Dual-Axis Solar Tracker

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ABSTRACT
Imagine increasing solar energy production by up to 40%. This can be done by implementing a solar tracking system that allows a solar panel to follow the sun as it traverses the sky. Current systems are historically difficult to install and expensive. The purpose of this solar tracker is to simplify everything and make it cost effective for residential use.

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Mechanical and Electrical Engineering
Senior Project
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INTRODUCTION

The optimum orientation for a solar panel’s position on the earth’s surface is normal to the emissions from the sun. That is to say, the solar panel must be perpendicular to the sun’s rays at all times of daylight if it is to generate the maximum amount of electrical energy. The problem is, however, that the position of the sun is not stationary. It changes throughout the course of a day, as well as throughout the seasons. This project was motivated by the need for a device that would effectively track the sun’s position in an energy-efficient manner. A successful prototype will increase energy production by at least 20 percent, be able to articulate a minimum of 90 degrees in both the azimuthal and the elevation axes, and be weather proof, amongst other requisites. In this report will be a description of the engineering requirements for the project, the analyses, design, testing, budget and other aspects of the project that needed to be considered to create a successful working device.

DESIGN AND ANALYSIS

As solar panels have continued to decrease in price, less emphasis has been given to ascertaining higher efficiencies through means of tracking the sun as it traverses the sky throughout the day. Part of the reason for this is because it has become more expensive to buy and implement solar tracking systems than it is to just install a couple extra panels as a means of compensating for the losses in production. However, there is no reason that further advances in both the solar panel tracking system, as well as the cost or simplicity of such a unit, can’t continue to progress in a similar manner. The point of this design is to further increase production capability, while maintaining profitable margins; all while using a system that is simple enough that it can be installed by a non-professional.

The image below shows how the decrease in panel costs has outstripped the increases in efficiencies:
This trend has resulted in an emphasis towards adding more panels to a solar power generating site rather than increases the efficiency of those panels themselves. The old argument for not using solar trackers has been that they use up most of the electrical energy they gain by tracking the sun. However, this does not have to be the case in modern systems. With the use of stepper motors, which are more efficient than linear actuators, and with proper programming to prevent the tracking system from being active the entire time, much better performance characteristics for the system can be achieved. If the system is not continuously operating, and the motors are not continuously energized, then the system does not require nearly as much electrical energy to track the sun as older systems used to. At the rate at which the planet rotates, there is a shift in the sun’s position in the sky relative to the surface of the planet of only 0.25 degrees per minute. A shift of less than a few degrees, relative to the surface of the solar panels, is not likely to cause a discernable decrease in the maximum performance of the panels. For this reason, a control system that only augments it’s position every several minutes would still generate an effective maximum amount of electrical energy, while preventing losses in the system due to continual checking and energization of the controls of the system overall.

The below trend lends itself to another trend where innovation and technological advancement will stall out as shown in the following graph:
As can be seen in the above graph, the curves for solar and wind follow a similar initial trend as what has already occurred with Nuclear power production. With Nuclear, the production flatlined once the cost of production began to outstrip the amount of money the plant would bring in by producing that energy. One way to mitigate this trend, however, is to continue to innovate and develop better methods for generating energy via the source. If scientists and engineers continue to develop more efficient ways of producing electricity from solar energy, and innovate these technologies in a systemic manner, the trendline for solar can become more of a step-wise function instead of stalling out as it did for Nuclear. This is the purpose of this dual-axis solar tracker, and the reason it was conceived.

