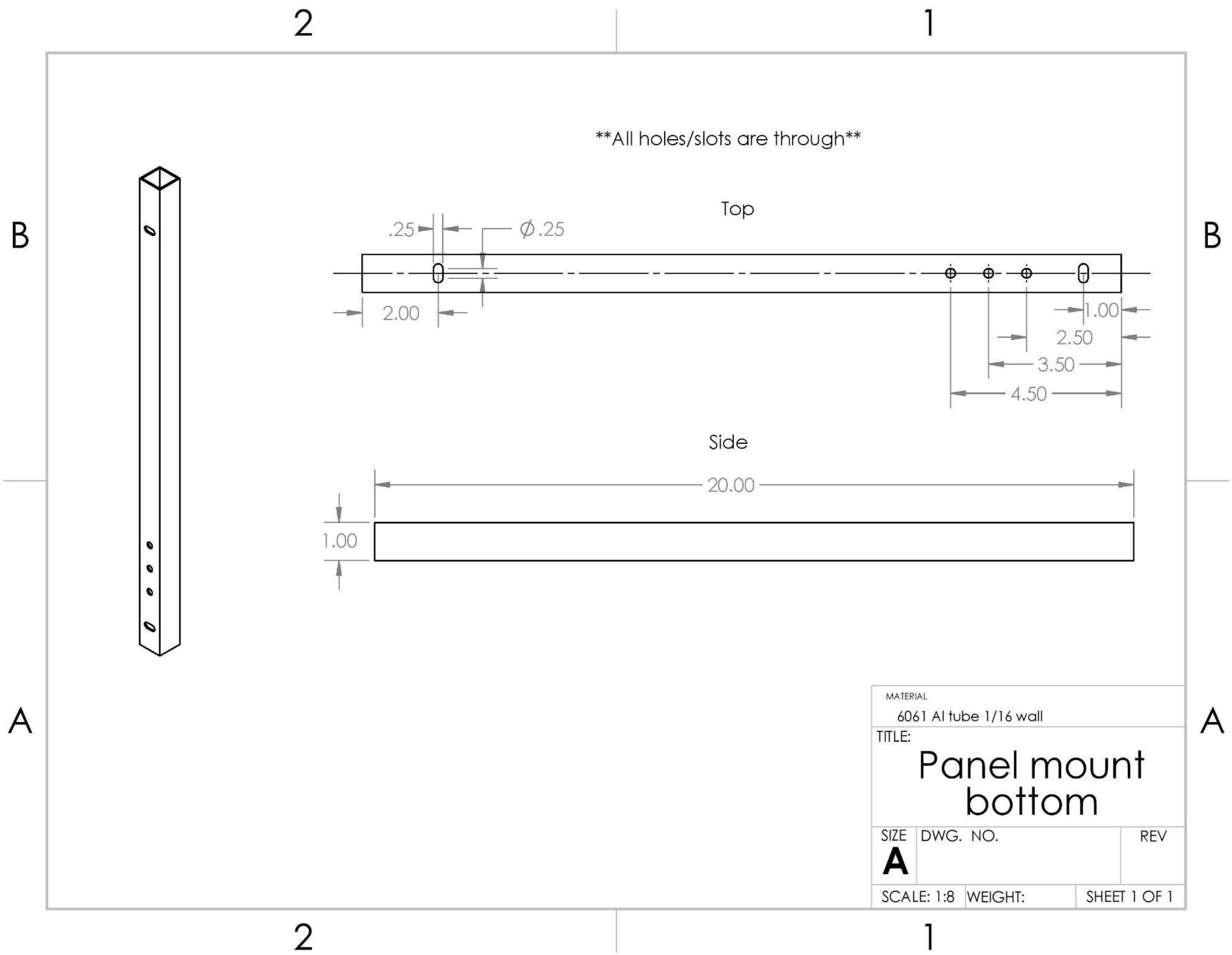


Figure G6: Detailed drawing of panel mount bottom.

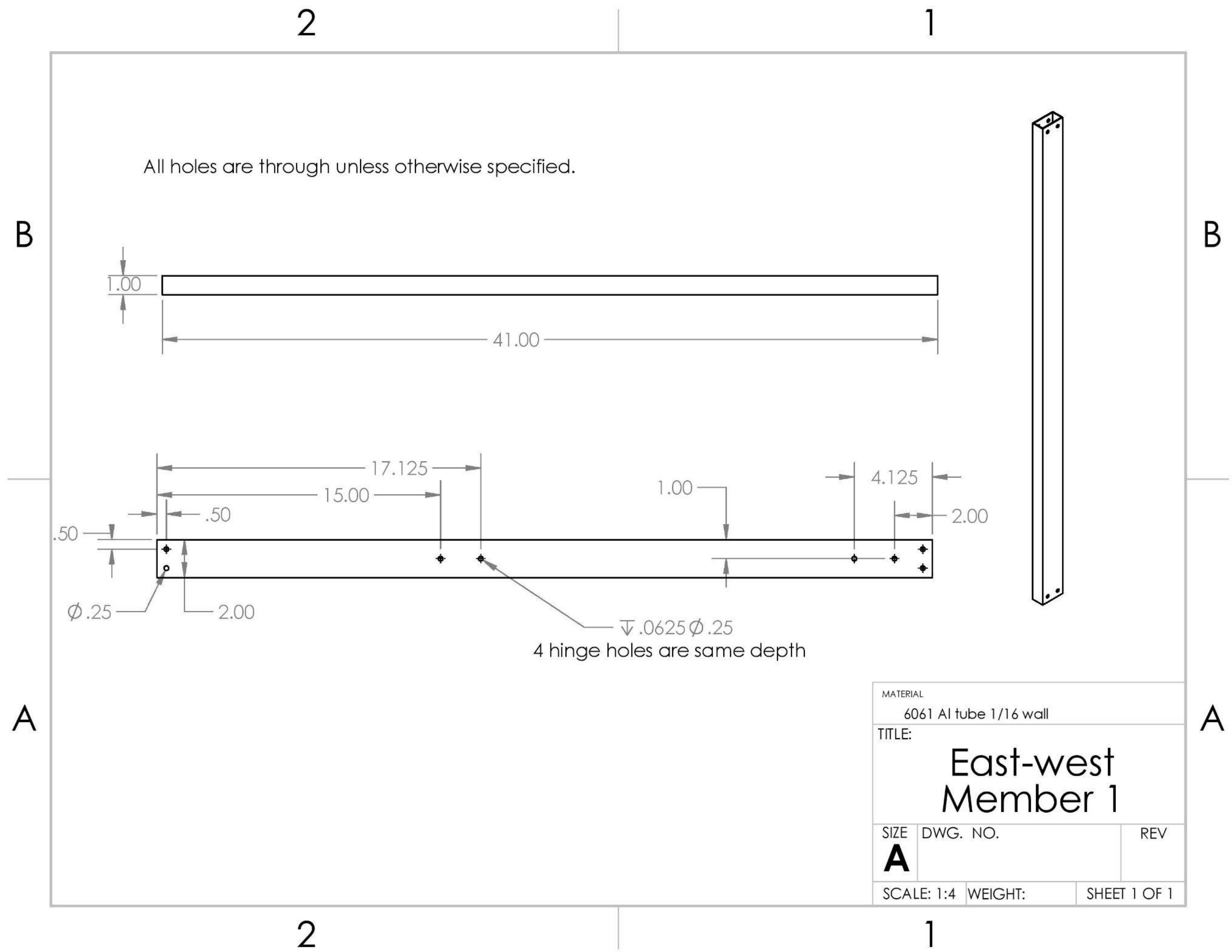


Figure G7: Detailed drawing of East-west Member 1

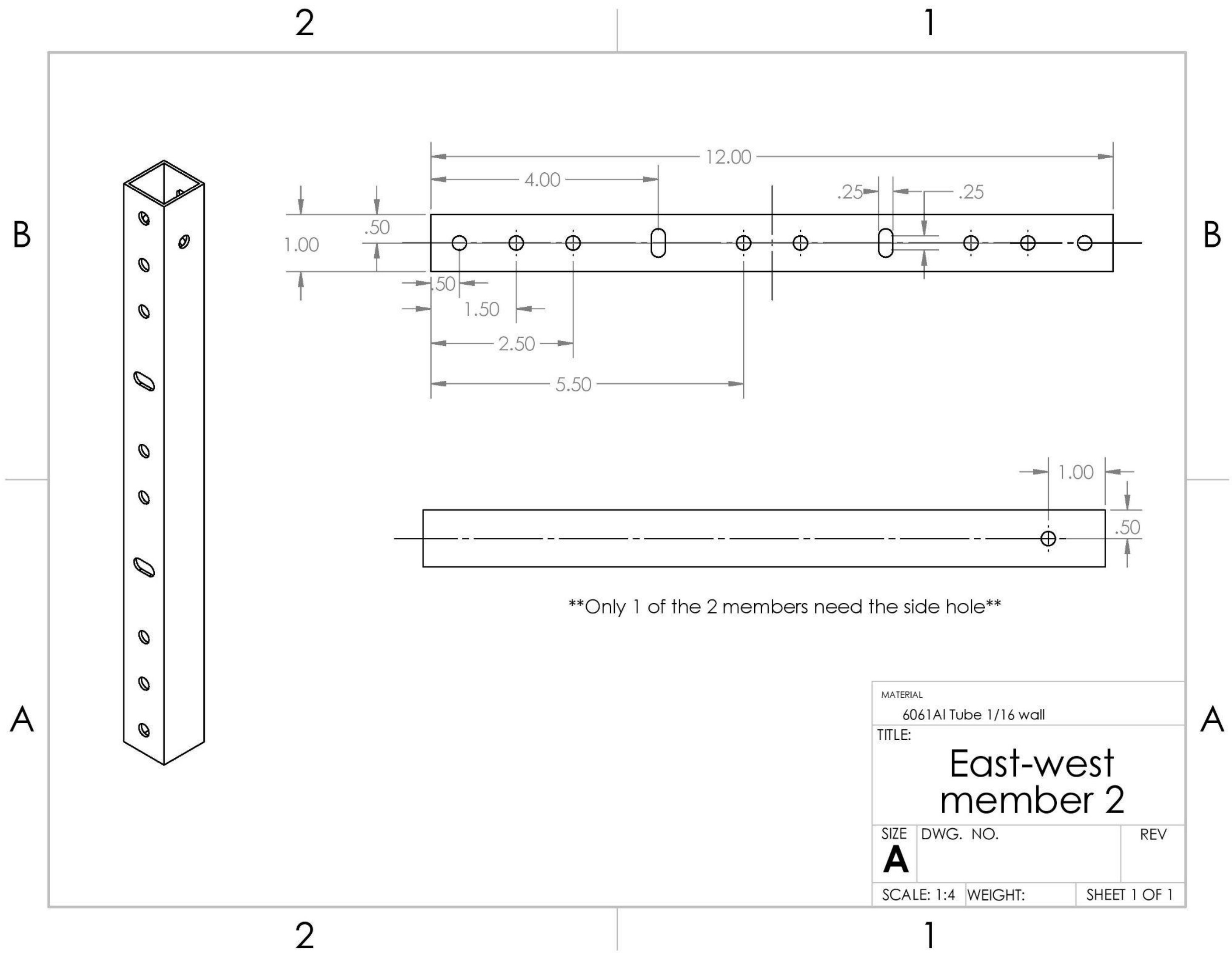


Figure G8: Detailed drawing of East-West member #2.

