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Sun Tracking Solar Panel (STSP1) Final Project Report

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Final Project Report

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Executive Summary

The purpose of this report is to present the final version of our design, which is a proof-of-concept regarding whether it is viable and beneficial to create a system that allows solar panels to track the sun in order to increase efficiency. The final design went through some changes compared to the version proposed in the Preliminary Design report, which are a reduction in a motor and a direction of rotation. This was due to the fact that it would have been difficult to safely mount our initial design to a rooftop. Our final design is much safer to put on a rooftop and can fit more panels per rooftop.

The final design was evaluated using several tests to ensure it meets all the requirements and constraints proposed. The results from the tests indicated that the final design was able to meet six of the requirements and came close to fulfilling the seventh. The final design satisfied three main requirements, including the weight limit requirements for Texas residential roof, the motion mechanism can rotate freely at 180-degree, and the tracking subsystem was able to track the sun accurately within 10-degrees. The final design also satisfies three out of four additional requirements, which are needed if the design is applied in the practical scenarios. Specifically, the product was able to handle 60mph wind, resist water and dust ingress following code IP54, and pay off within 10 years if two or more panels are used according to the result of margin cost-benefit analysis. Because multiple solar panels can be rotated based on measurements from a single tracking system, by adding more panels to the rooftop our design can pay off the increased costs. The fourth additional requirement is the ability to function within a range of temperatures experienced by Texas rooftops. Our design failed to meet the temperature requirement of operation in temperatures between -23 to 160℉ because of the servo motor's ambient temperature specifications (5-158℉). We found out that this is unavoidable in this price range for the servo motors. And purchasing a more expensive servo motor to meet this constraint will fail the requirement of paying off within 10 years which the team deemed as a more important requirement, and it is rare for a Texas roof to reach temperatures below 5℉.

Overall, the final design can be considered as successful since it meets the project objectives and most of the requirements.

1. Introduction

The purpose of this report is to demonstrate our design for a sun tracking solar panel and show the tests performed on the solar panel device with their results. The motivation behind our project is to create a sun tracking solar panel system for residential use, as well as to prove that the sun tracking solar panel can be a more effective solution than the traditional stationary panel. This can be proved by measuring the power generated by a traditional stationary panel and our sun tracking system, where the sun tracking system follows the angle of the sun, and comparing the results. So, the problem is to design a system that allows a standard solar panel to track the sun, thereby increasing its efficiency.

The top-level requirements to ensure a successful final design are the ability of the device to accurately track the movement of the sun throughout the day, withstand winds up to 60 mph, pay off costs within 10 years of use, be under the weight constraint of 15 lbs/ft^2, withstand temperatures from -23°F to 160℉, and should prevent the ingress of dust and water. This last requirement is based on the IP54 standard.

To meet these requirements, the team chose a system of a servo motor, light sensors, and Arduino code to accurately track the sun throughout the day. An Arduino uno board in tandem with the Arduino code to relay information collected from a set of light sensors attached to the panel to the motor is the basics of our tracking system. After measuring the power collected by a stationary panel and our tracking panel, on days with similar weather conditions, the team found that our tracking panel collected more power throughout a 12 hour period and could accurately track the sun. The motor was chosen based on our panel weight and wind requirement, as we intended to be able to rotate the solar panel system under winds reaching upwards of 60 mph. With the chosen design, if two or more rotating solar panels were implemented, the devices would pay off the additional construction cost of converting a stationary panel to a tracking panel within a ten year period. The reduction of cost is because we only need one tracking subsystem per system, and hence the price invested in the tracking subsystem does not multiply as we increase the amount of solar panels. The conclusion proposed was established based on the marginal cost-benefit model, assuming the energy gained is consistent throughout the year and no additional cost besides what we proposed.

As this project is a proof of concept project, our team decided to work with a relatively simple design to minimize the possible points of failure to prove simple changes will allow us to

increase the efficiency of the solar panel. During construction the team chose parts that would withstand the required temperature range. The only component that would not withstand the required temperature range was the motor. A motor that does fit this constraint will be discussed in a later section. The motor the team did implement is satisfactory for the temperature range of San Antonio whereas our requirement comes from the temperature for all of Texas. Finally, we used weatherproof parts where we could, such as the solar panel, and created an acrylic container for the electronics in order to prevent major contact with water and dust.

2. <u>Overview of the Final Design</u>

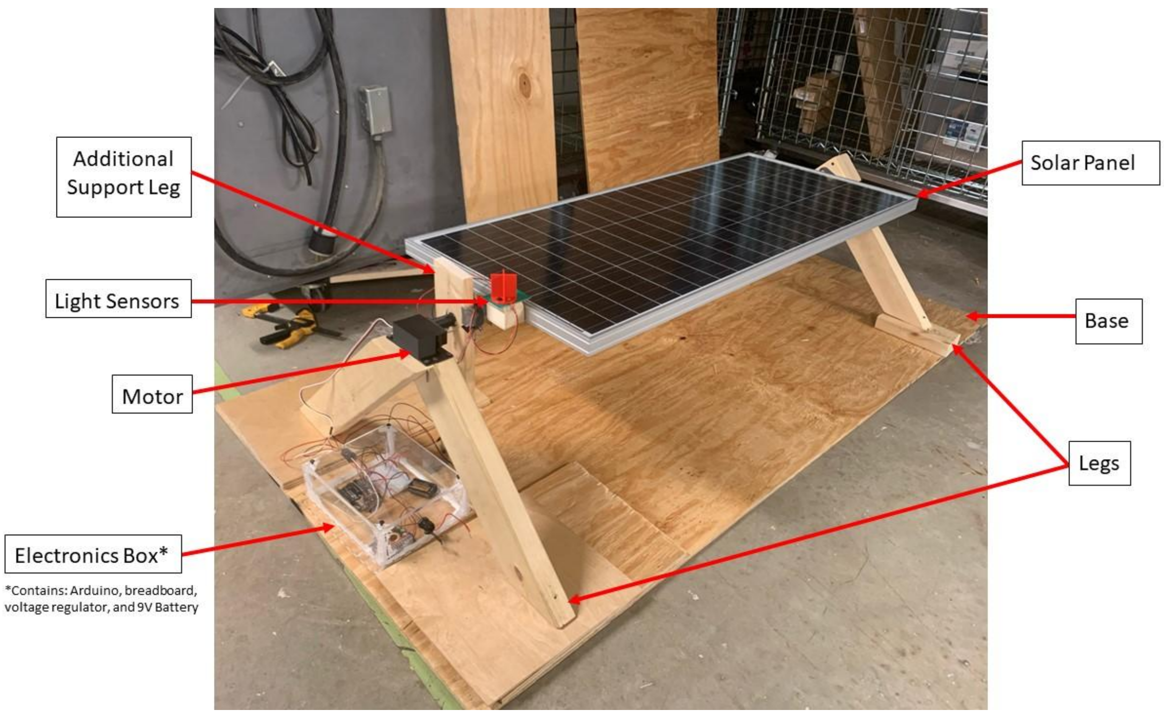


Figure 1: Overview Design Annotated

The final design of the sun-tracking solar panel is divided into two subsystems for construction and evaluation, and can be seen in Figure 1. The first subsystem is the movement subsystem, which consists of the rotation mechanism of the sun-tracking solar panel. The second subsystem is the tracking subsystem controls of the actions performed by the sun-tracking solar panel. A significant change was made in the control software compared to our design last semester such that it adapted the reduction from 2 motors to 1 servo motor. This change was made due to the large weight of the initial design. In order for that system to be placed on a

rooftop, a much larger base would be required to distribute the weight than our final prototype. This larger base would limit the number of sun tracking panels that could be used on a given rooftop, decreasing overall energy production.

To be considered successful, the project must achieve three main requirements and four additional requirements. The main requirements are the weight constraint, the ability to track the sun throughout the day, and the accuracy in tracking the sunlight. The additional requirements are requirements needed when the final product is applied to a real-life scenario, which state the final product should withstand winds up to 60 mph, pay off costs within 10 years of use, should be weatherproofed for dust and water , and our system should also be able to operate in temperatures range from -23℉ to 160℉.

For the first main requirement, the final product's weight must be within the allowable weight limit of the residential roof in order to have the project be viable. The maximum roof load is 15-lbs/ft^2 for a typical asphalt-shingle, wood-framed roof.

The second main requirement is that we need to ensure the final design has the ability to rotate in two directions around the axis parallel to the base surface without hitting any obstacles. The final product's rotation should cover a range close to the expected range of motion which is 180° about 1 axis parallel to the roof.

The third main requirement is the accuracy of the motion generated by the sun-tracking mechanism when responding to the movement of the sun throughout the day. The surface of the solar panel should be perpendicular to the sun rays within acceptable uncertainties during the time the tracking mechanism is active.

The satisfaction of 3 main requirements will suggest that our design was able to track the sun by rotating the solar panel accurately using one-axis of rotation. The satisfaction of 4 additional requirements will suggest that our design can be applied in practical scenarios and economically viable. The efficiency of the final product is economically viable such that it can pay off within 10 years if two or solar panels were included in the system.

Overall, all 3 main requirements and 4 additional requirements proposed are mostly satisfied according to the evaluated test results. We have successfully satisfied the 3 main requirements proposed. However, we were only able to satisfy 3 out of 4 additional requirements, which are the wind resistance, the water/dust resistance, and the economic viability. The last temperature requirement was only partially satisfied. All of the parts in the

design have the temperature specifications satisfying the temperature requirement (-23 to 160℉), except for the servo motor which has operating temperatures between 5℉ and 158℉. As applying a new motor that satisfies this requirement will fail the main requirement of paying off within 10 years, we decided to violate this temperature requirement to maintain the economical viability requirement.