The simplicity of the design of this solar tracking system is of paramount importance as well. It may be possible to add on to the system systematically, as funding becomes available, helps to mitigate high start-up costs and make these systems more available to the general public. By creating a price breakdown and engineering cost analysis, it would be possible to create payment plans and allow for projections to be made as to how long it will take to have a complete return on investment and continue to purchase further panels. This is something that can be done further on down the road, once an effective proof of concept is achieved, and sufficient testing has been done.
METHODS AND CONSTRUCTION

This project was conceived, analyzed, designed, and built using the constraints put forth to satisfy both the Mechanical and Electrical Engineering departments at Central Washington University. Working within the constraints of the Mechanical Engineering Department, a full mechanical analysis will be done to determine the forces that the structure will experience, as well as the design of the structure itself. To satisfy the requirements of the Electrical Engineering department, a sensor was developed using photosensitive resistors that will detect the orientation of the sun with respect to that of the panels. This sensor will be implemented into a control system that will drive the motor(s) necessary for articulating the panel. In conjunction with this solar sensor, if time allows, an anemometer will be installed to detect dangerous wind conditions so that the control system knows to lock the panels into a “closed” position to avoid wind damage.

Fall quarter will be focused mainly on designing and carrying out proper analyses of the mechanical aspects of the system. Structural analysis of the frame and pivot points will be done using snow, ice, and wind loading conditions. Worst-case scenarios will be used for these analyses. This includes circumstances where there are three inches of ice on the panel, 60 mph winds blowing perpendicular to the panel so that the panel offers the greatest amount of wind resistance, and one foot of heavy wet snow on the panels. It will also be investigated, if time is permitting, whether it might be possible to program certain sequences in the articulation of the panels in order to reduce snow and ice buildup and keep any articulating mechanics clear of ice. This, however, will be considered supplementary to the initial objective of this project, which will be to get a working device fully operational and take performance data of the system overall.

Simultaneously to the mechanical design will be the design of the electrical control systems of the device. It is anticipated that the system will use an Arduino-based microcontroller, with supplemental driver circuits for the stepper motors. There will also be some auxiliary circuitry built for the photoresistor sensor as well. A voltage divider circuit will be soldered together on a prototyping shield that will plug directly into the Arduino shield. This photoresistor circuit will be part of the system that will monitor the position of the sun and allow for the control system to know how to articulate the panel to follow the progress of the sun.

Winter quarter will be devoted to building the proof of concept and getting a working prototype finished before finals week. The building of the proof of concept will be done in stages. The overall frame will be built first. This includes the frame supporting the panel, uprights, base plates, and pivot points. This assembly, once together, can then be further augmented and changed to add the azimuthal pivoting mechanism and the Elevational pivoting axis. The reason for doing the build in this way is that it will reduce the ambiguity and uncertainty of construction-related issues along the way. There is an inevitable level of slop in the assembly of this device in some respects due to the fact that many of the interacting features and dimensions revolve around being mounted in the slots of the aluminum extrusions used in this design. This can be both good and bad. It will allow for the mismatching of dimensions and issues in GD&T to a certain degree, but it may also prove to increase the ambiguity of the assembly process in some respects as well. By building the system in these stages, some parts can be assembled and mounted completely, and then left in a fastened state while other systems are being built. This will allow for sub-assemblies to be completed and mitigate the aforementioned dimensional issues.
Once the azimuthal pivoting mechanics of the device are assembled, then the motors and gears can be mounted. This is where the slope of the aluminum rail extrusions can be most useful, as the gears will need to be maneuvered and finitely adjusted in order to ensure proper engagement with each other. The motor mounts, motors, gears, and shafts will be installed, and once done, the electrical systems can be installed onto the project. Afterwards, initial tests can begin.

During the manufacturing process, it was decided to make some of the brackets and hardware directly instead of purchasing them in an effort to reduce overall costs. Therefore, all the L-Brackets will be manufactured in the Fluke Machining Lab. Eight of these brackets will be used to mount the base plates to the uprights of the structure, and require custom hole patterns that differ from the standard L-bracket hole pattern for this t-slot railing. These eight L-brackets will also require further machining to account for spatial limitations on the base plate where they will be mounted.