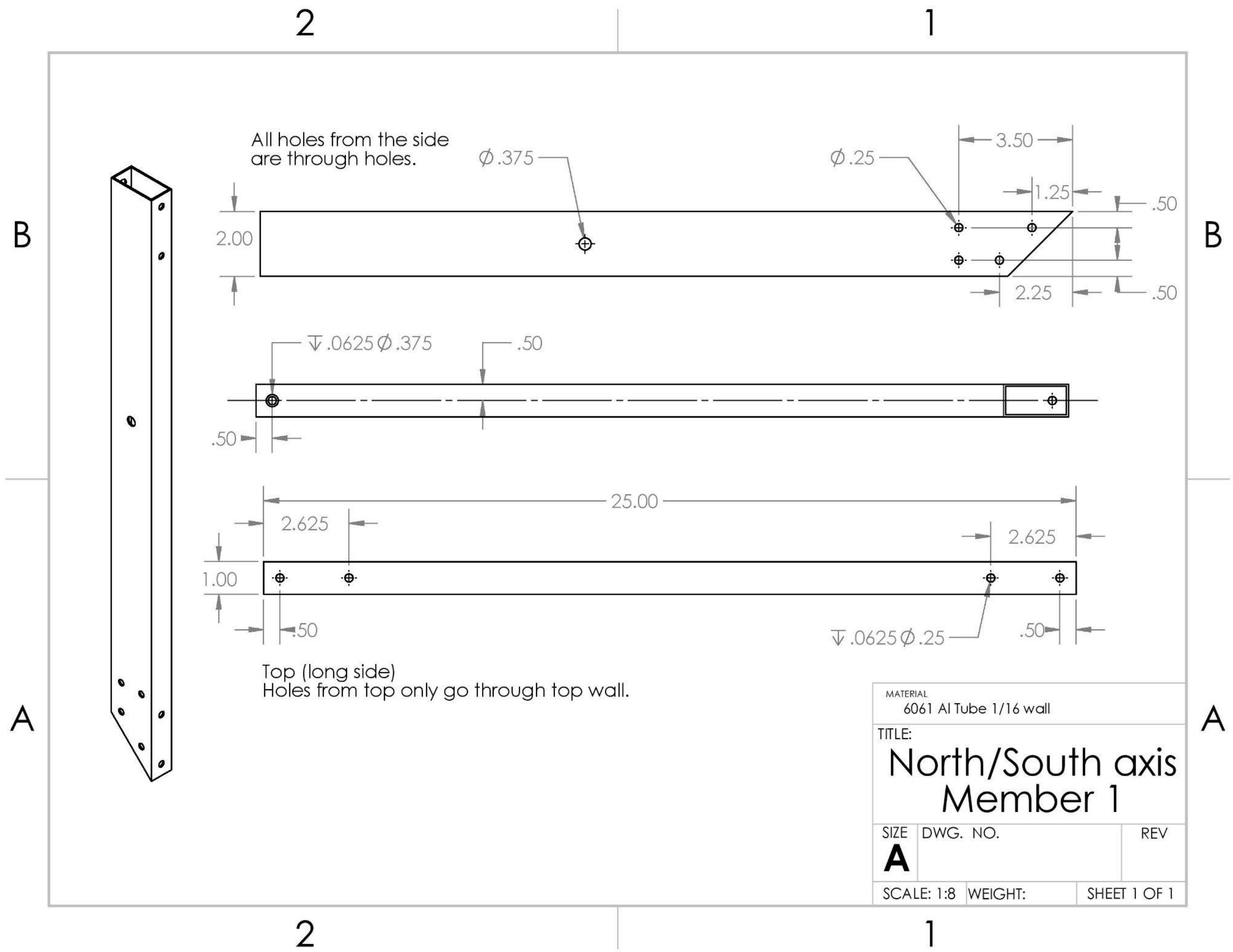


Figure G9: Detailed drawing of North-South member #1.

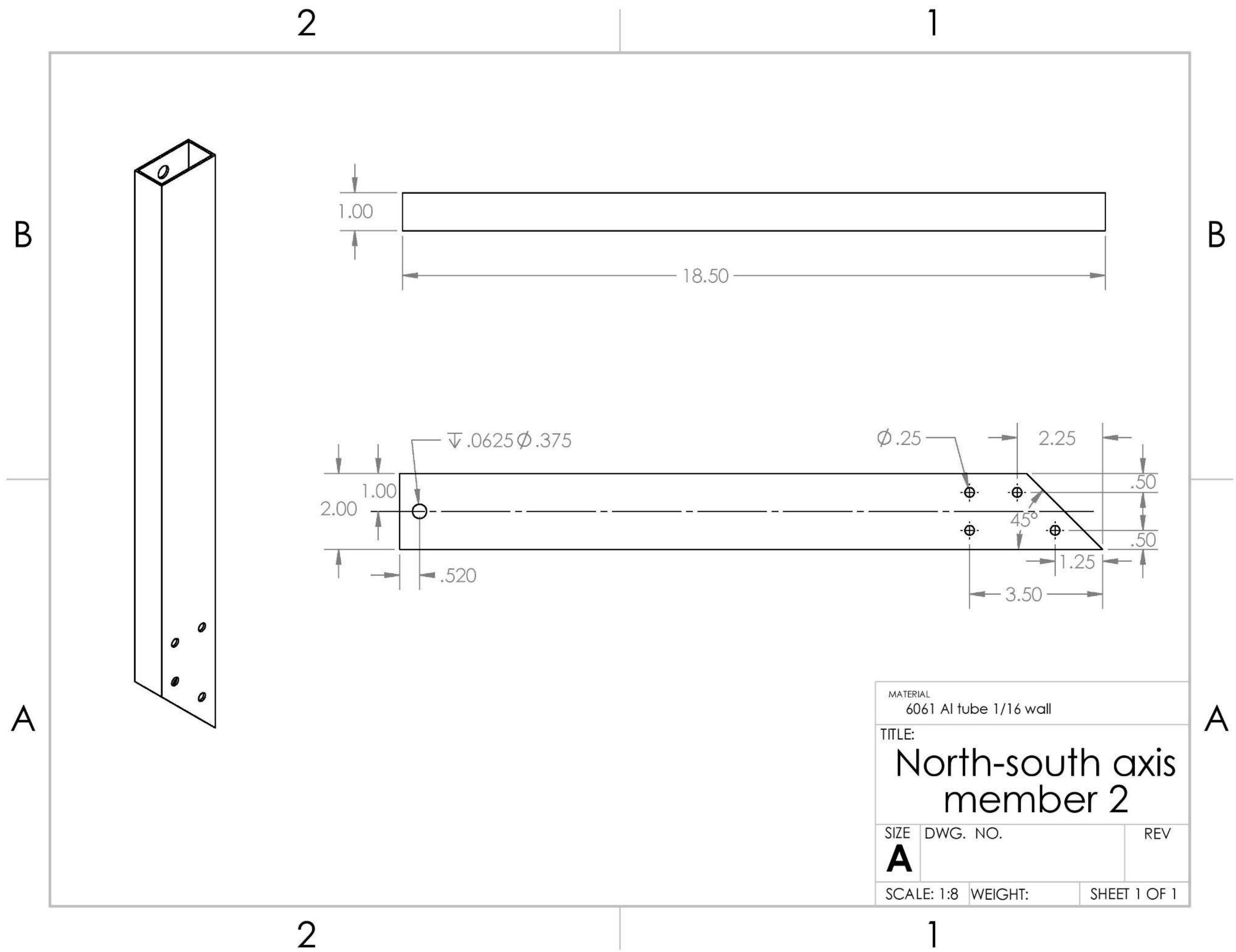


Figure G10: Detailed drawing of North-South axis member 2

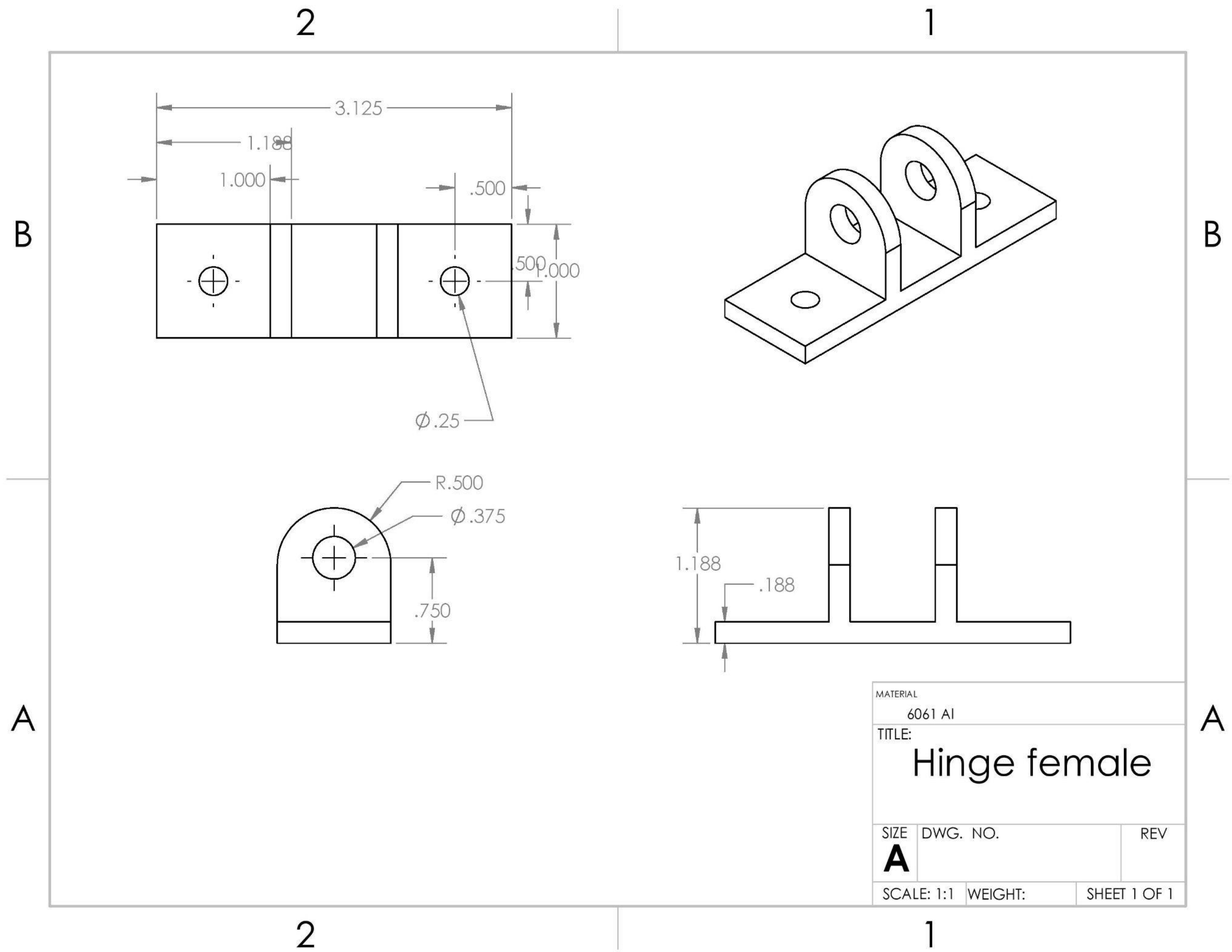


Figure G11: Detailed drawing of female hinge member.