2.1 Movement Subsystem

The movement subsystem is in charge of performing all the physical actions of the final product. This subsystem consists of a wood frame, two bearings, a steel shaft, and a servo motor.

There are some changes compared to the Preliminary Design Report where the small-scale version was designed and constructed. The first change was the elimination of the continuous motor in the design. This change was due to the shortened project timeline (Institution's academic schedule change due to COVID pandemic), large static load on the rooftop, and the amount of space taken up on the roof. The design is changed such that the system can rotate freely in one direction only. The final design of the system allows the solar panel to rotate around its long line of symmetry. As a result of this change, the gear-leg used to hold the solar panel is substituted by a wood frame in our final design.

The second change is the addition of a wooden pillar to support the weight of the solar panel. This change is due to the weight increase when we scale up the design, which led to the collapse of one of the legs. To attach the servo motor to one of the wooden legs, we 3D-printed a servo motor holder and screwed it to the leg. But due to the weight of the solar panel, the 3D-print material got ripped off and failed to hold the servo motor in place. This accident drove us to add a weight-supporting pillar to the system to help release the weight originally acted on the servo motor.

2.2 Tracking Subsystem

The tracking subsystem acts as a controller of the final product such that it decides the actions of the solar panel. This subsystem consists of a Arduino Uno, a 12-V and a 9V batteries supply, a buck converter, a cross-shape sensor holder, two photoelectric sensors, and some circuit components (10kΩ resistors, wires, etc.).

Theoretically, an indirect sunlight incident to the solar panel produces significantly less power than a direct one. Thus, we implemented a cross-shape sensor holder (Fig. C1), which will get shaded if the incident light is not directly overhead. The data passed to the Arduino, which

uses Arduino code (Fig. C2) to process data inputs - light intensity- and generate data output - servo motor's control signal (Fig. C3). And according to the differences in sunlight intensity data between sensors placed at shaded and non-shaded areas, the software program is able to direct the servo motor to rotate the solar panel and the sensor's holder until the incident light is at the right angle.

There are some adjustments in the design of this subsystem compared to the Preliminary Design. The adjustments are the results of the continuous motor being eliminated (as mentioned in the former subsystem). The first adjustment is the number of photoelectric sensors used in the final design. The original plan had four sensors needed to support a 2-axis rotation ability. But due to the changes discussed above, we only use two sensors in the final prototype. Additionally, we also adjusted the software program to consider two input signals and one servo-control output only.

In addition to the motion control, we also researched and built a protective box that has dust and water resistance according to IP54. This box is built from acrylic and sealed with fast dry acrylic latex caulk for outdoor use . The purpose of this box is to protect all electrical components which are exposed to the outdoor environment. Since the electronic components will be placed on the roof with the solar panel it is important that these components can withstand any weather conditions possible on the roof.

2.3 Methods and Construction

Construction techniques

The construction technique used to create the movement subsystem is a framing construction, which uses wood to give the structure support and shape. We chose this construction technique for the movement subsystem because it is simple, and is commonly used in the majority of residential buildings. Future iterations of this design would likely use more durable material for the frame.

The construction technique of the tracking subsystem is designed as a closed-loop feedback control system. The software program will check the status of the photoelectric sensors every 20 minutes. If there is a difference in the light intensity received from the sensors, the program will control the servo motor to rotate with appropriate direction. The motor continues to rotate with 1-degree steps while checking the value of sensors and stops rotating if the input from sensors are similar.

Tools and Makerspace equipments

The entirety of the frame and the control circuit were constructed using equipment from the Trinity Makerspace. The frame was built using various saws and sanders from the wood shop. A drill press was used to create a hole through one end of the metal rod which prevents the motor adapter from loosening over time. We used metal shears and a metal bender on an aluminum sheet to build some custom L-brackets to support parts of the frame. The motor housing, motor adapter, and bearing adapters were all printed on the Markforged Onyx Series 3D printer using Onyx filament material for strength and resilience. The CAD files for these parts are included in our final deliverables to be delivered to the project sponsor. The components of the control circuit were purchased but they were soldered together using the soldering station in the Makerspace.

3. <u>Design Evaluation</u>

3.1 Accurate Sun Tracking

Associated Test: Indoor and Outdoor Tracking Tests

The team tested whether the system could position the solar panel to face an incoming light source at various angles of incidence. We then placed the system on a rooftop for a full 12-hour period of daylight to see how well it performed.

Objectives

The goal of this test was to verify the system's ability to correctly position the solar panel relative to the sun.

Features Evaluated

This test examined the ability of the system to fulfill the tracking and movement requirements.

Test Scope

This test was meant to mimic the actual operating conditions of our design to ensure that, when left alone in a non simulated environment, it operated as anticipated.

Test Plan

Tools, Techniques, Skills:

- The team used a flashlight as a light source whose position relative to the panel could be easily measured

- The team utilized a protractor to ensure accurate measurement of the positions of both the light source and the solar panel
- Visual inspection: when observing the ability of the solar panel to track in an outdoor scenario, the team used visual inspection to ensure that the panel was being correctly oriented by the sensor array

Assumptions:

- For the first part of the test, the team assumed that the panel would operate the same with a flashlight as the light source as it would with the sun.

Data collection:

- The team carefully positioned the flashlight at a particular angle relative to the ground and then measured the angle that the solar panel was moved to.

Acceptance Criteria

The acceptance criteria for this test is that the panel will be able to move to track and adjust to both the artificial light and sun's locations with no more than 10 degrees of error.

Test Results

Table 1: The result of the tracking system's self-correction in adjusting to the artificial light source.

Angle of Incident Light [°]	Measured Panel Angle (°)	Percent Difference (%)
0	5	-
45	44	2.2
90	81	10.0
130	125	3.9
180	170	5.6

We found that our tracking system was able to successfully track the artificial light source well within the expected error as seen in Table 1 above. After discovering that the tracking system was successful with an artificial source, we went outside to test it with the sun. Since the values required for tracking the sun varied slightly compared to the values used inside, our code

needed to be adjusted. However, after a very small adjustment, the tracking system again was successful. Due to the difficulty in measuring the angle of the sun with only a protractor, we could not record results as easily. We started at 0 and 180 degrees, allowing the panel to rotate itself until it had tracked the sun.

Evaluation

As seen above, our system worked excellently, as it rotated to the correct position in order to face the sun within about 10 degrees of error. In both parts of this test, our tracking system functioned well.

3.2 Withstand High Winds

Associated Test: Wind Resistance Test

The team used a 3-D model of our system to simulate the force loads created by 60mph winds on our device at various angles of incidence.

Objectives

The purpose of the wind resistance test was to ensure that the final prototype can withstand 60 mph winds during operation.

Features Evaluated

This test ensured that our final prototype fulfills the wind resistance requirement of our project.

Test Scope

Our prototype needs to be able to operate in wind speeds up to 60mph. We were focused on ensuring that our system had enough structural support to remain undamaged by such winds. The team does not have access to a wind tunnel for physical testing so we used Autocad CFD to perform this test.

Test Plan

Materials:

- Autocad CFD software

Tools, Techniques, Skills:

- 3-D modeling: this technique was used to create an accurate full-scale model of our prototype for wind load analysis.

Assumptions:

- Autocad CFD does not have material properties for a solar panel so that part of the model was made of aluminum as that is what the structure of the solar panel is constructed from.
- The flow of air generated by the Autocad CFD is laminar, which theoretically applies the same force on the upper and lower side of the solar panel. Thus, there is no significant torque generated by the wind that affects the performance of the servo motor.

Data collection:

- Autocad CFD provided the drag and lift forces exerted on the model at each angle of incidence.

Acceptance Criteria

This test is considered to be successful as long as the 3D model of our prototype is able to withstand a 60mph simulated wind load at the different angles. The team determined the most likely point of failure due to high wind force loads would be the screw that connects the motor to the shaft which rotates the solar panel. So long as the wind force did not exceed the shear strength of the screw, then the requirement would be satisfied.

Test Results

In Autocad CFD we found the drag force and lift force each model would experience if the wind was blowing at the solar panel which was determined to give the maximum forces which can be seen in Table 2.

Table 2: Forces on the Panel When a Direct 60mph Wind is Blowing on the Device

Orientation [°]	Drag Force [lb_f]	Lift Force [lb_f]
90	-136.8	**0.5**
60	-98.9	-47.0
45	-78.6	-65.5
30	-53.3	-67.5
0	**-15.9**	6.4

The maximum forces for both categories are highlighted and the minimum forces are bolded. The most likely point of failure is the M4 size screw that connects the motor to the rotating shaft. This screw has an ultimate strength around 790 lb_f which is well above the maximum wind load exerted on our system. Because of this, we are satisfied with the ability of our system to operate under the given wind conditions.

From the wind test simulation we were able to see the smoke traces of the wind as it traveled around the device shown in Figure 2a-e. These help to visualize the path of the wind as it passes over our system in order to determine when the forces are likely to be greatest.