One of the issues with machining these parts manually is that the aluminum extrusion material that they will be made out of is a 90-degree angled piece, with 3-inch-long walls. This will create some clearance issues for the chuck of the milling machine when trying to countersink the holes nearest the back edge of the brackets. One means of remedying this situation will be to purchase a collet extension that has a smaller profile than the existing chuck so that it can be fed into the confined space of the bracket without interfering with the material. Another issue will be the machining of the top and bottom plates for the azimuthal axis pivoting mechanism. All these holes will require tight tolerances in relation to each other as they will need to remain concentric in order for the pivoting to happen on the central axis as expected. This may prove difficult to achieve as there are many holes in these plates, and all the holes, as well as the turntable and stepper motor have specific tolerances that need to mesh properly to ensure proper functioning of this subassembly. Further complication may come from the plates not being flat or warping in the jaws of the vice or while being drilled. All of these issues will likely exist, and all will have to be addressed effectively in order for the subassembly to be installed and operate properly.

Modifications will likely need to be made to the motor mounts as required. One modification that will likely occur will be to use slots in the mounting bracket rather than holes. This will allow for vertical articulation of the motor, and thus allow for better alignment of the intermeshing gears. By slotting out the hole in the bottom plate where the motor shaft protrudes, horizontal articulation can be allowed as well without negatively impacting the structural integrity of the mounting system itself.

**TESTING**

The testing of this project will be done in stages. The structural analysis conclusions will be tested to ensure that the values for stress loads are an accurate representation of what the structure is capable of withstanding. An analysis of the shear stresses on the pivot points, and as well as the various loads on the structure will be done, and experiments will take place to prove the validity of the results. This will be done by applying stresses to key members of the structure and
measuring the deflection, and by applying a shear stress onto the pivot points and making sure no visible distortion or permanent damage has occurred. Next, the electrical system will have to be fully evaluated as well. The interface between the motor controls and the light sensor will need to be fully operational and functional, the Arduino control system will need to be fully operational and able to articulate the panel in two axes simultaneously, and the entire system will need to be waterproofed, enclosed, and otherwise contained to ensure protection from adverse environmental conditions. Testing for waterproofing will be done with a garden hose. Dust and particulate testing can be done in any field where loose dirt can be easily ascertained and blown around. All these tests will include duration and cyclic or repetitive aspects to better gauge how much damage occurs under these adverse conditions, if any. The main focus for testing, however, will be more oriented around functionality than endurance tests. Therefore, the focus will be in ensuring that the axes articulate properly and do not collide or overtravel in any way, the panel tracks the light source correctly and accurately, and that the structure itself functions as required to sustain high wind and snow load conditions. With these functions working correctly, the next stage of testing can be the endurance and durability tests for dirt and water contamination. Once the device is deemed operational and working as expected, performance tests will take place to compare the overall amount of electrical energy generated by the panel when it is positioned at 30 degrees, 45 degrees, and at two different azimuthal angels for each iteration of angular articulation. These same positions will be done without the solar tracking being active, and then compared to the results in power generated after the tests have been completed using the tracking system. These results will then take into account the amount of electrical energy used by the tracker, and that amount will be accounted for in the analysis of the performance of the tracking system.

The first test performed was an articulation test. The panel needed to meet the previously declared minimum angel of articulation in both axes. This means that the panel needed to be able to articulate in both the horizontal, and the vertical axes for at least 90 degrees. For the purposes of this test, the home position as shown below is considered the zero-degree position, and the angle was measured from this point. So the axes needed to be able to articulate in at least 45 degrees from this central starting position in either direction from the zero-degree point. In the Azimuthal axis, the panel is able to rotate a full 360 degrees, thereby meeting and exceeding the 90 degree requisite. In the vertical axis, the panel is able to rotate until the top end, where the sensor will be mounted, comes all the way around and hits the base. This means that, in this direction, the panel is able to articulate in approximately 160 degrees, also meeting and exceeding the 90 degree requisite. Therefore, the articulation test was a success.