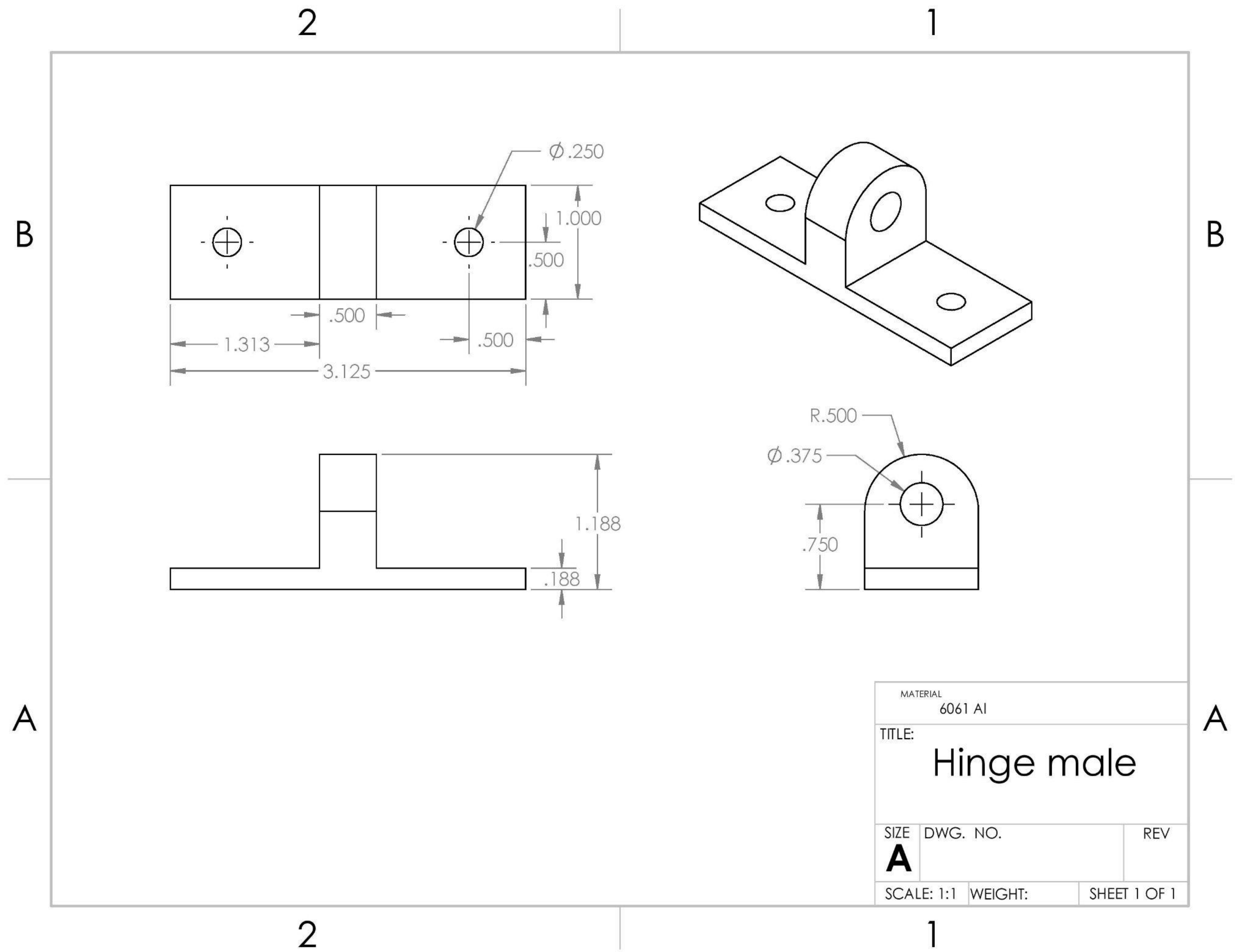


Figure G12: Detailed drawing of male hinge member.

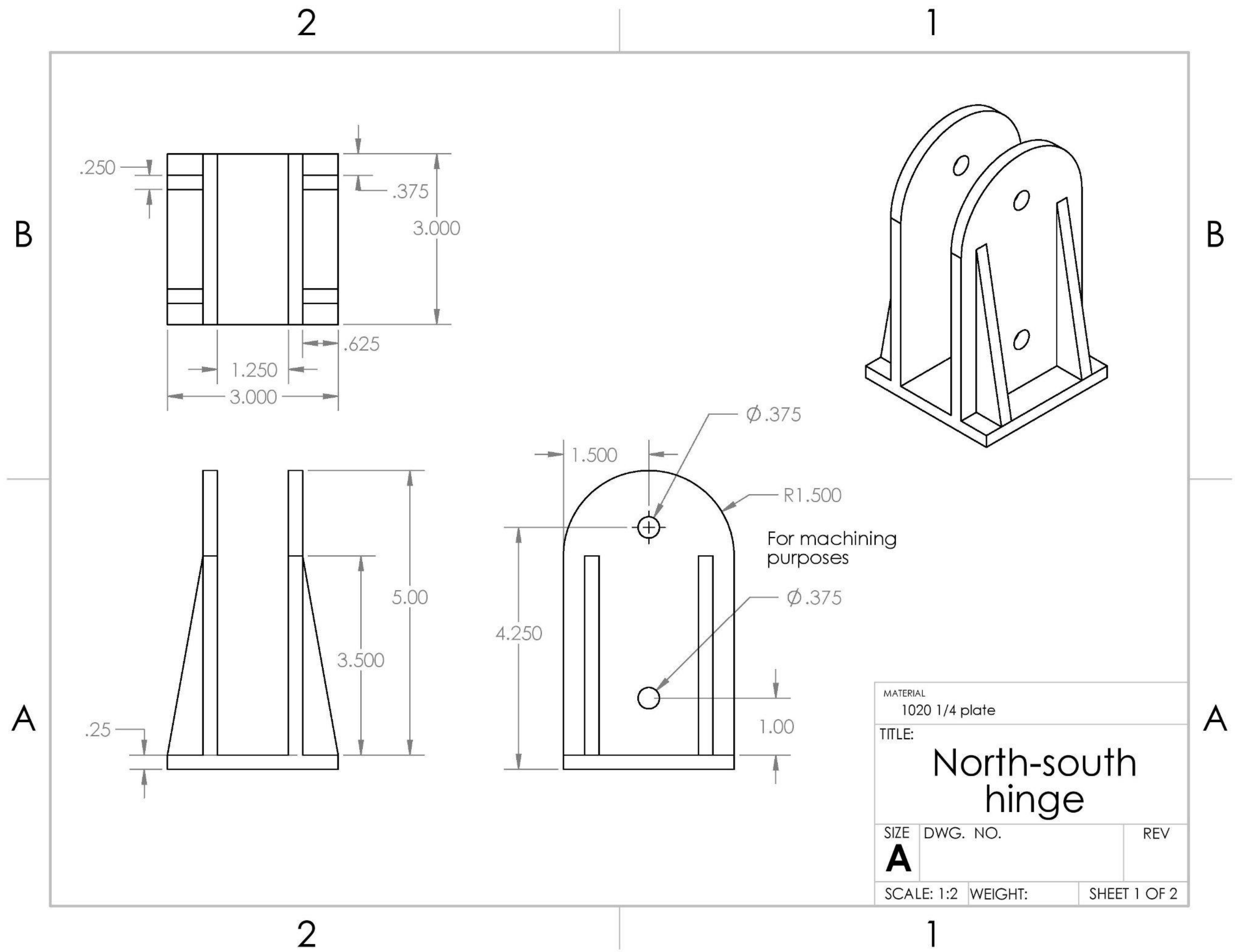


Figure G13: Detailed drawing of North-South hinge

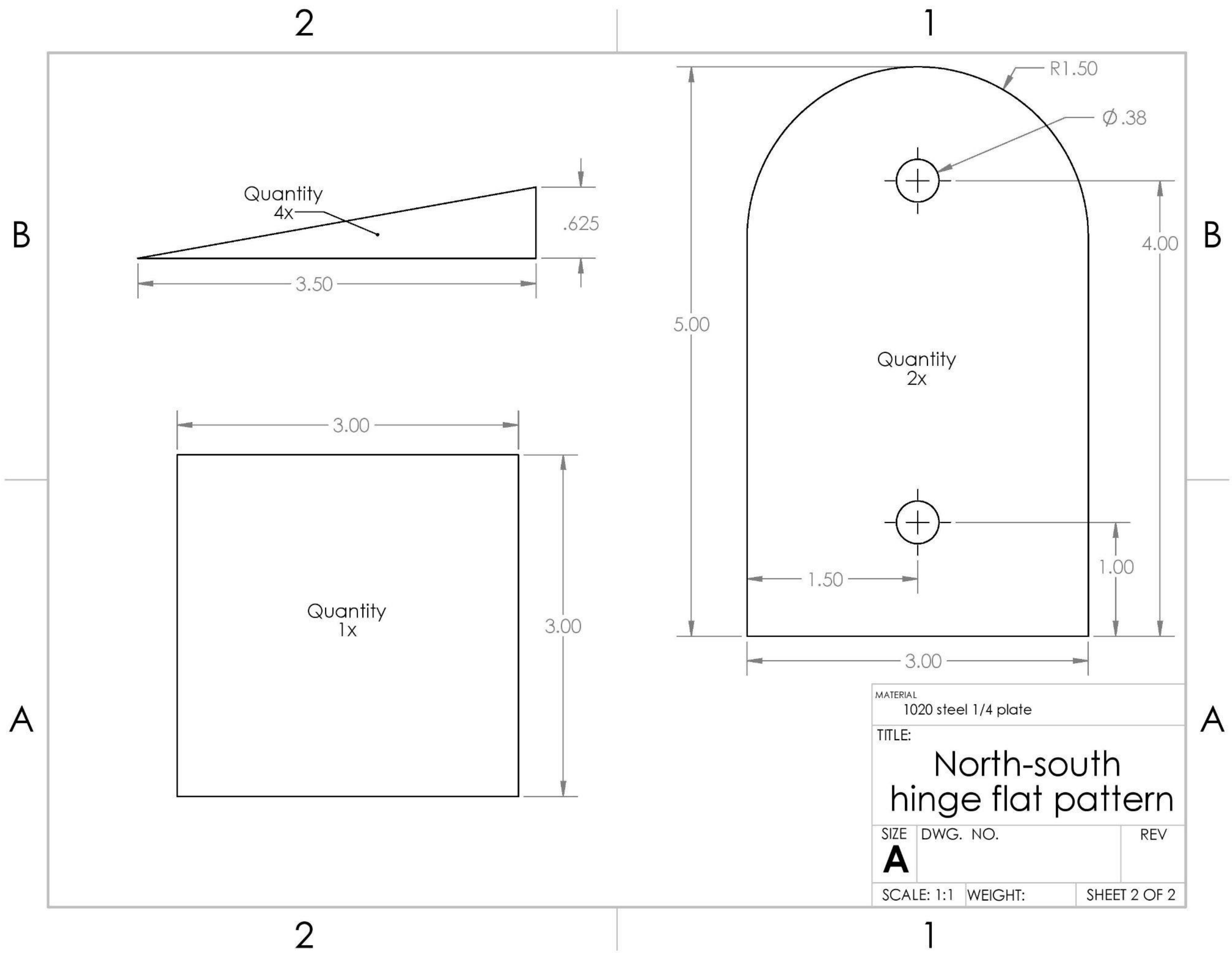


Figure G14: Detailed drawing of North-South hinge flat section.