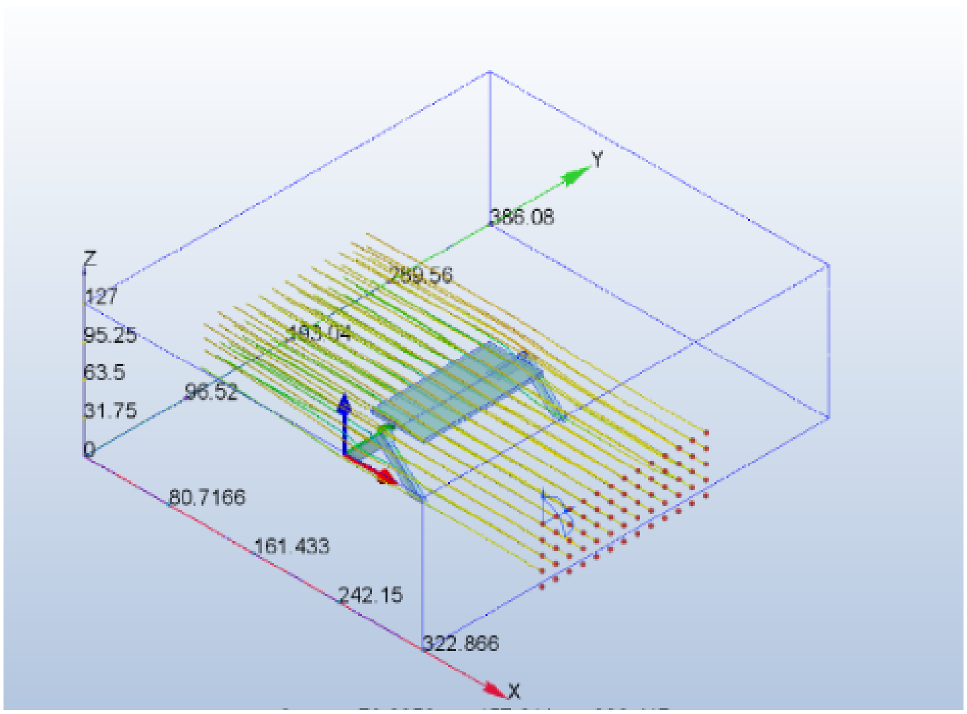


Figure 2a: Wind Force Distribution at 0°

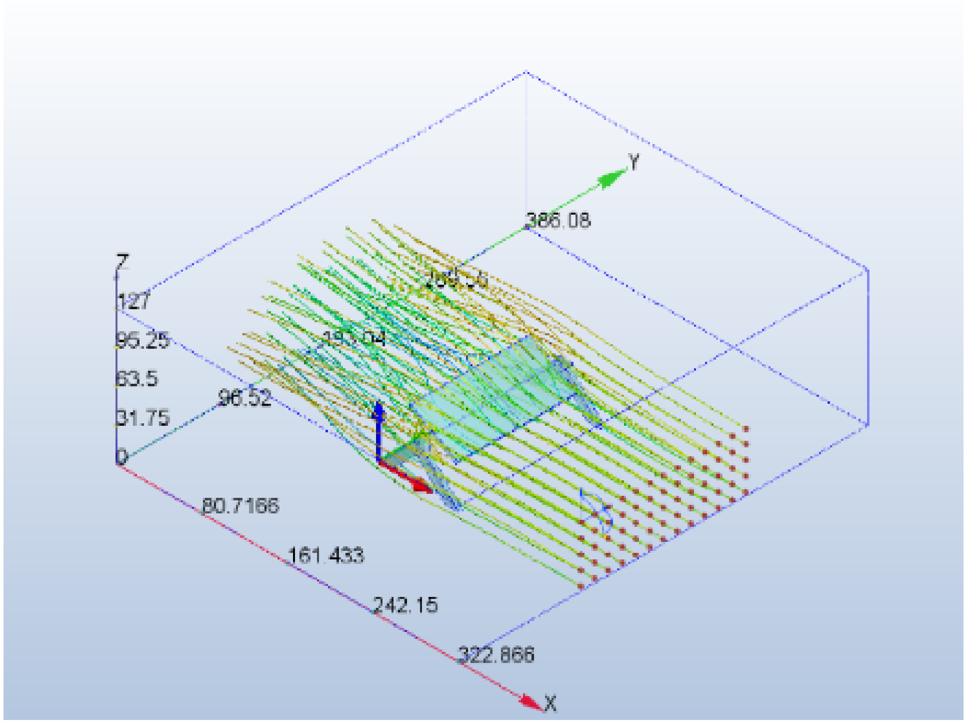


Figure 2b: Wind Force Distribution at 30°

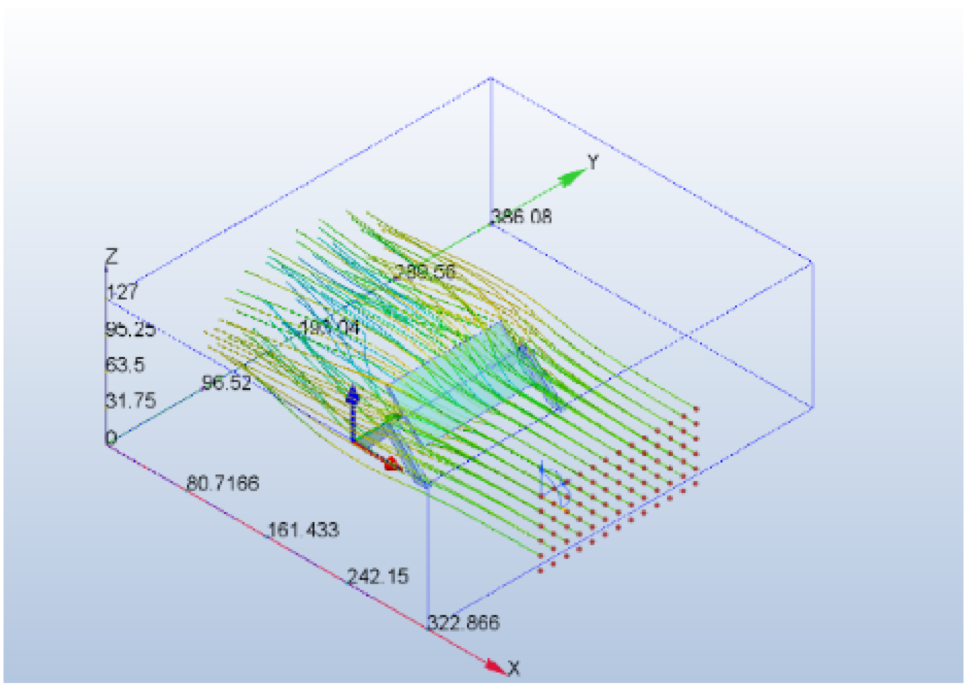


Figure 2c: Wind Force Distribution at 45°

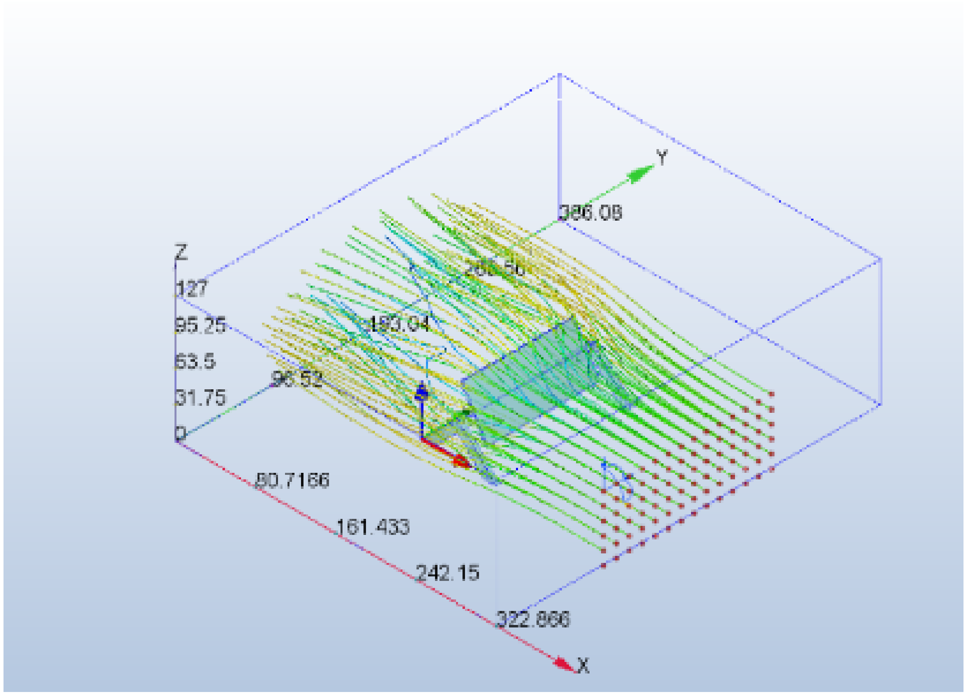


Figure 2d: Wind Force Distribution at 60°

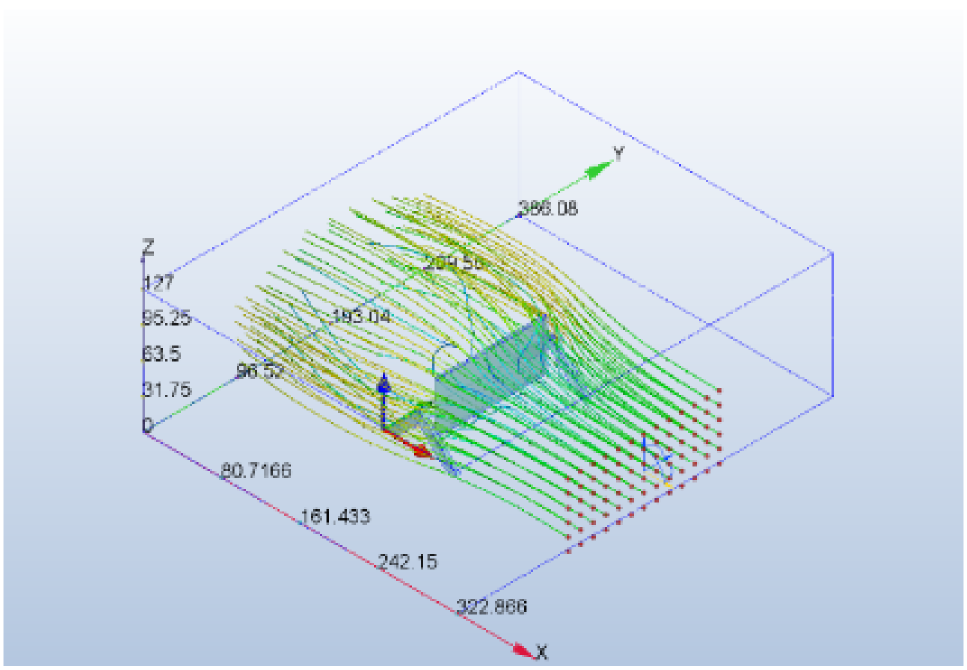


Figure 2e: Wind Force Distribution at 90°

Evaluation

As seen above, the force exerted on our panel by the wind is far less than the ultimate strength of the screw. Since this is our most likely point of failure on the device, we believe that it will be able to operate as intended under the prescribed wind conditions.