This level of articulation will make it very important to ensure that the cables are managed in such a way that they do not tangle, and that the panel does not over travel. Therefore, limit switches, and parameters in the coding will both be implemented to prevent the solar panel from colliding with itself and ripping out its wiring.
BUDGET

The budget in Appendix C reflects the total actual current cost of the project. There will be more items added as further construction takes place. The biggest changes in cost have come from the decision to scale down the project, simplify the pivot design, and save on hardware costs by buying a section of 90-degree aluminum extrusion to machine into L-brackets instead of buying the L-brackets individually. The L-brackets from McMaster-Carr cost about $5-$15 each, whereas by making them in-house the price can be reduced by approximately 75%. The decision to scale the project down was done in an effort to mitigate costs as well. Due to the fact that the design is smaller, the pivot did not need to be custom built anymore, as McMaster-Carr sells one that would be suitable for the application. This change is reflected in the overall budget.

A couple other aspects of the project that greatly affected the budget were the invention of the azimuthal axis to replace the originally planned linear actuator and the fact that freight charges were inadvertently incurred. The addition of this subassembly to the project required an additional stepper motor, more aluminum plates, a high-quality turntable, an extension for the motor shaft, shaft coupler, spur gears, and a plethora of auxiliary fasteners and hardware. More L-brackets will need to be manufactured as well, which will further increase the manufacturing time and complexity of the build. The freight charges came when ordering the aluminum rails in 10-foot lengths. It was decided to use this length because it decreased the amount of wasted material. However, McMaster-Carr does not advertise their shipping costs, and it was not made obvious that getting the material in these lengths would result in an extra $190 in shipping charges. The increased shipping costs would have, alone, paid for the majority of this project. Due to these changes in design, and unforeseen shipping charges, the cost of this project is projected to surpass 200% of its originally anticipated costs.

SCHEDULE

The general timeline for the project was to complete the entire mechanical design by the end of Fall Quarter on 12/6/2019, spend Winter quarter building the prototype, and Spring quarter is expected to be devoted to the testing, redesign, and improvement of the prototype. Due to the increase in complexity of this project, as well as other unforeseen issues, however, the mechanical design will take much longer to complete than anticipated. Most of the month of December was devoted to continuing to develop and refine the design, as well and update the Budget so that parts can be purchased. Ideally, the build phase will begin in December as well. See Appendix E for the Gantt chart that represents the approximate timeline for the project.

As of Winter quarter, eight parts were successfully manufactured. The original design for this project required approximately 25 manufactured parts, however after the addition of the
azimuthal axis, the new number of manufactured parts is 44. This represents a much greater increase in the complexity of the project, as well as a tremendous increase in the amount of work required to manufacture this device in its entirety. The completed build of the prototype is expected to be done by the middle of the week before Finals during Winter quarter. This timeline will be very difficult to meet given the changes to the design of the project.

One source of problems with regards to scheduling and time conlictions was due to issues between senior project classes. The different requisites and deadlines for both senior project classes require large amounts juggling and prioritization that are difficult to remedy. This, along with the changes in design, have resulted in the majority of the drawings and parts having to be redone. This, in turn, created conflicting interactions between parts within the overall assemblies and the respective drawings. Fixing these issues represents a daunting amount of rework in which initial timelines no longer apply.

**DISCUSSION**

This project presented a number of major engineering difficulties. It required several complete redesigns, and augmentations to the corresponding drawings and analyses were changed each time the design was. Analyses and drawings for the pivot points at the top of the uprights, as well as all subsequent Solidworks drawings and part models became obsolete. Addition of the azimuthal axis articulation mechanism, and subsequent deletion of the linear actuator, represented enough design requirements and curriculum satisfactions to qualify for a separate senior project in and of itself. The drawings and analyses needed for this augmentation to the design, as well as the hardware considerations, gear positions and sizes, motor positions, shaft lengths, and all other related areas of newly required attention represented a major change in design and time required to complete the project. Dozens more parts will be needed to be modeled in Solidworks, and dozens more drawings will be required to fully define the project. Hundreds of hours were lost due to infeasibilities in previous designs and necessary augmentations. Each of these alterations required the subsequent deletion or substitution of the original SolidWorks drawing and models, which presented further troubles due to the inevitable clashing of corresponding mates and relationships within the assembly drawings and models. This caused many of the mates in the subassemblies and substitutions of parts to cause the need for the redoing of the models several times over. The current design, however, should represent a feasible model to continue the build process with.