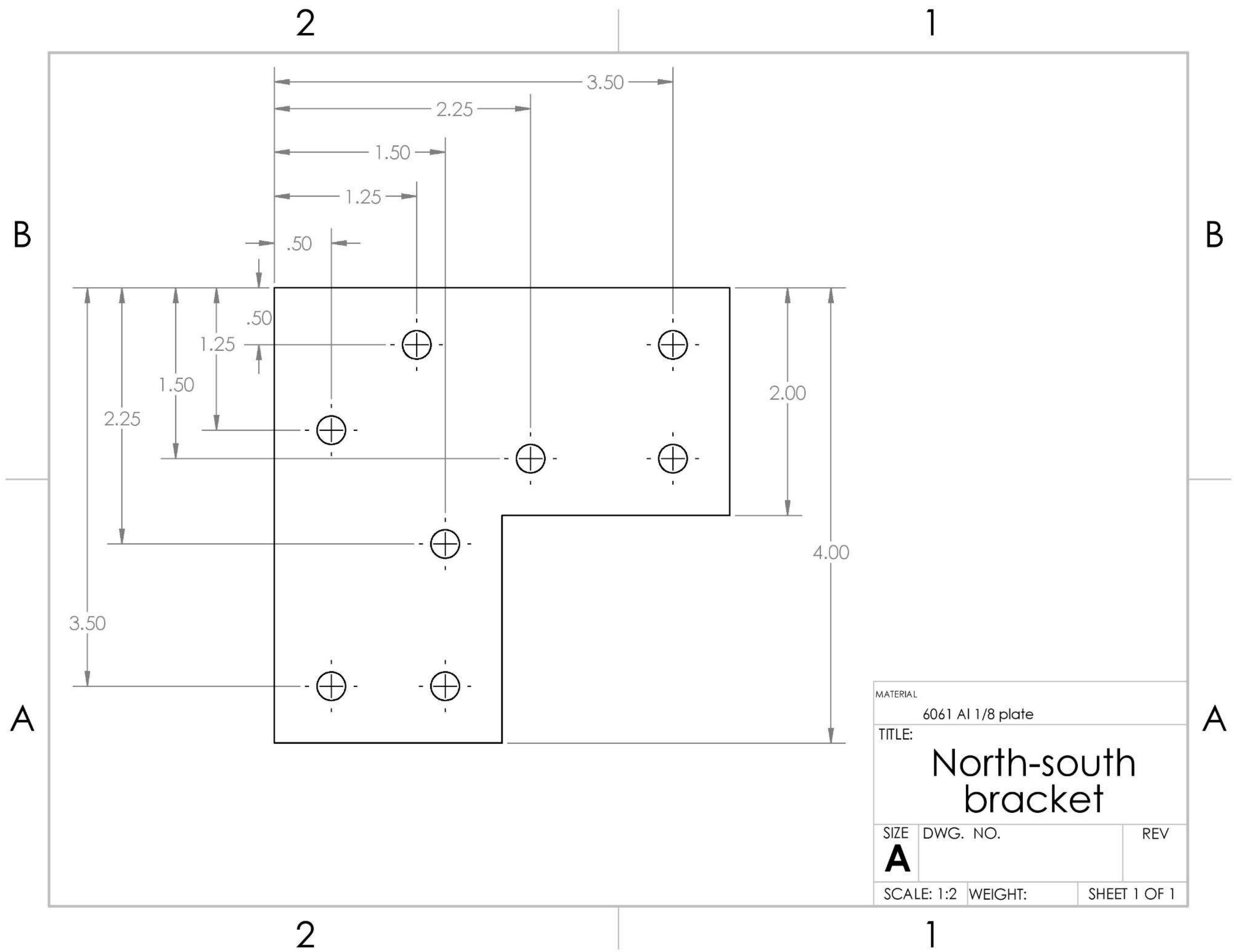


Figure G15: Detailed drawing of North-South bracket.

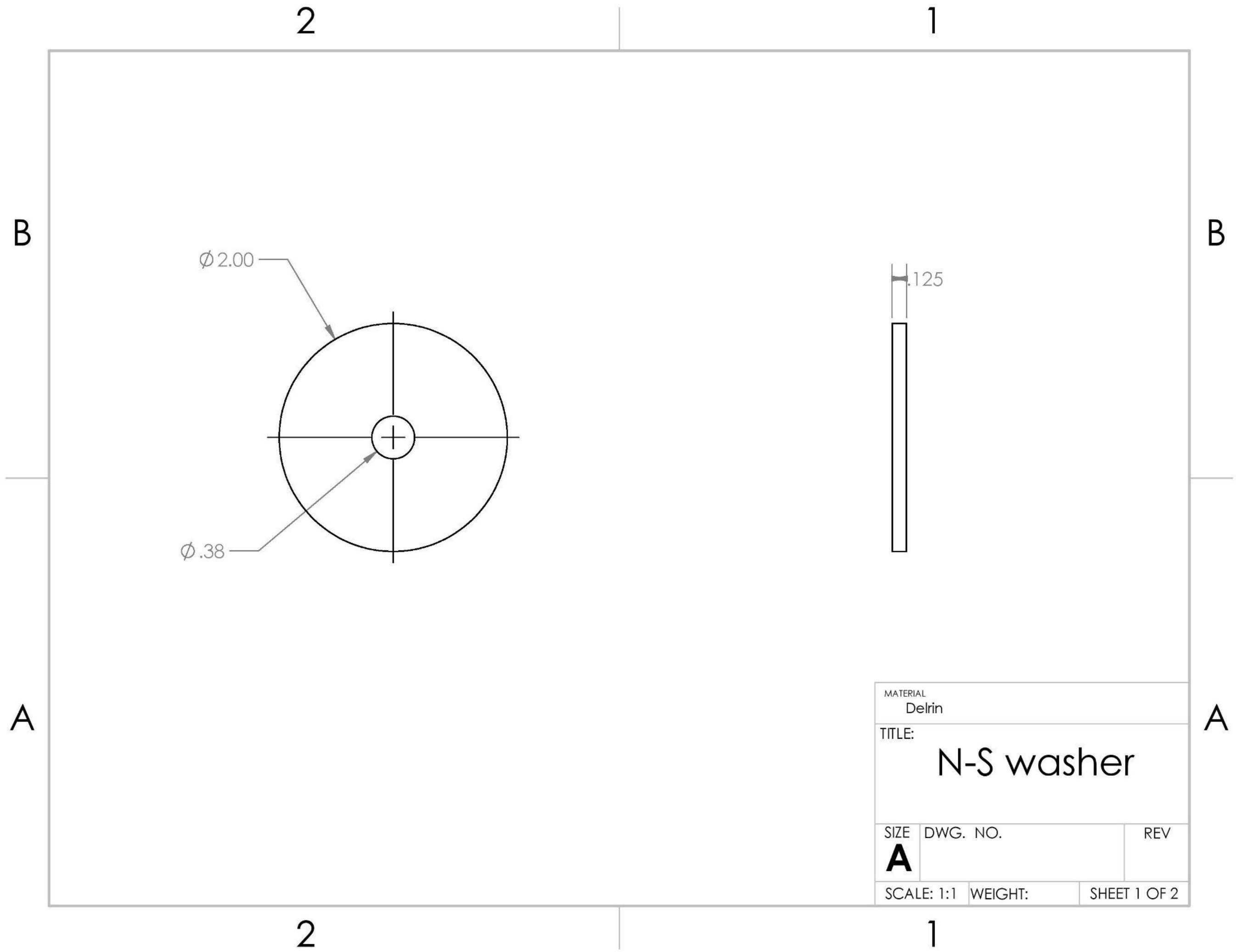


Figure G16: Detailed drawing of N-S washer

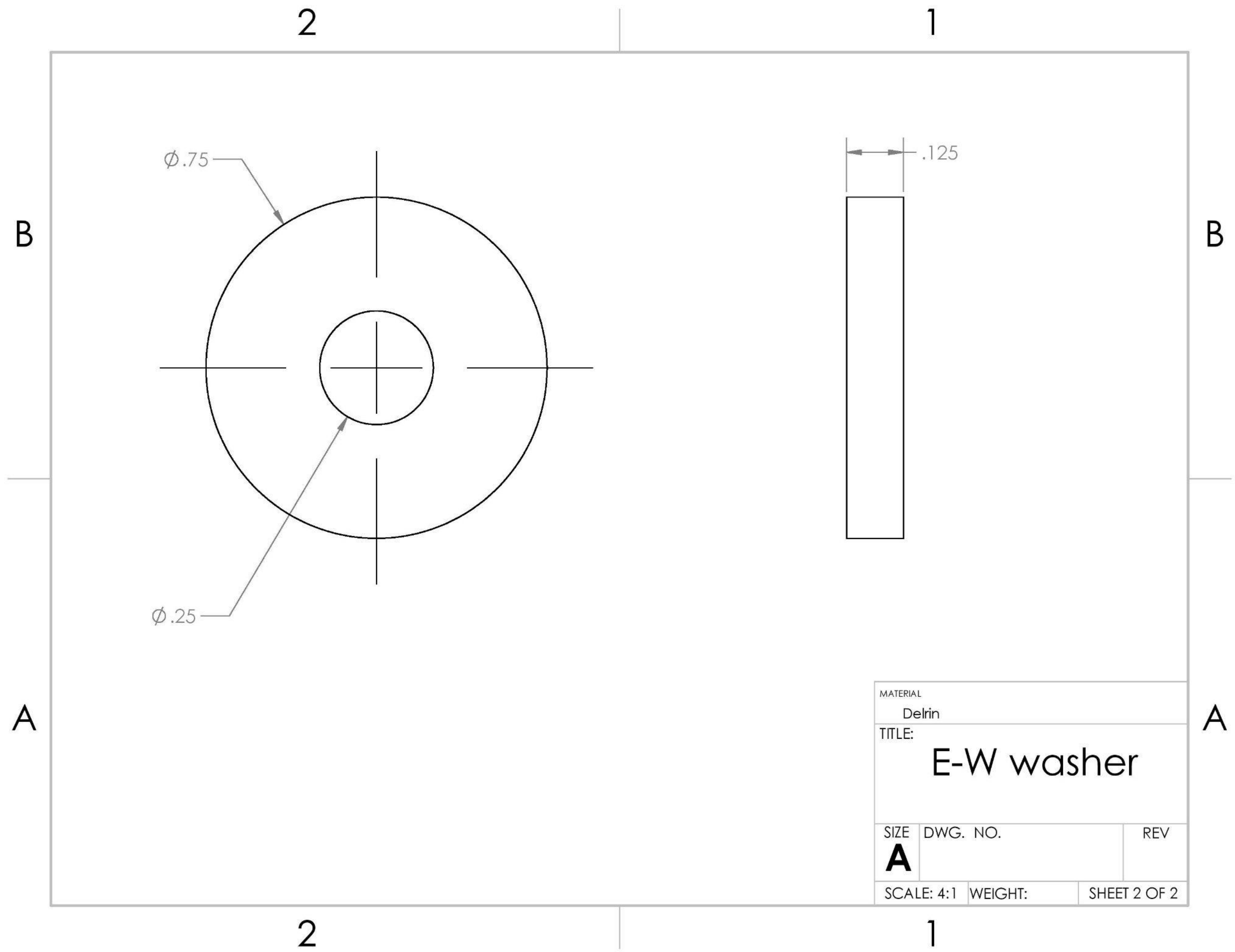


Figure G17: Detailed drawing of East-West washer.