3.3 Pay Off Costs Within 10 Years

Associated Test: Power Test

This test compared the power generation of a stationary panel and our sun tracking solar panel system.

Objectives

The objective of this test was to determine if the tracking device increased the amount of energy collected by a solar panel by enough to pay off costs within 10 years.

Features Evaluated

This test ensured that our system could pay off the costs of the additional components.

Test Scope

Our intent behind this test was to mimic optimal operating conditions, such as a sunny environment on a roof to show that there was a significant increase in efficiency. We utilized the 5th floor CSI roof access as a way to measure this, which unfortunately lacked direct sunlight during the morning. By doing this, we were able to calculate the power our device could generate on a sunny day. Using this data, prices for electricity in San Antonio, and the costs of constructing our prototype, we were able to determine the economic viability of our design.

Test Plan

Materials:

- A computer necessary for researching costs and uploading the Arduino code.

Tools, Techniques, Skills:

- A digital multimeter for use in measuring the voltage and current for the solar panel at any given time of the day.
- The calculations involved with finding the power and averaging it over the entire day.
- The ability to research costs online, as well as keep track of our own budget to find the total and future costs of the system.

Assumptions:

- That the morning hours were similar to the evening, as we had to mirror the evening hours to account for the lack of sunlight in the morning.
- That the system would still be viable even in cloudy weather, as our cost calculations do not account for the power found in cloudy conditions.

Data collection:

- Excel was used to collect the data as well as graph the results.

Acceptance Criteria

It should be possible for a number of sun tracking solar panels to pay off their costs within 10 years.

Test Results

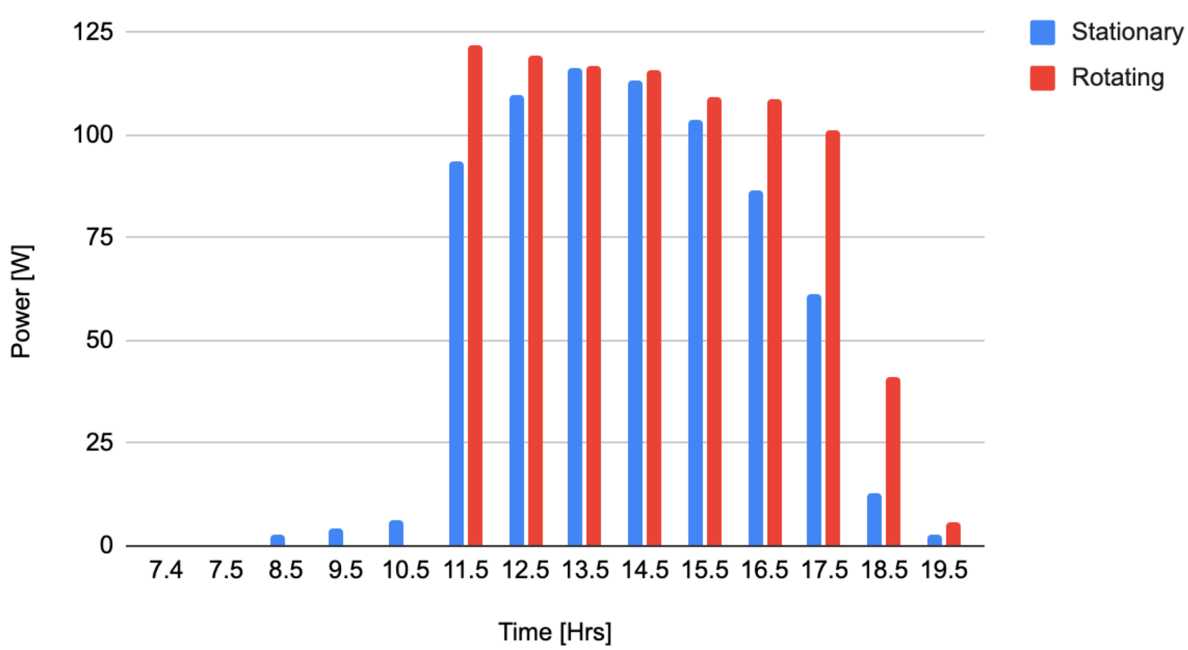


Figure 3: The plot of the power gained by the solar panel when stationary and rotating.

The plot above shows the power generated from the solar panel during the day. The stationary data was taken on Friday, March 25 on Trinity University's CSI rooftop, while the rotating data was taken on Sunday, April 3 at the same location. The stationary power followed a sinusoidal pattern as expected, while the rotational power followed a more linear pattern. In the first 4 hours, the power generated was low because the sunlight was blocked by the CSI building.

In the last two hours, the light was blocked by the railing on the rooftop walkway, causing a reduction in power. We found that on average, there was a 24.8% increase (24.0% increase with accounted power consumed) in power generation when switching to the rotational system. This difference in generation was most pronounced in early morning or evening hours, when the sun was at a large angle from the stationary panel.

To see whether this significant increase can bring a positive economic interest, we conducted further research into the costs of electricity in San Antonio, using (1) and accounting for all purchases made to construct our design. We calculated that the cost of building sun-tracking solar panels increases by $93.04 per tracking system with an additional cost of $23.99 for the Arduino microcontroller which can control multiple tracking systems on the same roof. On another hand, each tracking system only gains $106.59 more than a stationary panel in 10-year use. In our final analysis, we found that the initial investment is paid off at about 1.77 solar panels, which needs to be rounded up to 2 tracking systems on a roof.

$$P = \frac{\sum E}{t_{total}} = \frac{\sum P t_{operated}}{t_{total}} = \frac{\sum I V t_{operated}}{t_{total}} \quad (1)$$

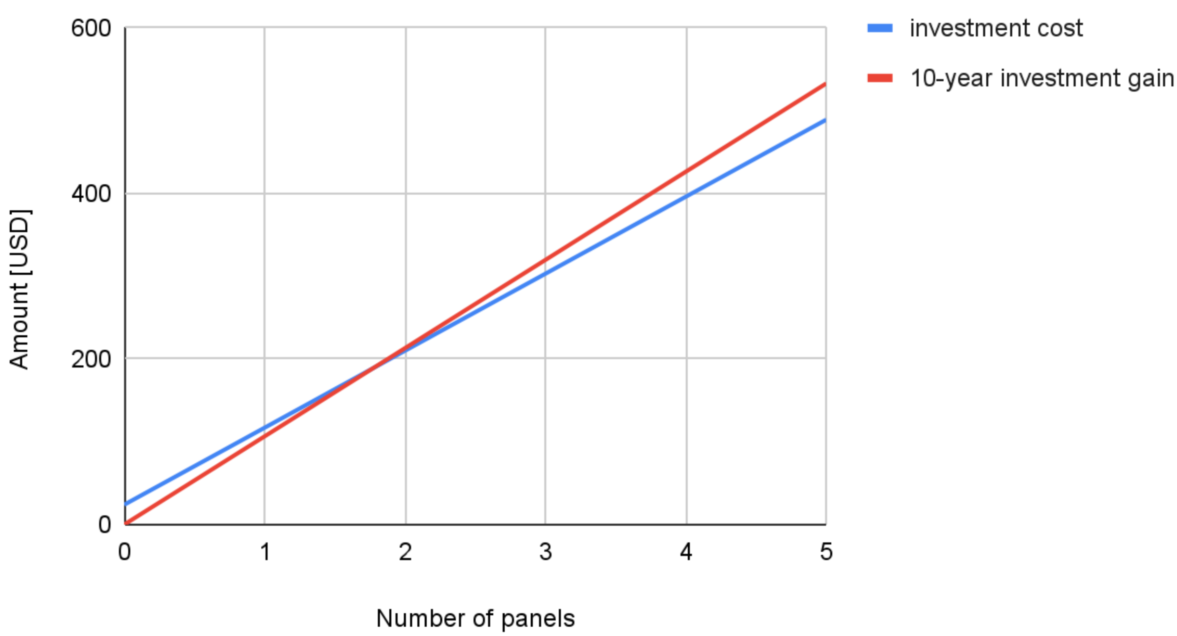


Figure 4: The plot of the economical cost and gain by the number of rotational solar panels.