The first redesign involved going away from a design similar to that of the solar tracker system that was created last year. The reason this design was deemed infeasible was because it is not suitable for being arranged in an array of panels. Due to the fact that the panels would need to articulate simultaneously while being surrounded by other panels, the geometry needed to be reconsidered. Subsequent redesigns had to do with similar issues, as well as the necessity to
change the structural properties of the model. Previous renditions did not have enough ease of manufacturability, nor did the structure remain sound when adding onto it. All preliminary designs were oriented around the concept of creating a modular system that can then be added onto as time progresses. This requisite is no longer a part of the scope of the project, as the design was simplified to expedite the process of manufacturing and reduce complexity of the overall project.

The most recent redesign was to the method by which the tracker will articulate. Originally, the intention was to use a linear actuator to track the sun in the vertical axis, but due to changes in how the machine will pivot horizontally, such a mechanism was no longer feasible due to the space the linear actuator would take up; when fully extended it was 28.8” long. Therefore, it was decided that the horizontal articulation will occur with the aid of a stepper motor of the same type used for the other axis, in conjunction with an industrial turntable and gears to interface the motor and turntable. This redesign to the azimuthal axis was rather drastic because it required the upper portion of the frame to be separated from the remainder of the base and connected via the turntable and motor pivot point. This fix was not simple. It required a good amount of machining, a custom mounting bracket/base for the turntable, new drawings, new analyses, and the purchase of approximately 10 of new parts or more, not including the mounting base and subsequent mounting and support brackets and hardware. A fully updated BOM is included in the Final Report to reflect these changes.

Another aspect of the building of this project that presented difficulties had to do with the stepper motors. The motors are geared motors with a gear ratio of 100:1. The purpose for this is that a small amount of input torque from the motor is then magnified 100 times at the armature after the gearing. This results in much more torque force being applied to the axis of rotation, as well as a greater holding force in adverse wind conditions. This increased torque force is necessary for turning and holding the axes in place. However, one motor proved to be of an insufficient gear ratio so that it could not articulate the axis properly, and the 100:1 motor that was on hand ended up having damaged gears. For this reason, both of the old motors needed to be detached and replaced by new 100:1 stepper motors of a higher quality.

The testing for this project included three pinnacle landmarks. First, the solar tracker needed to be capable of tracking the sun in both the vertical and the azimuthal axes for more than 90 degrees of articulation. Next was the requisite that the tracker accurately followed the sun throughout the day as it moved across the sky. This was the most important test, as failing to be able to accomplish this task with the device would defeat the overall purpose of the project. Finally, the tracker needed to be able to incorporate fail-safes that would prevent it from colliding with itself as it moved around in both its degrees of freedom. Given the redesigned azimuthal axis, the articulation and tracking were accomplished as required, and once limits for angular rotation were set in the programming of the device, the collision issue was solved as well.

The graph below shows the increases in efficiency and power generated by using the dual-axis solar tracking system.
Both curves tapered off slightly as sunset approached. This was due to the fact that the sun approaches the Cascade Mountains here in Washington before it begins its true sunset over the ocean. This results in a shadow being casted earlier than what is deemed the official sunset time for Ellensburg, and this is what is responsible for this premature tapering effect on the overall solar power generated. However, the area under the curve is approximately 35% greater for the solar tracking system. This means that the dual-axis solar tracker produced roughly 35% more power over the course of the day when compared to the fixed position solar panel. Any deviations and jumps or dips in output power are due to cloud cover situations that occurred during the time that the data was ascertained.