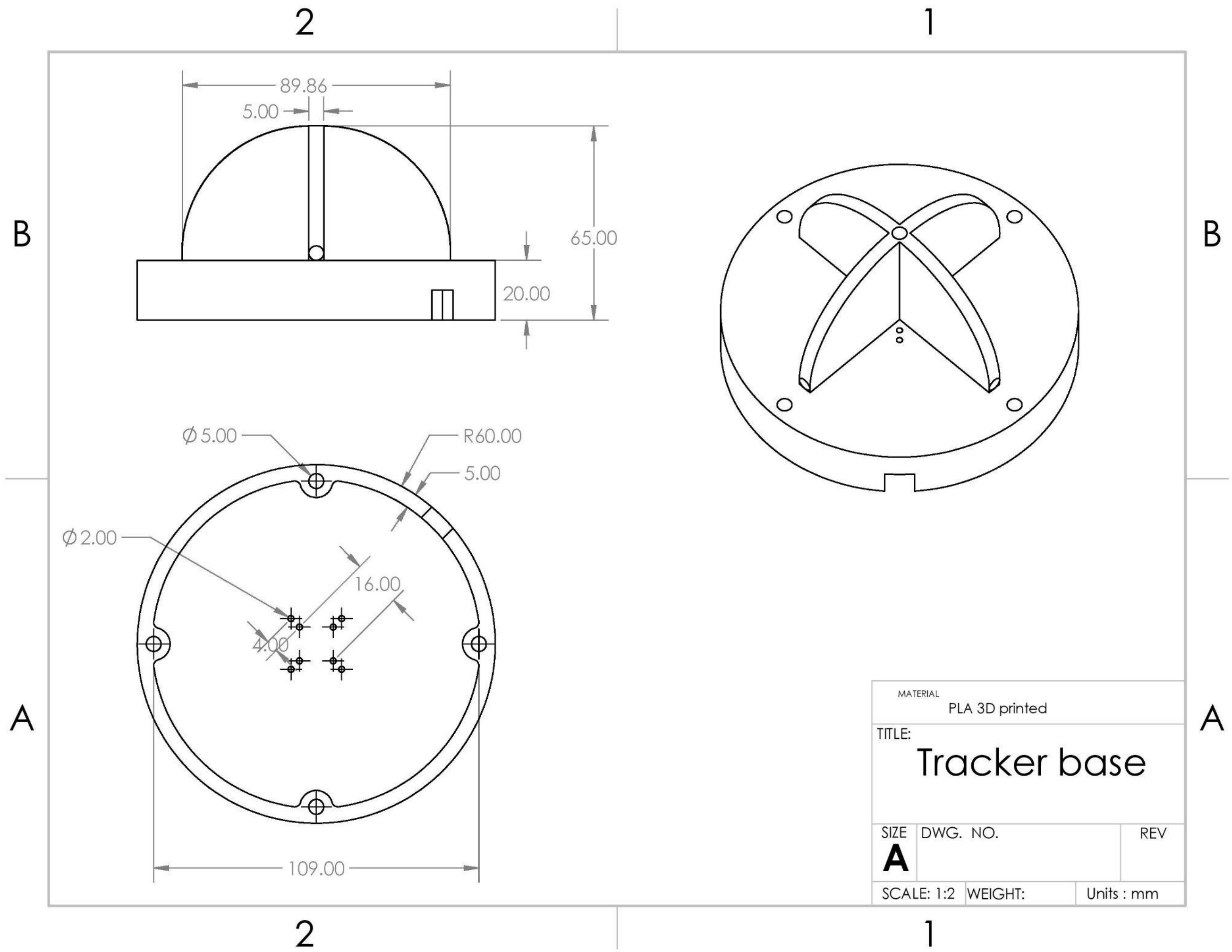


Figure G18: Detailed drawing of tracker base. Part to be printed with PLA 3D material.

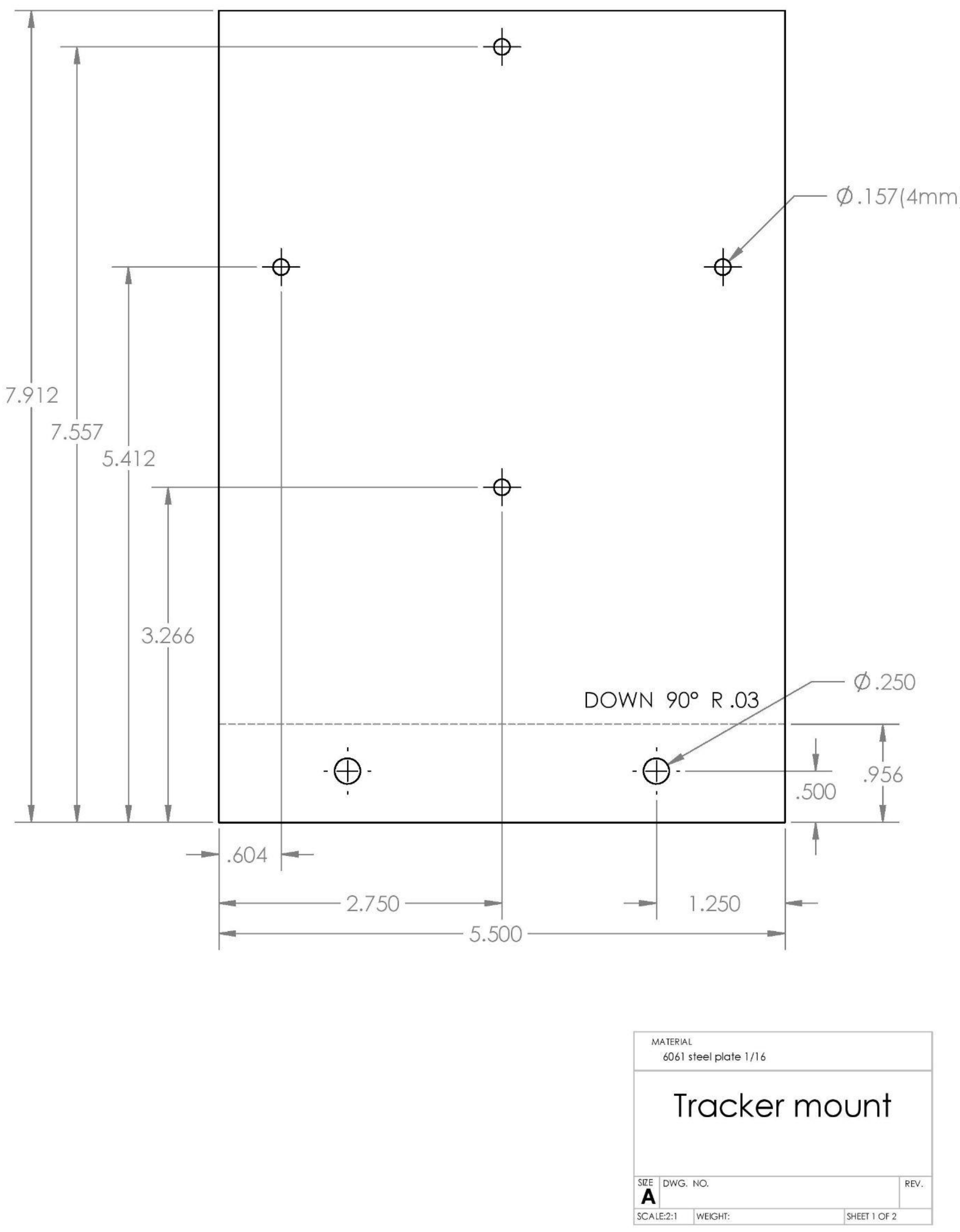


Figure G19: Detailed drawing of tracker mount

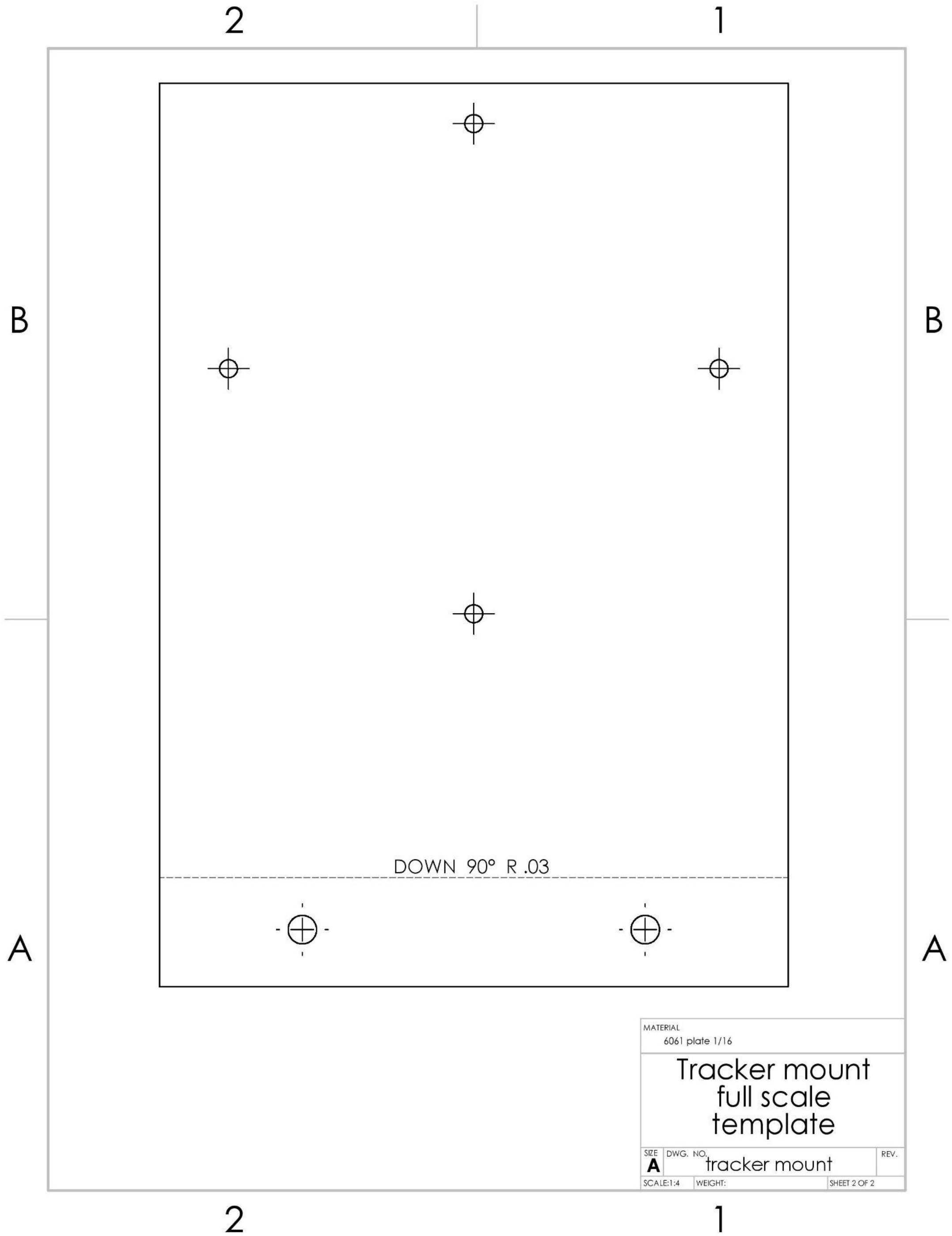


Figure G20: Detailed drawing of full scale template for tracker mount.