Evaluation

To evaluate whether the design is economically viable, we analyzed the model using the marginal cost-benefit analysis (see Figure 4). The data for this analysis was constructed based on our measurements, budget report, and local price of electricity. According to the plot, the investment will return positive interest only if two or more tracking solar panels are used in the system. Based on our criteria for this test, the design we proposed is accepted while meeting all the design requirements and constraints. The major caveat with this conclusion however, is that it assumes 12 full hours of sunlight every day of the year for ten years. A more efficient panel would be required or less expensive tracking systems via mass production are likely required for the economic viability of this project.

3.4 Do Not Exceed Residential Roof Weight Limit

Associated Test:

The team weighed the entire system in order to determine the size of the base it would need to be placed on.

Objectives

The purpose of this test was to ensure that our system was safe to place on the rooftop of a Texas residence.

Features Evaluated

This test evaluates the ability of our system to be safely mounted to the rooftop of a Texas residence by ensuring that our system does not exert a pressure on the roof in excess of 15 lbs/ft^2.

Test Scope

This requirement is one of the reasons that sun tracking solar panels are not in widespread use as many of them are too heavy to safely put on a rooftop. By placing our system on a wide base and using multiple feet on which to balance, we hope to be able to minimize the area taken up by a single sun tracking system.

Test Plan

Materials:

- Scale: the team used a small kitchen scale to measure the weight of the smaller-scale components (electronics, acrylic housing) and a large scale to measure the weight of the larger components (solar panel, wooden frame).

Tools, Techniques, Skills:

- N/A

Assumptions:

- The team does not have a way to measure the exact weight distribution in our system so we are assuming that the pressure exerted on the rooftop is equal to the weight of our system (including the base itself), over the area of our base.

Data collection:

- The team weighed the whole system, without a base, to determine the minimum allowable area of a base that would let our design fulfill the weight requirement. From there we attached a sturdy plywood base of the appropriate size and reweight the system to ensure that with the base attached, our design was within the bounds of the weight requirement.

Acceptance Criteria

The weight of the entire system with the base attached should exert less than 15 lbs/ft^2 on the ground below it to make it safe to put on a Texas residential roof.

Test Results

The total weight of our sun tracking solar panel system, with the base attached, is 56.5 pounds. We used a base with an area of 15 square feet, meaning that our system exerts 3.8 lbs/ft^2 which is well below the maximum allowable value.

Evaluation

As seen from the test results above, our device is certainly safe to mount on a Texas residential rooftop from a weight per area perspective. We could have used a smaller base but the size of the wooden structure which supports the panel is rather large and we wanted the whole system to fit comfortably within the bounds of the base.

3.5 Withstand Both High and Low Temperatures

The device must be constructed so that it can withstand and operate at the range of temperatures associated with a Texas rooftop environment.

Associated Test: Temperature Test

This test allowed the team to determine if the device will operate within the temperature range of an average Texas rooftop environment. This test analyzed each component of the device individually to see if the component was built to withstand a range of -23℉ to 160℉.

Objectives

The purpose of this test was to determine if each component of our device is rated for the expected temperature range for Texas. The final prototype needs to be able to function in -23℉ to 160℉. The probable points of failure for this test were the electrical components.

Features Evaluated

This test ensured that the device will be able to function in Texas with a temperature range of -23℉ to 160℉. By showing that each component can withstand this range of temperature the conclusion would be that the overall system would be able to withstand these temperatures.

Test Scope

This range is important because it was determined to be the expected temperature range of an average Texas roof. The design proposal specified that the device was intended for residential rooftop use in Texas. However, the team does not have access to a device that would allow us to directly test the temperature range of the device; therefore, instead of a physical test we will be using engineering analysis.

Test Plan

Materials: Computer

Tools, Techniques, Skills:

- Engineering analysis: the understanding that if each individual component is rated for this temperature range then the whole device is rated for this temperature range.

Assumptions:

- The temperature range indicated on the components data sheet is correct and accurate.

Data collection:

- The temperature rating of each component was found and compared to the specified working range.
  - Data Recorded: Qualitative data was collected in a way such as yes this component is rated within our range or no this device can not operate at all temperatures within our range.

Acceptance Criteria

This test will be successful if each subcomponent has an operating temperature range greater than or equal to -23℉ to 160℉.

Test Results

Each component's operating temperature range was found and placed in Table 3.

Table 3: Operating Temperature Ranges of Prototype Components

Component	Minimum Operating Temperature (°F)	Maximum Operating Temperature (°F)
Physical Components		
Wood legs	-	572
Steel all thread	-103	750
Aluminum Brackets	-103	350
Acrylic Box	-150	190
Electronic Components		
Arduino Uno	-40	185
Voltage Regulator	-40	185
Servo Motor	5	158
Solar Panel	-40	185

Evaluation

Most of the components used in our prototype were designed to operate, or have material properties which allow them to function, at temperatures beyond our required range.This means that almost our entire system should be able to reliably function at any temperature which could be reasonably expected to occur on a Texas rooftop. Unsurprisingly, the materials used to create the structure of our prototype (steel, aluminum, etc) have operating temperature ranges well beyond our expected range. It was the electronic components used for control of our device which were more likely to fail at the extremes of our temperature range. Most of the components

have operating temperatures beyond our required range, however the servo motor is not designed to operate within our required temperature range. The high end of its operating range is very close to what we need, but the motor is not rated to operate at temperatures near the bottom end of our temperature range.

Because of the motor's failure to operate at all temperatures within our range we found a motor that was able to withstand the range. This motor is the Hudson Brushless DC Servo Motor with an operating temperature of -40°F to 158°F. However, this motor is $307 which is 7.5 times more expensive than the motor we actually implemented in the design. We decided to continue on with our current motor in order to save time and money. Additionally, since our current device is only being operated in San Antonio, the current motor is sufficient within the range of temperatures of a roof in San Antonio. The other components can withstand our predicted rooftop temperatures and operate in them.

3.6 Prevent the Ingress of Dust and Water

The device must be constructed to be water and dust resistant in accordance with the IP54 standard.

Associated Test: Water and Dust Test

The team tested the overall water and dust resistance of the device with special attention to the electrical components and their housing. This test analyzed whether or not the final design is properly meeting the IP54 requirements.

Objectives

The purpose of this test was to determine if the final design is properly protected from water and/or dust for the intended environment of a residential roof. Special attention was paid to the electrical components of the device.

Features Evaluated

The features evaluated in this test were each individual component's IP54 rating. By showing that each component meets the standard, we said that the entire prototype meets the standard as well.

Test Scope

As most of the purchased components are already IP64 rated, these do not need to be tested. Rather, we will be analyzing the housing for the electronic control system for the design.

Test Plan

Materials: A faucet or hose with a nozzle, access to water and paper towels, and dust/debris

Tools, Techniques, Skills:

- Nozzle and water access: this was used to spray the exterior of the electronics house and deposit water in the interior
- Water retention technique: fill the electronics box with water and see if any leaks out
- Visual inspection and before and after pictures: before and after the test took place a visual inspection was done of the box
- Manual simulation: the team modeled conditions of wind debris

Assumptions:

- If the water inside the electronics housing did not seep out then water hitting the outside would not be able to get into the housing. The nonelectrical components of the device were rated as water proof at the time of purchase and the wooden frame is covered in water resistant wood sealant.

Data collection:

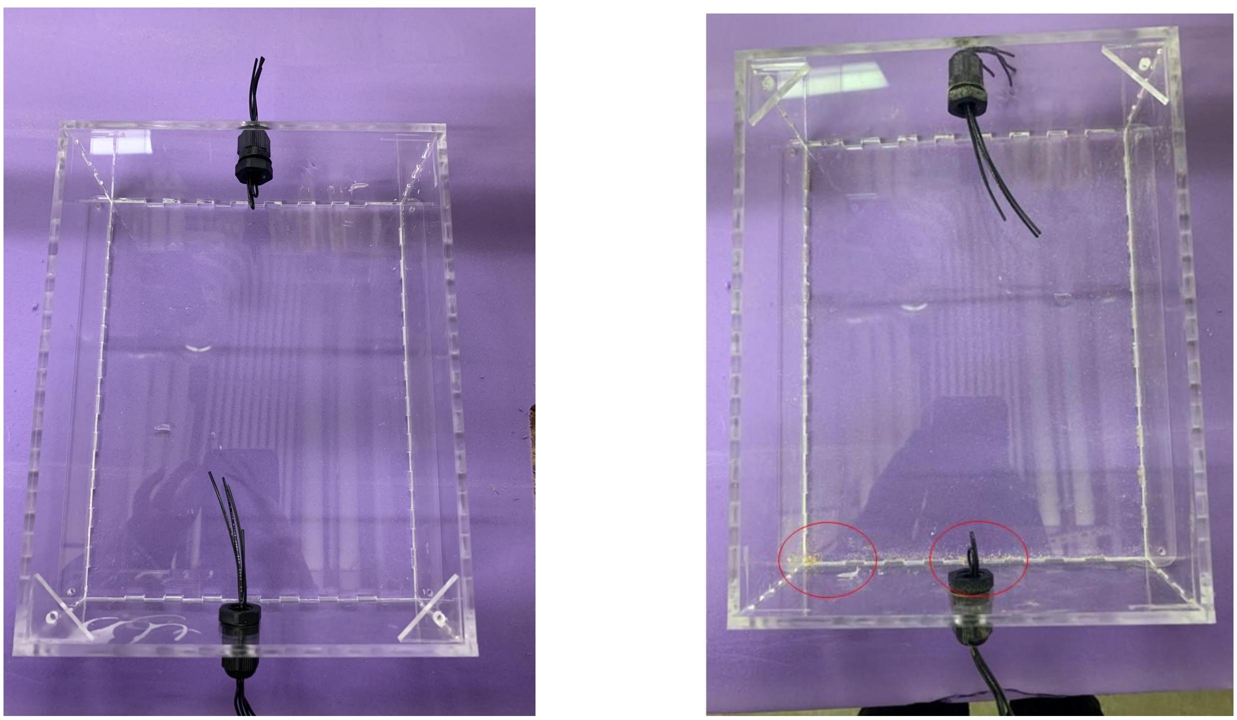
- The dust test was performed once when the box was dry. A photo of the dry electronics house was taken as a before photo for later comparison. The box was then closed and secured. The team then collected saw dust and debris from the CSI woodshop and blew debris at the box. After a substantial amount of dust and debris was deposited on and around the electronic housing, the test was complete. The exterior of the housing was then brushed off and the housing was opened and an after photo was taken.
    - Data Recorded: Qualitative data was taken by visual inspection and comparison of the before and after photos of the interior of the housing.
- For the water resistance test, the team placed about a centimeter of water in the bottom of the housing. The team then waited about 2 mins to see if any water was leaking from the housing.
    - Data Recorded: Qualitative data was visually taken. This test was a yes or no question; therefore, if water came out it was a no and if no water came out of the housing it was a yes.