CONCLUSION

In conclusion, the device is far more complicated in its current design iteration than it was when this project began. Changes were made to how the azimuthal articulation will occur that greatly increased the complexity of the design and manufacturing requirements. The concept, however, remains simple and the proof of concept will most definitely remain a rough draft by which further development can continue. Once a working prototype is fully functional, and all required design parameters have been met, attention can be given to what was done right and what was done wrong in the project, as well as how to improve upon the project. There is not likely to be another catastrophic redesign issue, but rather evolutions of the current design. Therefore, it is expected that the results from testing should be highly favorable and the project will be fully operational during SOURCE presentations. Data will be taken and compared to that of stationary panels, and overall performance characteristics can then be ascertained. These
results will validify the proof of concept and be used as data to represent the reasons by which using a solar tracker is good for generating more electrical energy and increasing the efficiencies of solar panels. After which, more thought can be put into determining how to improve upon the design, simplify it, and make is easier to manufacture.

ACKNOWLEDGEMENTS

Thanks to Professors Johnson, Pringle, and Professor Choi for help and understanding provided on this project. Matt Burvee and Tedman Bramble were invaluable assets in the machining lab, and the machining lab technician Jim had some very good thoughts as well. Rowdy Sanford provided valuable insight into the best ways to go about 3D printing parts and with regards to various circuitry and Arduino topics of discussion. Greg Lyman provided me with access to facilities and tools to ensure I could accomplish the tasks required of me, and Jeff Wilcox provided valuable insight into the original design parameters and methods of controlling the device.
APPENDIX A: Analyses

Snow Loading

Analyses: GS for 10/18

1. Max loads on panels

Given:
- Panel Dims: 39’x65” Res., 39”x77” Comm.
- Panel weight: 33lbs Res., 70lbs Comm.
- Snow load factor (Max): 1.28
- Snow weight: 1.21 lbs/ft^3

Find:
Max weight load on panel structure

Assume:
- Weight load of 21.46 lbs/ft^2 for Snow
- Max depth of 3” for Snow
- Max panel weights for both sizes
  3.16 lbs/ft^2 for Commercial panels

Method:
- Solve for load on residential-sized panels
- Solve load for commercial panels

Solution:
- Residential panel:
  - 3’x65”
  - Load:
- Commercial panel:
  - 77”
  - Load:
Snow: 65 in X 39 in X 3" = 7605 in³ of snow

\[
\frac{7605 \text{ in}^3}{1728 \text{ in}^3} \approx \frac{2116}{44 \text{ lb}} = 92.42 \text{ lb/ft}^3
\]

Total weight = 92.42 lb/ft³ + 51 lb
(Res) = 143.4 lb

Ice: 39 in X 27 in X 3" = 9009 in³

\[
\frac{9009 \text{ in}^3}{1728 \text{ in}^3} \approx \frac{2116}{44 \text{ lb}} = 109.5 \text{ lb/ft}^3
\]

Total weight = 109.5 lb/ft³ + 32.5 lb
(Comm) = 162.5 lb

172.1 lb
Wind Loading

12. \( \text{Max Day Force on Panels by Wind} \)

**Given:** Drag of Flat Panel: 1.28


**Find:** Max Drag Force of Wind @ Anti

Assume: worst case scenario of wind 1 to panel.
Air Density (\( \rho \)) = 1.225 kg/m^3 (sea-level, 14°C)

**Method:**
1. Determine area of panel
2. Convert \( D \) units to US standard.
3. Use Drag formula to calculate force.

**Calculation:**

\( \text{Res.} \): 65' x 39' = 2,535 in^2

\[ \frac{2,535 \text{ in}^2}{144 \text{ in}^2} = 17.60 \text{ ft}^2 \]

\( \text{Wt.} \): 1,225 kg/m^3

\[ \frac{2,205 \text{ lb}}{5.315 \text{ in}^3} = 420 \text{ lb/ft}^3 \]

\( D = \frac{1}{2} \rho \text{C} \text{A}^2 \)

\[ \frac{1}{2} \times 62.4 \times (0.0765 \text{ lb/ft}^3) \times (17.60 \text{ ft}^2)^2 \times (17.60 \text{ ft}) \]

\[ = 6,673 \frac{\text{lb}}{\text{ft}^2} \times \frac{1 \text{ lb}}{16 \text{ in}^2} \times \frac{1 \text{ ft}^2}{1 \text{ in}^2} = 207.4 \text{ lb/ft}^2 \]
Cumulative Wind and Snow Loading