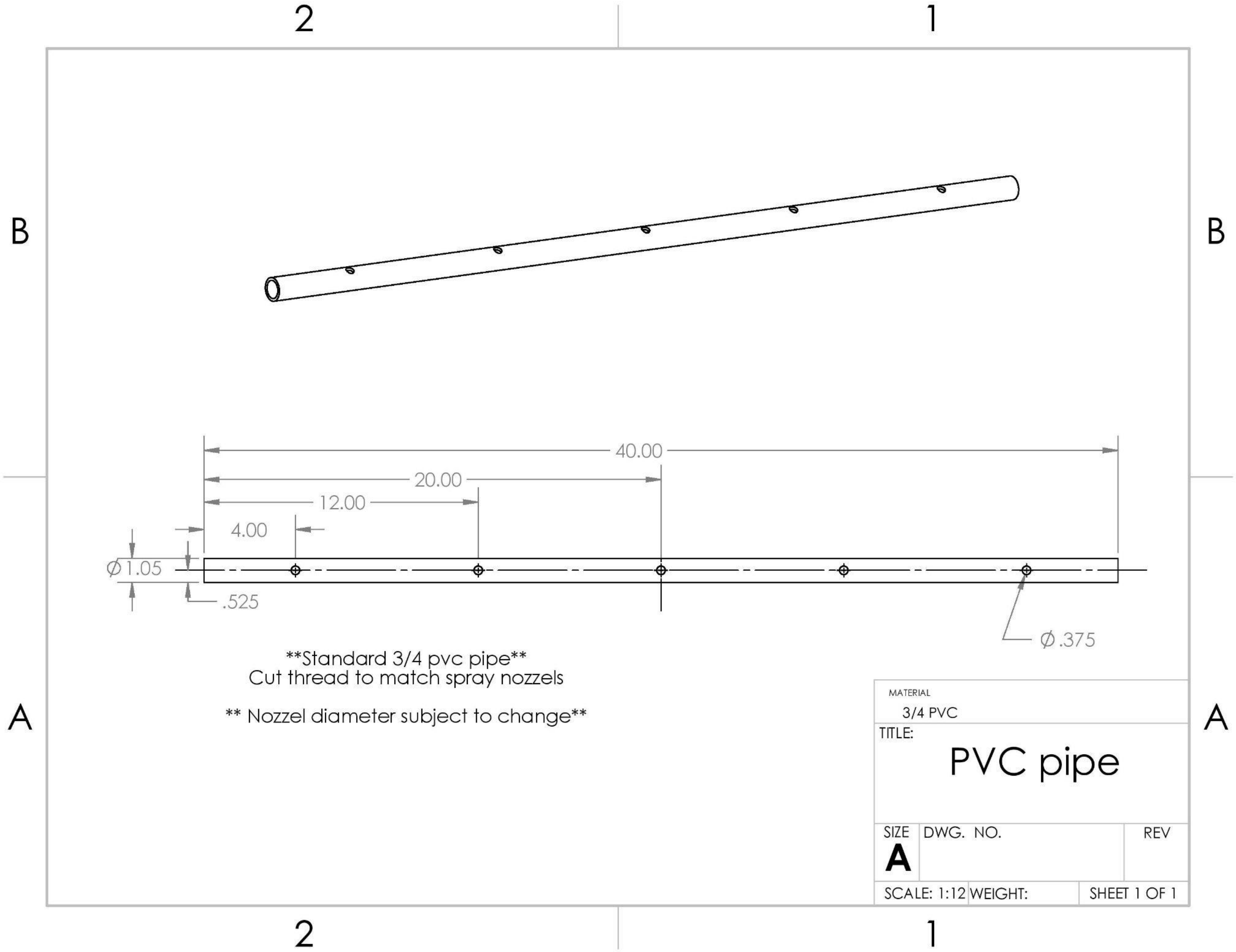


Figure G21: Detailed drawing of standard PVC pipe with cut thread.

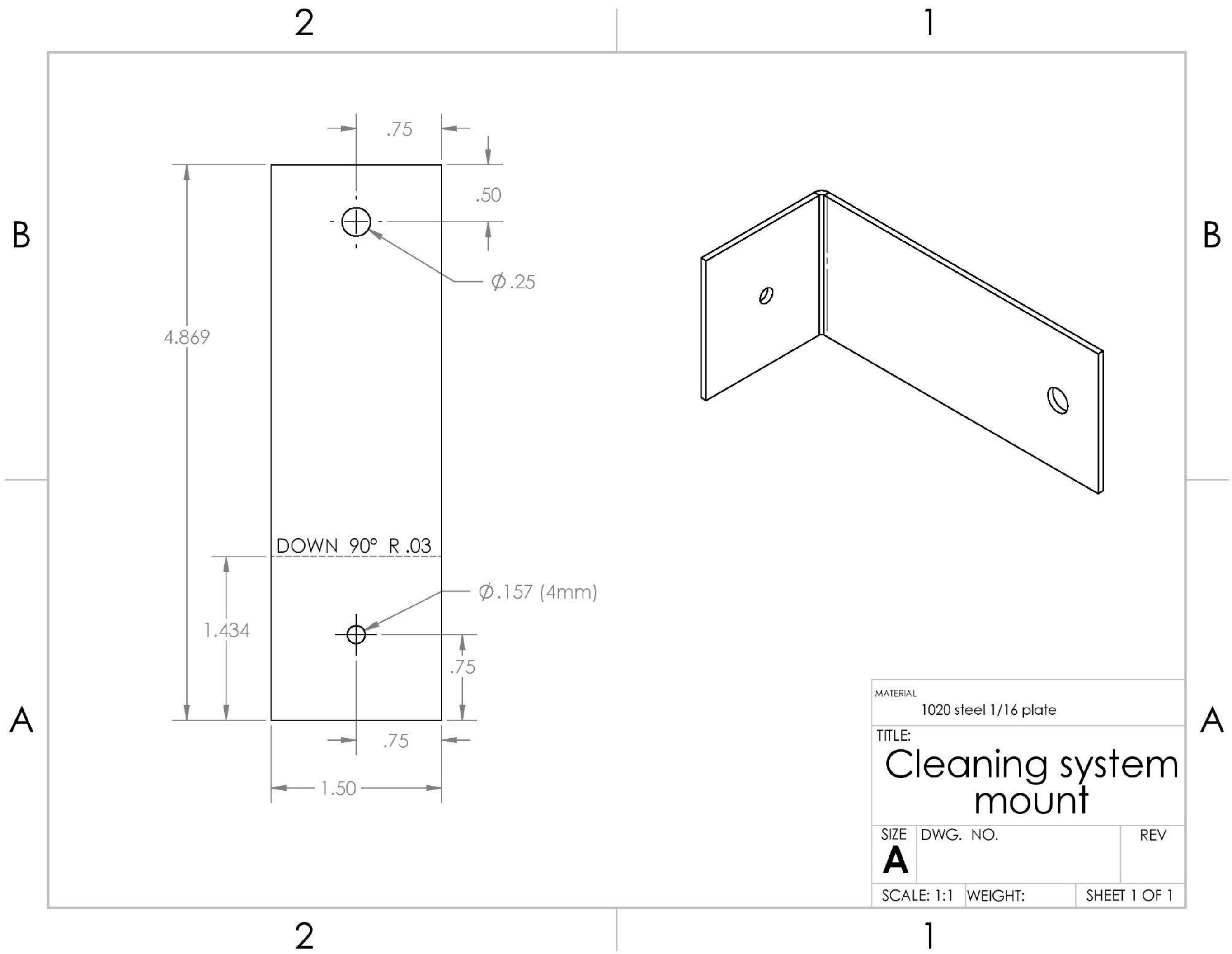


Figure G22: Detailed drawing of cleaning system mount, including necessary holes.

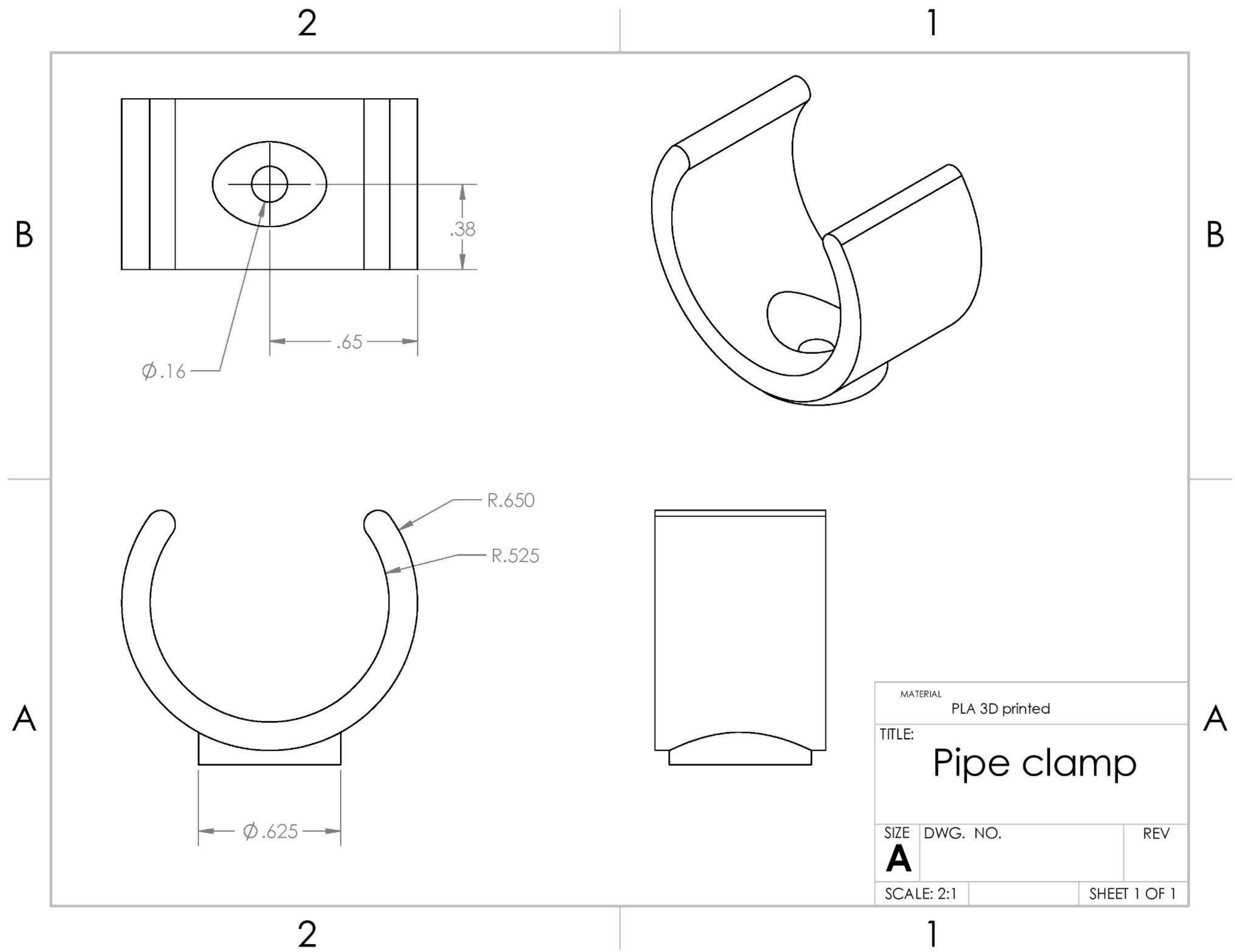


Figure G23: Detailed drawing of pipe clamp to be printed using PLA.