Acceptance Criteria

The acceptance criteria would be that the control system can withstand water and dust similar to IP54 rated components and function properly. We will know that our system has passed the test if a negligible amount of dust enters the housing and no water exits the housing when filled with water for 2 mins.

Test Results

During the dust resistance test, we found that a very negligible amount of dust was able to enter the system. The small amount of dust that did enter seemed to come from the bottom edges of the box where the acrylic walls and bottom are joined. Which can be seen in Figure 5a and b.



(a) (b)

Figure 5: Before (a) and After (b) pictures of the electronic house from the dust test

During the water resistance test, the team found that no water escaped the housing since the team had added outdoor waterproof sealant caulk to the joints of the housing. The same caulk in practice would be used to seal the lid of the housing on but for prototyping the team has elected to not permanently secure the lid on so that they can access the electrical components as needed.

Evaluation

The team was able to satisfy the acceptance criteria by allowing no points for water to enter the electronics housing and only negligible amount of dust to enter the system. Additionally, the other components of the design were rated as water resistant at the time of purchase and the wooden frame is covered in outdoor wood water proof paint in order to ensure a long life span of the device and not rotting of the wood.

4. Conclusions

Currently, our project follows all but one of the specified requirements and acceptance criteria laid out for our design. All but the temperature requirements were fulfilled, as our design can track the sun, pay off costs within 10 years with two sun-tracking solar panels, sustain high winds, has a sufficiently low weight load onto a roof, and has been properly water and dust proofed electronic components. The only requirement not fulfilled is the temperature, as our motor fails to reach both ends of our temperature range, especially the lower end. An alternative motor was found, but would make our design much more expensive and make it financially unviable for a 10 year payoff. Temperatures close to -23℉ are unlikely in San Antonio and most of Texas, but are something to watch out for.

Since most of the requirements were met, our design is considered a working prototype that could be improved with more time and money. Some of our requirements may have been too strict, such as the temperature requirement, as further research indicated temperatures close to our minimum operating temperature are near impossible in San Antonio.

To produce a working prototype, further research should be conducted into temperature data as well as motors, to determine if a cold resistant motor is necessary, and to see if a temperature resistant motor can be found at a financially viable price. Further, there are future tests to consider, such as testing our system in different kinds of weather conditions. In non-sunny weather conditions, our tracking code might get confused, so testing and adjusting it for these conditions will be important.

Additionally, if this device is mass produced for residential roofs, research should be done for alternate materials to build the base and legs. The team has built the base and legs out of wood coated in water proof paint which could deteriorate over time; therefore the materials should most likely be made out of a lightweight sturdy metal.

Appendices

Appendix A: User Guide

Our sun tracking system's simple design allows for easy maintenance and little interaction during operation. The tracking code is already uploaded to the microcontroller so once the device is connected to power, it will begin tracking. For ongoing maintenance, there are two main concerns: solar panel misalignment and obstruction of the PV panels themselves. Should the solar panel somehow slip and rotate about its metal axis, it can be reattached easily. The steps required to realign the panel are as follows:

- Loosen the nuts holding the panel in place on the bar
- Shine a bright light near the light sensors and oriented straight up. This will ensure that the motor is set to a know position before reattaching the panel
- Once the motor position is set, hold the panel with the PV array face up. Then tighten the bolts

During use, solar panels can become covered in dust and other small particles which stick to the panel face, decreasing the efficiency of the panel. This issue can be resolved by simply wiping down the panel if a decrease in energy production is noticed. For further guidance on cleaning the panel, see the manufacturers website.

Finally, for the sake of practicality and to allow for use in our final presentation, the lid of the acrylic electronics housing has been left unsecured. Before implementing this system for operation, the lid should be attached with screws and waterproof caulk should be applied around the edges to ensure that water and dust cannot enter the housing.

Appendix B: Bill of Materials

Part	Manufacturer	Source	Description
Structural Components			
2 X 4 Whitewood (8ft Long)	Home Depot	https://www.homedepot.com/p/2-in-x-4-in-x-8-ft-Prime-Whitewood-Stud-058449/312528776	Wood 2 X 4 which was used for the legs of the device
1 X 4 Moulding Board	Finished Elegance	https://www.homedepot.com/p/FINISHED-	Wood 1 X 4 which was used for

		ELEGANCE-1-in-x-4-in-x-8-ft-MDF-Moulding-Board-10003222/204468314	additional middle support
11/32 4 X 8 Plywood	Home Depot	https://www.homedepot.com/p/11-32-in-x-4-ft-x-8-ft-Rtd-Southern-Yellow-Pine-Plywood-Sheathing-112590/100003677	Plywood which was used for the base of the device
½” Steel Threaded rod (8ft Long)	Superstrut	https://www.homedepot.com/p/Superstrut-1-2-in-x-10-ft-Galvanized-Threaded-Electrical-Support-Rod-ZR1048/100140304	Threaded Rod which was used to connect the panel to the motor and the bearings
½” Nuts, Washer, & Lock	Everbilt	https://www.homedepot.com/p/Everbilt-1-2-in-Zinc-Plated-Nuts-Washer-and-Lock-Washer-6-Piece-per-Pack-803552/204276480	½ in Zinc-plated nuts, washer, and lock washer set which was used to connect the threaded rods to all components
Outdoor waterproof window sealant	DAP	https://www.homedepot.com/p/DAP-Alex-Fast-Dry-10-1-oz-White-Acrylic-Latex-Plus-Silicone-Caulk-18425/100634323	Alex Fast Dry 10.1 oz White Acrylic Latex Plus Silicone Caulk which was used to seal the edges of the acrylic electrical box
Wood sealant	Olympic	https://www.homedepot.com/p/Olympic-Maximum-1-Gal-Clear-Exterior-Waterproofing-Sealant-57500A-01/305230334	Maximum 1 Gallon Clear Exterior Waterproofing Sealant which was used to waterproof the wood legs and base
Pillow Block Bearings	NorTrac	https://m.northerntool.com/shop/tools/product_200407621_200407621?cm_mmc=Google-LIA&utm_source=Google_LIA&utm	Frictionless Bearings used to allow free rotation of the steel rod while supporting the downward weight of the panel

		_medium=Hydraulics%20%3E%20Hydraulic%20Pillow%20Blocks&utm_campaign=NorTrac&utm_content=189782&gclid=Cj0KCQjw06OTBhC_ARIsAAU1yOVC44Wff-WZLqls-s_SDxwrpeqBt0SOvKOKEw1D1_6vvDNmgnzKbxoaAkYcEALw_wcB&gclsrc=aw.ds	
Acrylic Sheet	OPTIX	https://www.homedepot.com/p/OPTIX-18-in-x-24-in-x-0-093-in-Clear-Acrylic-Sheet-Glass-Replacement-MC-05/202038047	Clear Acrylic Sheet which was used to laser cut the electrical component box
Electrical Components			
Solar Panel	New Powa (amazon)	https://www.amazon.com/dp/B01LY02BOA?ref_=cm_sw_r_cp_ud_dp_96H0FXHW74H2EVN5Z4KJ	100W-12V Solar Panel; used to build the tracking solar panel.
Elegoo (Arduino) Board	Elegoo	https://www.amazon.com/gp/product/B01EWOE0UU/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1	The Arduino board used for our project. It is made by Elegoo as a cheaper alternative.
12V Battery	Mighty Max	https://www.amazon.com/dp/B00K8MQF7W?ref_=cm_sw_r_cp_ud_dp_75BBH34PMQM4FX9JA2WJ	12V battery used to supply the servo motor.
9V Battery	Energizer	https://www.amazon.com/dp/B00451Y26I?ref_=cm_sw_r_cp_ud_dp_C63XAFS52MP5FBV76EW7	9V battery used to supply the Arduino board.