Res:
\[ 207.4 \text{ lb} + 143.4 \text{ lb} = 350.8 \text{ lb} \]

Comm:
\[ 207.4 \text{ lb} + 172.1 \text{ lb} = 379.5 \text{ lb} \]

Note:
For simplicity of design, I will assume the loads for commercial panels as my standard value.

\[ \Rightarrow \text{Max Load} = 5F(380 \text{ lb}) \]
\[ = 1.5(308) \text{ lb} = 570 \text{ lb} \]
Beam Analysis

**Given:**
- \( L_x \) in
- \( M_{max} = FL/4 \) in

**Find:**
- \( \sigma = -\frac{Mc}{I_{xx}} \) in

**Method:**
1. Use dimensions to calc I: \( I_x = I_{yy} = 6.15094 \text{ in}^4 \)
2. Find \( c = 0.5 \text{ in} \)
3. Determine \( M \)
4. Calculate \( \sigma \)

**Calc.:**
1. \( I_{xx} = I_{yy} = 6.15094 \text{ in}^4 \)
2. \( \text{C.O.M.} \) at \((0,0)\)
   - \( c = 0.5 \text{ in} \)
3. \( M_{max} = \frac{FL}{4} = \frac{172.113 (77/2)}{4} = 1656 \text{ in-lb} \)
4. \( \delta_{max} = \frac{FL^3}{48EI_{xx}} = \frac{172.113 (28.5)^2}{48 (10.106) (6.15094 \text{ in}^4)} = 656 \text{ in} \)

\( \sigma = -\frac{Mc}{I_{xx}} = -\frac{1656}{656} \text{ in} \) in

\( = -52.8 \text{ in}^2 \)
10/24 Beam Analysis

Given:
- 1" x 1"
- $M_{max} = FL/4$
- $A = 0.4794 \text{ in}^2$

Find:
- $\sigma = -\frac{Mc}{I_{xx}}$

Method:
1) Use dimensions to calc $I$: $I_x = I_y = 6.15074 \text{ in}^4$
2) Find $C = \frac{D}{2} = 0.5\text{ in}$
3) Determine $M$
4) Calculate $\sigma$

Calculation:
- Calculated in SolidWorks
1) $I_{xx} = I_{yy} = 6.15074 \text{ in}^4$
2) $C_{OM} = (0,0)\Rightarrow C = 0.5\text{ in}$
3) $M_{max} = \frac{FL}{4} = \frac{172.113 (77/2)}{4} = 1656.169\text{ in} \cdot \text{ lb}$
4) $M_{max} = \frac{FL^3}{4EI} = \frac{172.113 (28.5)^2}{48 \times 15.676 \text{ in}^4} = 1656.169\text{ in} \cdot \text{ lb}$

$\sigma = -\frac{Mc}{I_{xx}} = -1656 \text{ in} \cdot \text{ lb} / 15.676 \text{ in}^4$

$\sigma = -52.8 \text{ psi}$
Wind Shear Force on Locking Pin

Given:
- 300 lbf shear force
- Young’s Modulus of 3/16 Stainless Steel, Annealed & Cold Drawn: 25,000 psi

End: Pin size needed to support shear force at 3X the max expected load.

Method:
1) Use $F = \frac{V}{A}$ to determine max force.
2) Use max force to determine pin size.

Calc:
1) $25,000 \text{ psi} = \frac{300 \text{ lbf}}{A}$
   \[ A = 0.032 \text{ in}^2 \]
2) $0.032 \text{ in}^2 = \pi \Gamma^2$
   \[ \Gamma = 0.101 \text{ in} \]

$\Rightarrow 0.250”$ diameter pin made of 3/16 SS should satisfy for up to 3X the expected max force that would be exerted on the panels by 60 mph winds.
Required Motor Power