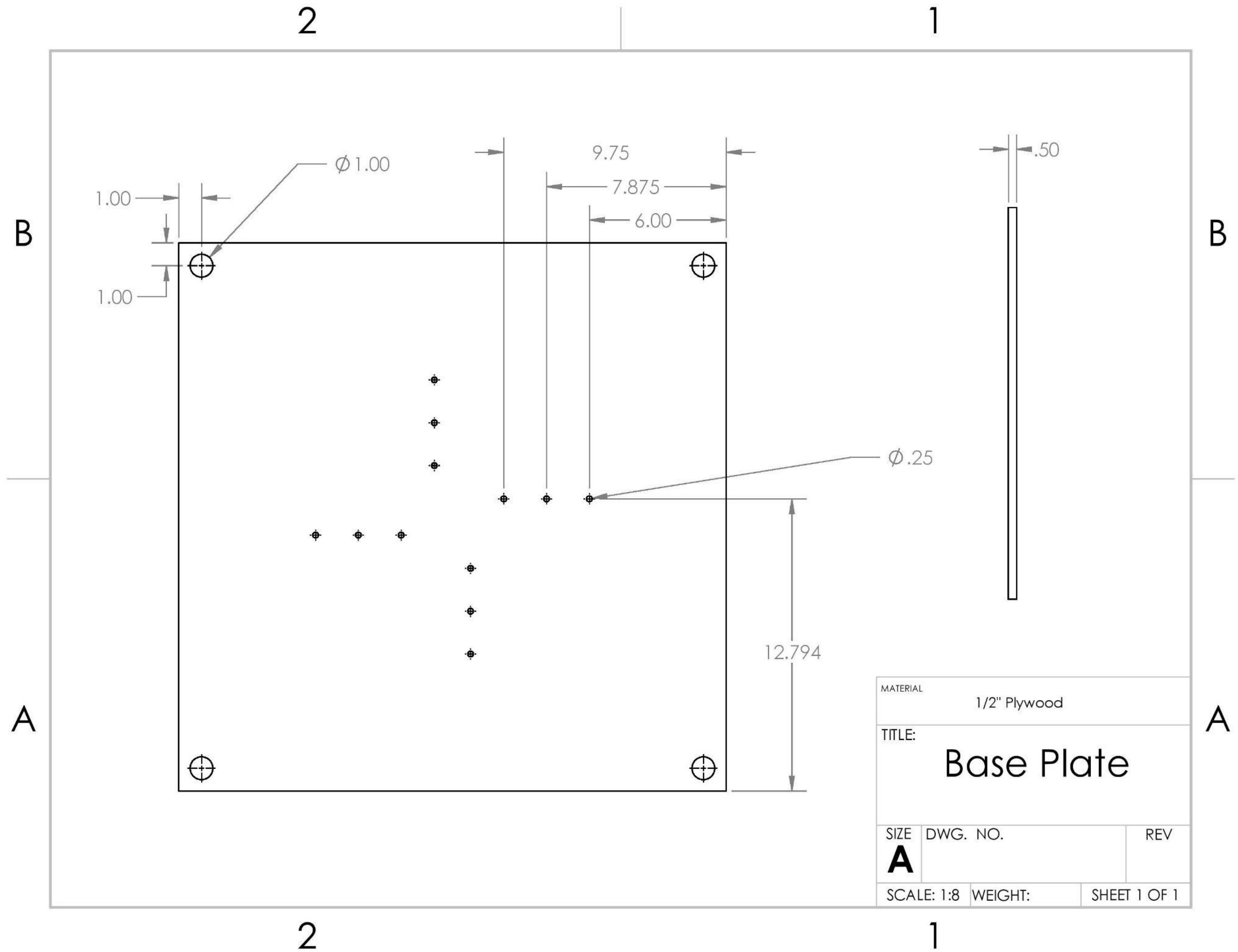


Figure G24: Detailed drawing of base plate including mounting holes.

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Appendix H: Senior Design Slides

As a reference note, the Senior Design Slides do not include table or figure captions. This is due to the Senior Design Slides existing outside the thesis environment. The instructions are intended to be used in order to understand the presentation made during the annual SCU Senior Design Conference.

SANTA CLARA UNIVERSITY
SCHOOL OF ENGINEERING

Dual Axis Solar Tracker with Automated Cleaning System

Matthew Kelley, Nicholas Gallo, Jonathan Lung, Kevin Ehlers, Justin Eng, Brian Weitzenkamp

Santa Clara University

SANTA CLARA UNIVERSITY
SCHOOL OF ENGINEERING

Motivation

Growth

Footprint

Maintenance

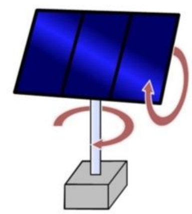
Santa Clara University

SANTA CLARA UNIVERSITY
SCHOOL OF ENGINEERING

Project Goals

Create a solar system with **maximum** energy capture using a combination of **improvements** made to a traditional fixed photovoltaic panel system

- Two-axis tracking system
- Water-based cleaning system
- Microcontroller integration



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Technical Challenges

Mechanical Design

- Multi-hinge design
- Method of movement

Electrical & Control

- Electrical board layout & wire routing
- Tracking system

Component Selection

- Ensuring compatibility
- Sufficient specifications and production

Cleaning System

- Nozzle selection and spray coverage
- Electromechanical integration

Design Validation Testing

- Overall systems validation

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Presentation Roadmap

- Concept of Operations
- Budget and Product Specifications
- Systems Development and Overview
- Finite Element Analysis & Safety Simulation
- Manufacturing Results, Testing & Future Considerations

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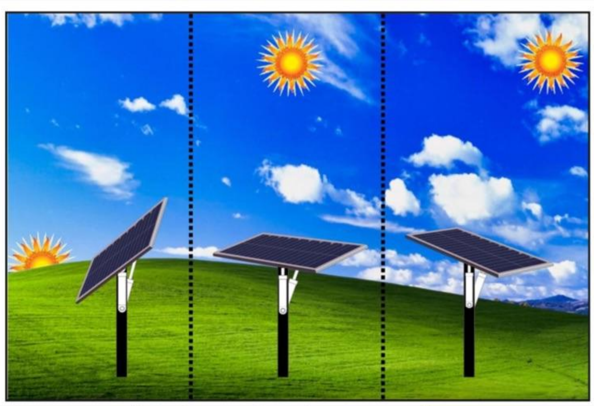
Concept of Operations (CONOPS): Tracking



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Concept of Operations (CONOPS): Cleaning

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Summary of Efficiency Gains Research*

+13-25%	+25-40%	+17%
Single Axis Gains	Dual Axis Gains	Cleaning System Addition

*In reference to a traditional stationary PV System

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Customer Needs

- Homeowners
- Industry professionals
- Members of academia
- Independent solar enthusiasts

Customer Need	Description	Notes/Measure of Effectiveness
CN 1	Easy to integrate with current infrastructure	Usage of standard water hookup and 110V standard home power.
CN 2	Little hands-on maintenance is required	Components are well protected from the elements.
CN 3	Easily Programmable by consumer	Cleaning system can be set on the desired schedule.
CN 4	System is a good investment	Tracking + Cleaning yields a net positive boost to solar efficiency.
CN 5	System is easy to understand	Feedback to the user should be concise, measurable, and comparable to a reference value.

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Product Specifications

Efficiency Gain · Manufacturing Cost · Sale Price

Importance	Metric	Units	Target
3	Apparatus height	ft	5
2	Power output	W	Any panel
1	Efficiency gain	%	20
1	Manufacturing cost	USD	Subj.
1	Sale price	USD	2000
4	Customizability	Subj.	Battery, 4 panels/100W-400W
3	Wind speed resistance	ft/s	30
4	Weight capacity	lb	300
3	Material corrosion resistance	Subj.	Paint/Aluminum
4	Installation time	min	60
4	Time for maintenance	min	20
4	ROM	degree	-60 - 60
5	Actuation Type	Subj.	Actuator
5	Control System	Subj.	Raspberry Pi
2	# of axes	Subj.	2

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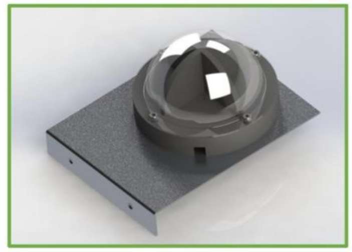
Systems Overview



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Structure & Articulation

ASME Y14.5 GD&T Standard

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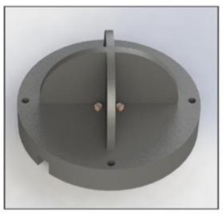
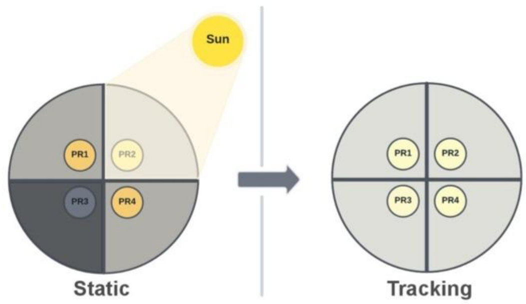
Tracking System

- Utilizes four PhotoResistors
- Measures light intensity based on capacitor charging time





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Cleaning System

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Final Cost
$1,373.94

Part	Quantified Cost
CanaKit Raspberry Pi 4 Starter PRO Kit	$130.00
Renogy 100W 12V Compact Panel	$196.00
Renogy 700W Inverter	$146.00
Renogy Rover Elite 20A Charge Controller	$130.00
Mighty Max Battery Mighty Max SLA Rechargeable Sealed Lead Acid 12180 Backup Power Batteries	$69.00
200mm Linear Actuators	$110.00
Wiring Kit	$19.00
Nuts/Bolts	$130.00
Max 31855 Thermocouple amplifier/signal converter	$15.00
Water Pump	$60.00
Thermocouple	$44.00
Thermal Adhesive Tape	$16.97
JBtek 4 Channel DC 5V Relay Module	$16.00
Aluminum Tubing	$157.50
Acrylic Dome	$15.59
Flat Spray Nozzle	$28.60
Photo resistors	$3.80
Pipe Fittings	$50.00
Solar Shield Coating	$36.48
	Total Cost
	$1,373.94

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Systems FEA

Maximum Wind Load:
100.8lbf*

*Calculated using a maximum wind speed of 85 ft/s (58 mi/hr) per **ASCE 7**

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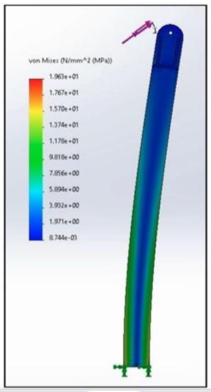
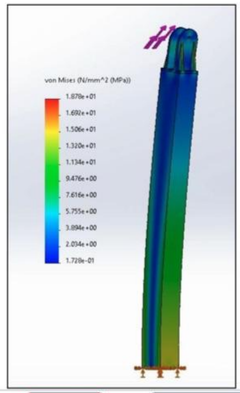