Servo Motor	ANNIMOS (amazon)	https://www.amazon.com/dp/B07KTSCN4J?psc=1&ref=ppx_yo2ov_dt_b_product_details	60-kgcm Servo Motor 270-degree; used to rotate solar panel arounds horizontal axis.
Voltage Regulator	DROK (amazon)	https://www.amazon.com/dp/B00C4QVTNU?psc=1&ref=ppx_yo2ov_dt_b_product_details	DCDC Buck Converter; to supply 7.2V for servo motor from 12V battery source.
Bread Board	Qunqi	https://www.amazon.com/Qunqi-point-Experiment-Breadboard-5-5%C3%978-2%C3%970-85cm/dp/B0135IQ0ZC/ref=asc_df_B0135IQ0ZC/?tag=hyprod-20&linkCode=df0&hvadid=198091709182&hvpos=&hvnetw=g&hvrand=6058846815701761852&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9028053&hvtargid=pla-407203040794&psc=1	Mini Breadboard 5.5 X 8.2 X 0.85 cm which was used as our circuit board
Resistors	E-Projects	https://www.amazon.com/Projects-10EP51210K0-10k-Resistors-Pack/dp/B0185FKB0K/ref=asc_df_B0185FKB0K/?tag=hyprod-20&linkCode=df0&hvadid=241966061463&hvpos=&hvnetw=g&hvrand=15697093655243926460&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9028053	10kΩ used to build the circuit (designed for voltage divider to read light sensor data).

		&hvtargid=pla-634596523597&psc=1	
Light Sensors	Vetco	https://vetco.net/products/photoresistor-cds-cell-ldr-d60?gclid=Cj0KCQjw06OTBhC_ARIsAAU1yOWvVK2KhIfJs9tDSMmcan-jbygA4V9jlsjCzkDME44bWWOYbQhoSpkaAgXNEALw_wcB	2 Photoresistors used as light sensors for the tracking systems
Wires	TUOFENG	https://www.amazon.com/TUOFENG-Wire-Solid-different-colored-spools/dp/B07TX6BX47/ref=asc_df_B07TX6BX47/?tag=&linkCode=df0&hvadid=366430786295&hvpos=&hvnetw=g&hvrand=5484919214192463557&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9028053&hvtargid=pla-793870383734&ref=&adgrpid=75985294733&th=1	22 gauge wires used to build the circuit of the tracking system.
Hardware Materials			
Acrylic Glue	WELD-ON	https://www.amazon.com/Weld-Acrylic-Adhesive-Applicator-Bottle/dp/B0096TWKCW/ref=asc_df_B0096TWKCW/?tag=hyprod-20&linkCode=df0&hvadid=312719382368&hvpos=&hvnetw=g&hvrand=6875942070205045273&hv	Acrylic glue that was used to attached the sides of the box together

		pone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9028053&hvtargid=pla-404766667839&psc=1&tag=&ref=&adgrpid=63696814698&hvpone=&hvptwo=&hvadid=312719382368&hvpos=&hvnetw=g&hvrand=6875942070205045273&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9028053&hvtargid=pla-404766667839	
Wood Screws (24 Count)	Grip-Rite	https://www.homedepot.com/p/Grip-Rite-9-x-3-in-Star-Drive-Bugle-Head-Construction-Screw-10-lbs-Box-3GCS10BK/204959302	Wood Screws were used to connect the legs together and to the base
Machine Screws and Bolts (M3 and M4)	Home Depot	M3: https://www.homedepot.com/p/M3-0-5-x-25-mm-Phillips-Pan-Head-Stainless-Steel-Machine-Screw-2-Pack-842748/204283766 M4: https://www.homedepot.com/p/M4-0-7-x-14-mm-Phillips-Pan-Head-Stainless-Steel-Machine-Screw-2-Pack-842858/204283758	Machine Screws were used to hold the motor to the 3D printed adapter
Hex Washer Head Masonry Screws	Confast	https://www.confast.com/1-4-x-2-1-4-confast-410-stainless-steel-hex-washer-head-mas	Machine Bolts were used to attach the bearings to the wood legs

		onry-screw-50-box/	
Aluminum Sheet	Everbilt	https://www.homedepot.com/p/Everbilt-6-in-x-18-in-22-Gauge-Aluminum-Metal-Sheet-801487/204225785	Aluminum Metal Sheet that was used to construct L brackets to secure parts of the device

Appendix C: Supplemental Schematics and Figures

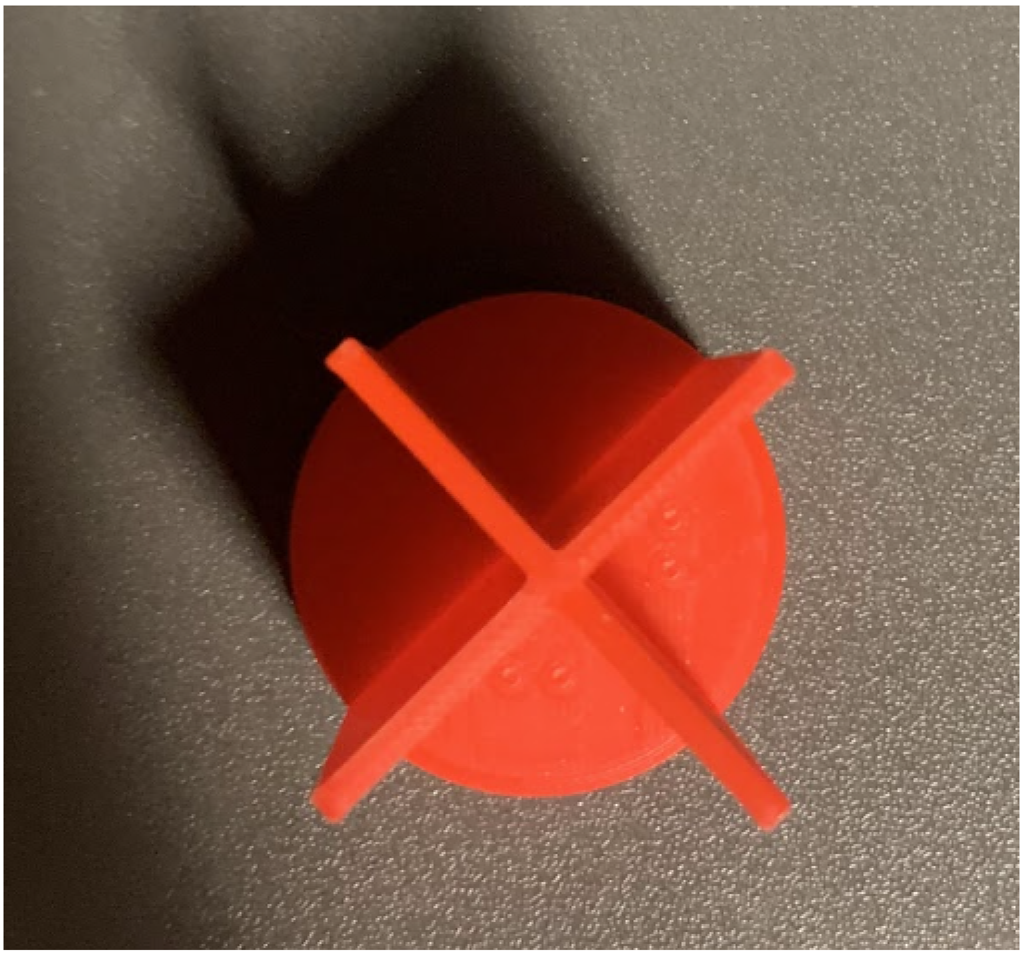


Figure C1: The photoelectric sensor holder.

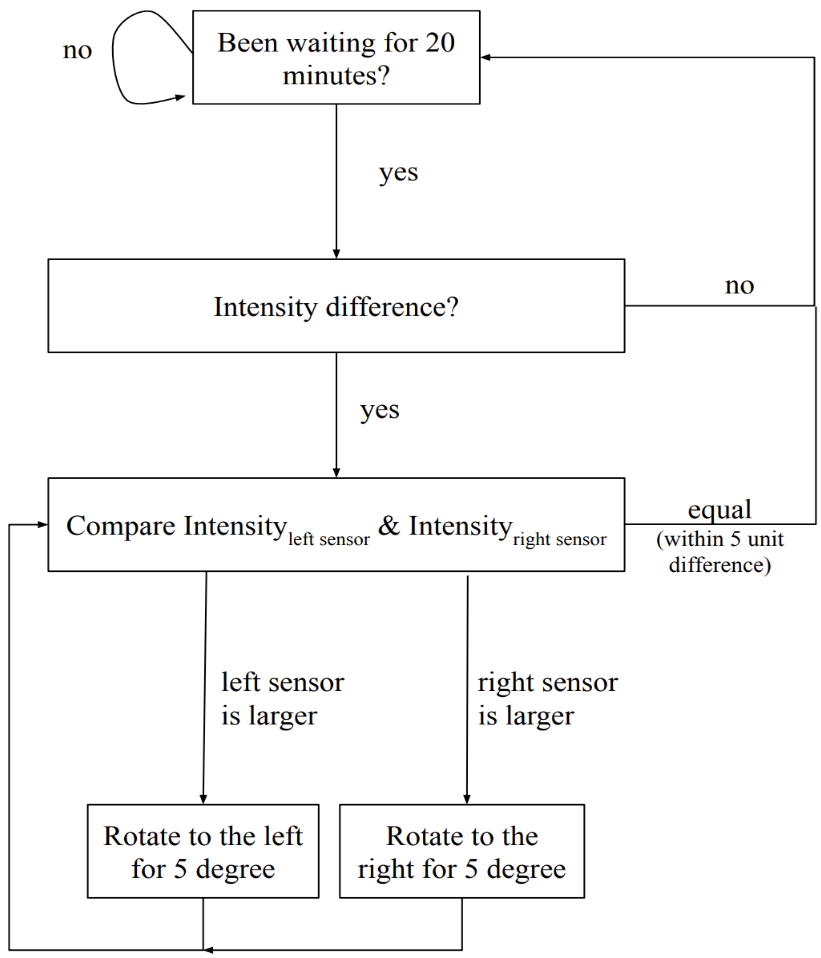


Figure C2: The logic diagram of the tracking subsystem.

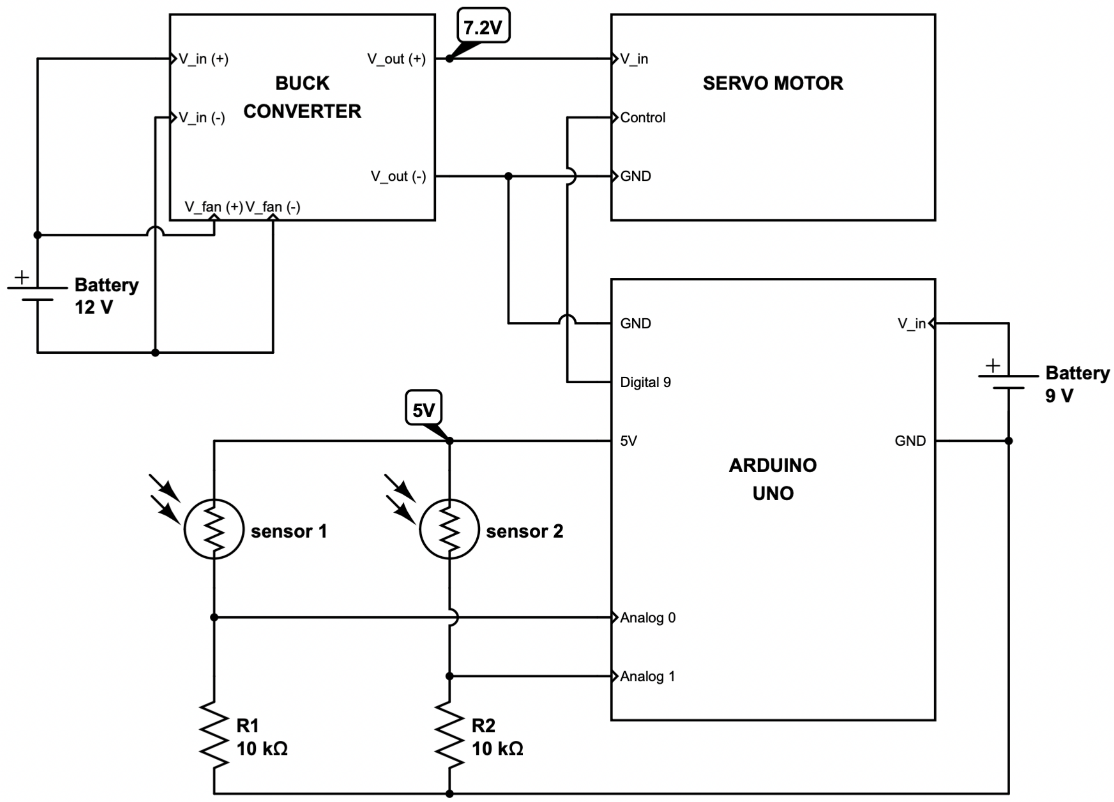


Figure C3: The schematic of the tracking subsystem.

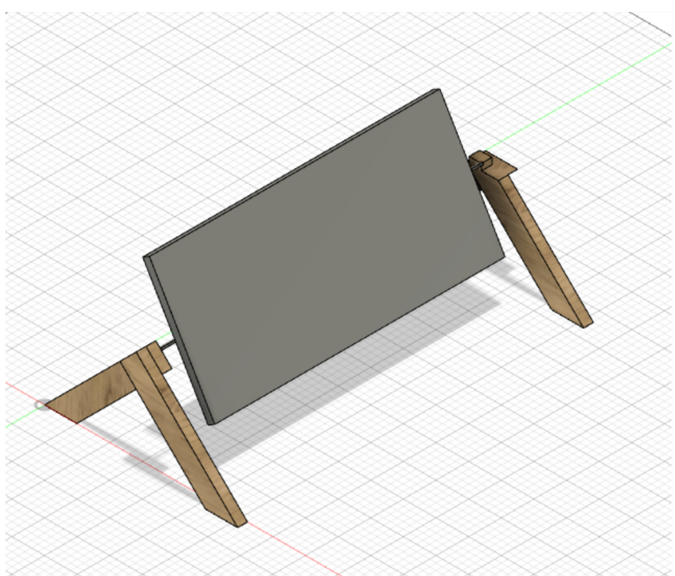


Figure C4: 3D Model of the Prototype

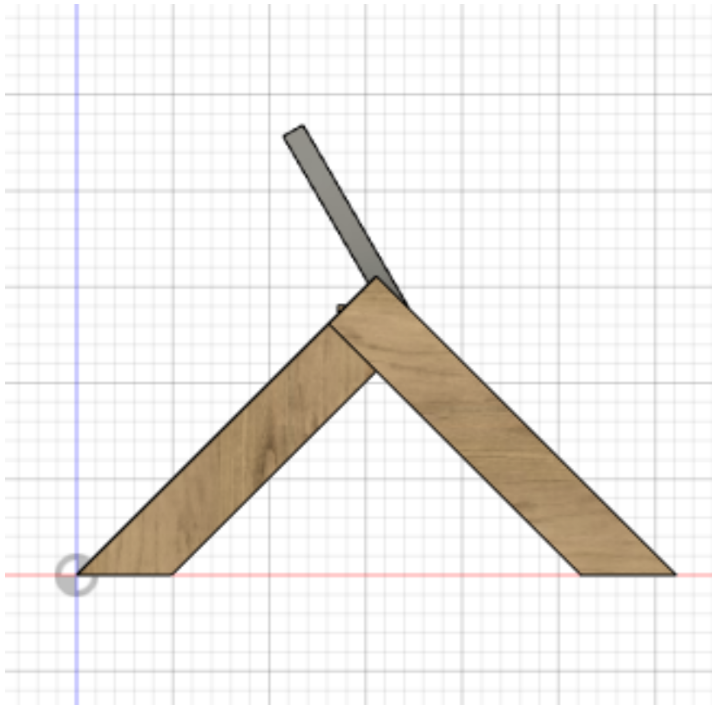


Figure C5: Side View of Model

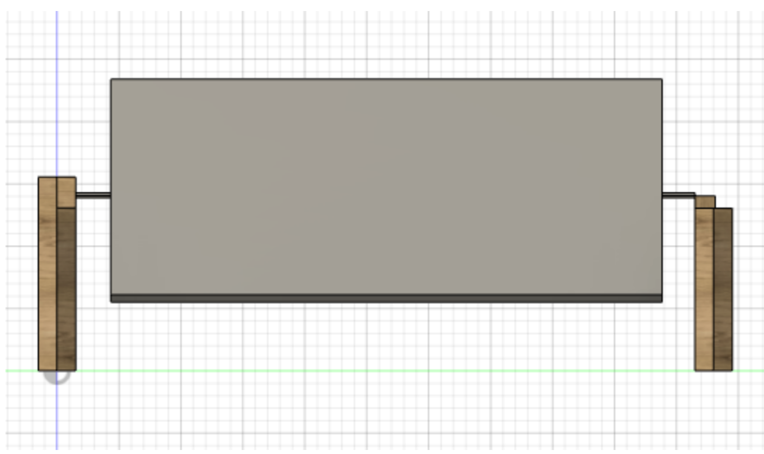


Figure C6: Front View of Model

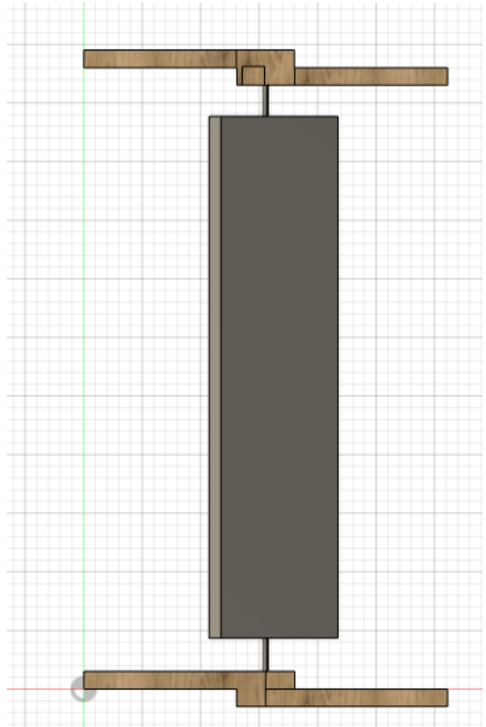


Figure C7: Top View of Model

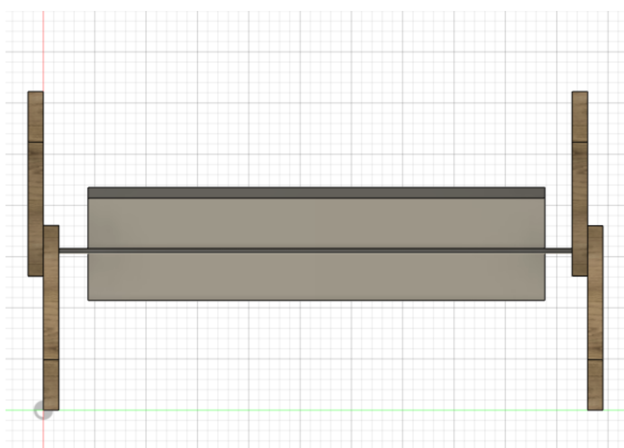


Figure C8: Bottom View of Model

Bibliography (IEEE)