Case 1

- 100.8 lbf
- 37° from vertical
- 1020 steel



Case 2

- 100.8 lbf
- 47° from vertical
- 1020 steel

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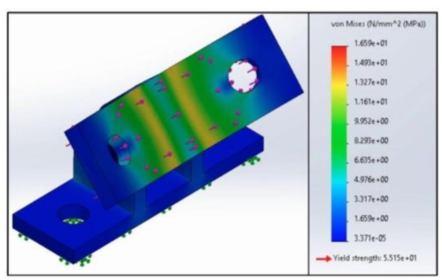
Case 3

- 50.4 lbf
- 47° from vertical
- 6061 Al



Von Mises Stress (MPa)

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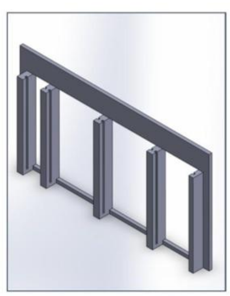
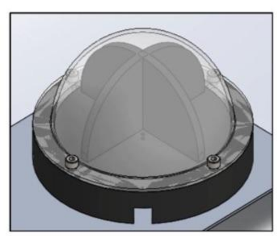
Use of 3D Printed Parts

- 3D printed parts for efficiency & complexity
- Filament used: Tough PLA, PLA





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Summary Results

Case 1	Case 2	Case 3
Stress: 19.6 MPa	Stress: 18.8 MPa	Stress: 10.6 MPa
Displacement: 0.80mm	Displacement: 0.79mm	FOS: **5.2**
FOS: **17.8**	FOS: **18.6**	

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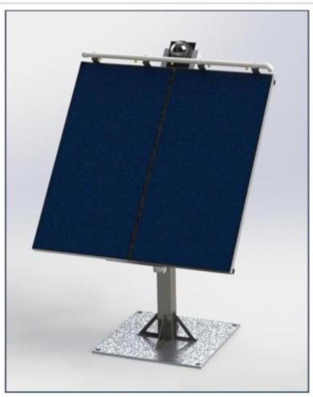
Results



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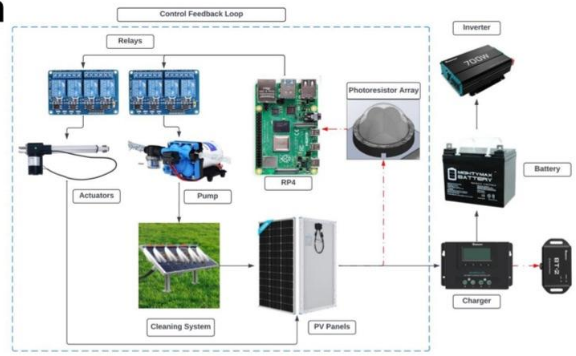
Electrical Diagram

- Bluetooth Module pairs with an app for easy monitoring



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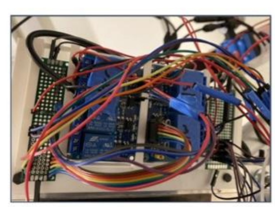
Raspberry Pi Control System

- Programmed in Python
- Tracking system runs between sunrise and sunset
- Continuously monitors time of day
- Orientation resets to neutral position at end of day
- Remote desktop from anywhere with WiFi signal



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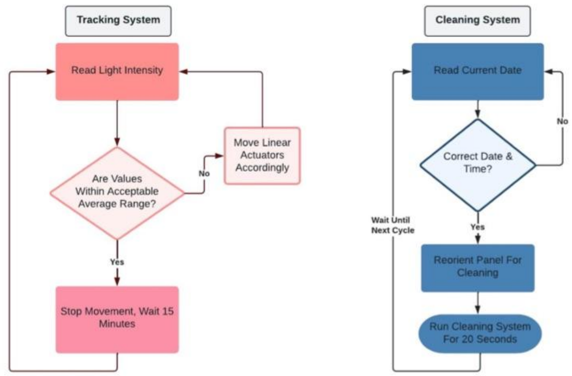
Tracking & Cleaning Logic Flow



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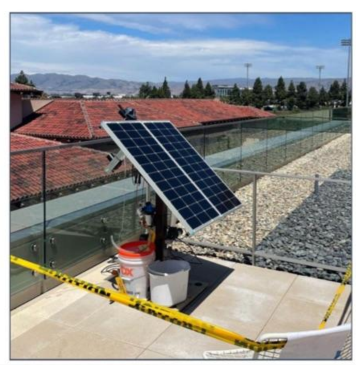
Tracking Testing Methods

- Testing ran over two 24 hour periods
- Santa Clara, CA partly cloudy weather
- One day of static testing
- One day of dynamic tracking test



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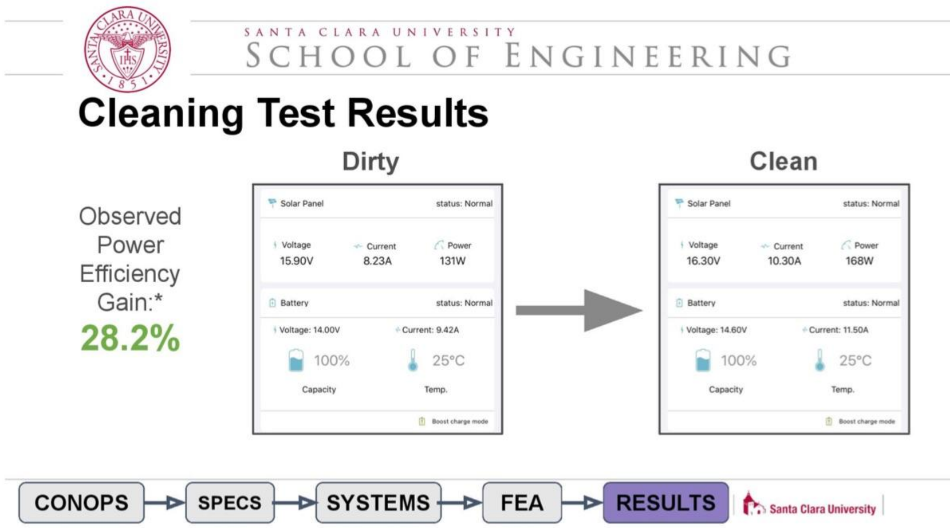
Tracking Testing Results

Test	Power Generated [kWh]	Weather Conditions
Fixed	0.861	- Scattered clouds in am and partly sunny in pm - High of 68℉
Tracking	1.314	- Partly Sunny from 6am to 6pm - High of 68℉

- Tracking system increased power generated by **0.451 kWh**
- Increase of **52.61%**
- Tracking system increases total output power generated

Cleaning System Testing

- Simulated multi-month debris accumulation
- 20 Second Cleaning
- Santa Clara, CA sunny weather
- Power delivery from panel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Cleaning Test Results
Dirty
Clean
Observed Power Efficiency Gain:*
28.2%
Solar Panel
status: Normal
Voltage
15.90V
Current
8.23A
Power
131W
Battery
status: Normal
Voltage: 14.00V
Current: 9.42A
100%
Capacity
25°C
Temp.
Boost charge mode
Solar Panel
status: Normal
Voltage
16.30V
Current
10.30A
Power
168W
Battery
status: Normal
Voltage: 14.60V
Current: 11.50A
100%
Capacity
25°C
Temp.
Boost charge mode
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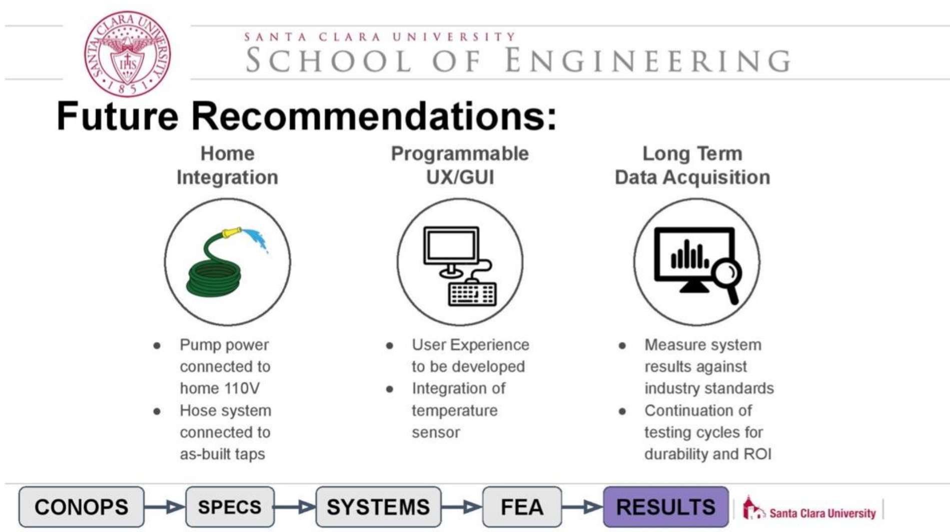
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Future Recommendations:
Home Integration
• Pump power connected to home 110V
• Hose system connected to as-built taps
Programmable UX/GUI
• User Experience to be developed
• Integration of temperature sensor
Long Term Data Acquisition
• Measure system results against industry standards
• Continuation of testing cycles for durability and ROI
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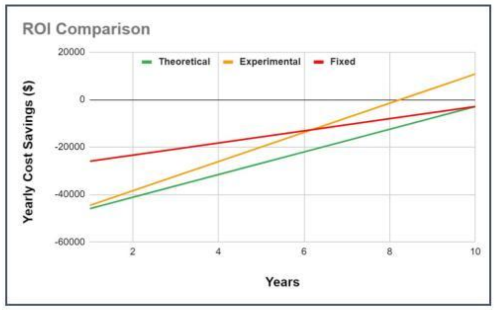
Return on Investment

Breakeven:
< 8.2 years



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Return on Investment Continued

	Theoretical 2-Axis + Cleaning	Experimental 2-Axis + Cleaning	Fixed
Base System Power Output (W)	6000	6000	6000
Efficiency Gain	32.5%	52%	0%
Total Power Output (W)	7950	9157	6000
Manufacturing Cost ($)	41,220.00	41,220.00	22,500.00
Electricity Cost (c/kWh)	0.39	0.39	0.39
Yearly Power Generation (kWh)	23214	26737	17520
Yearly Power Consumption (kWh)	10950	10950	10950
Net Yearly Power Generation (kWh)	12264	15787	6570
Potential Yearly Savings ($)	4,782.96	6,157.04	2,562.30
Installation Cost ($)	9000	9000	3000
Cleaning Cost ($/yr)	100	100	3000
Potential ROI (years)	10.5	8.2	11.1
1-Year Cost Savings ($)	-45537.04	-44162.96	-25937.70
10-Year Cost Savings ($)	-2490.4	8739.60	-2877.00

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Customer Needs Final Evaluation:

- CN 1: Outside of Scope
- CN 2: Accomplished
- CN 3: Accomplished
- CN 4: Accomplished
- CN 5: Interim Solution

Customer Need	Description	Notes/Measure of Effectiveness
CN 1	Easy to integrate with current infrastructure	Usage of standard water hookup and 110V standard home power.
CN 2	Little hands-on maintenance is required	Components are well protected from the elements.
CN 3	Easily Programmable by consumer	Cleaning system can be set on the desired schedule.
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Accomplishments

Project Management
- 12 Month project lifecycle
- Six member team organization

Systems Integration
- Integration of distinct mechanical, electrical, and computer based subsystems

Panel Articulation
- Dual Axis rotation pushes limits of energy generation

Microcontroller Integration
- Integration of off-the-shelf hardware into robust product design

Cleaning Integration
- Eliminating homeowner or utility need to frequently clean panels

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Acknowledgements

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Thank You!

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