Given:

\[ P_{rot} = Tw \]

\[ P_{rot} : Rotational Power \]

\[ T : Torque \]

\[ w : Angular Velocity \]

\[ \omega_{rad} = \omega_{rpm} \left( \frac{\pi}{30} \right) \]

\[ T = Fd \]

\[ F = \frac{102}{5 \pi} \]

\[ T : 2.8 \text{ in-oz} \]

\[ \omega_{rad} : 750 \text{ RPMs} \]

Find: \[ P_{rot} \]

\[ P_{rot} = T \omega_{rad} = 2.8 \text{ in-oz} \times \frac{16}{12} \text{ in} \times \frac{12}{16} \text{ in} \]

\[ = 1.745 \text{ ft-lb} \]

\[ = \frac{1.745}{4.172} \]

\[ = 0.42 \text{ Hp} \]

Solution:

If \[ T = 2.8 \text{ in-oz}, \] then:

\[ T = Fd \]

\[ F = \frac{102}{51} \text{ in-oz} \]

\[ F = \frac{102}{51} \times \text{Amount of pulling force} \]

\[ 51 \times 0.2 \times \frac{16}{160} = 9.19 \text{ in-oz} \]
Max gravitational weight of panel:

172.1 lb w/ 3" heavy snow.

Including extra aluminum supports = 200 lb.

- If we assume ice buildup in winter, 250 lb may be a realistic value.

\[
T = \frac{250 \text{ lb}(0.5 \text{ in})(16 \text{ oz})}{1.16} = 200 \text{ in.-oz torque required}
\]

*Conclusion:

A method of gear reduction will be necessary to achieve enough torque to drive panel.
Design Ideas

$67" - 40" = 27"

$27" - 16" = 11" / 2 = 5.5" - 1"$ for bars' width = $4.5"$

$4.5"$ of hanging t-bar if bars moved to left

$8"$ of panel.
\[ c = \left( \frac{12 + 12}{2} \right)^{1/2} = 1.414" \]

\[ 1" \]

\[ \text{T-Slot} \]

\[ 1.414" \]

\[ \text{T-Slot} \]

\[ 0.703" \]

\[ 1" \]

\[ 5" \]

\[ 1" \]

\[ 2" \]

\[ 2" \]

\[ \text{Diagram with dimensions and calculations} \]

\[ C = \sqrt{8} = 2.828" \]

\[ 6 = \frac{1.414}{0.703} \]

\[ a^2 \times 2 = 6^2 \]

\[ 2a^2 = 1.414^2 \]

\[ a^2 = 1" \]
Leg Support Angle + Length

Subassemblies:
- Base
- Leg
- Res Pi Panel w/ Frame
  → Initial Panel Structure
  "Contains "Res W.""
- Addition +1
- Pilots

Pilots

\[ a = \frac{b}{2} \]
\[ \cos \theta = \frac{4.243}{12} \]
\[ \theta = 63.29^\circ \]
To do:

- Holes for pivot arm on 3x1 end (top)
- Holes for 2x1 float bracket in center of 2x1
- Finish pivot
Max Allowable Load on Frame
Max Allowable Load on Support Structure
Max Allowable Torsional Defection in Rotational Axis Shaft
APPENDIX B: Drawings
Singular Support Structure - Frame
Singular Support Structure - Vertical Support
Motor Shaft Extension
2X1 Flange
Sleeve Bearing Long
Sleeve Bearing
Residential Frame – Long
Residential Panel Frame – Short
Double Rail
Single Rail
Triple Rail
### APPENDIX C: Parts List/Budget

#### SENIOR PROJECT: Solar Tracker

<table>
<thead>
<tr>
<th>ITEM ID</th>
<th>ITEM Description</th>
<th>Item Source</th>
<th>Brand Info</th>
<th>Model/SN</th>
<th>Price/Cost (US $)</th>
<th>Quantity</th>
<th>Subtotals</th>
<th>Tax</th>
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|          | Shipping                               | 129.57     | |         | Tot Est. $ | 587.89     | |         | | Tot Act. $ | 724.07 | 348.95 | 2.07497979 |

*Note: All costs are in US dollars.*
## APPENDIX E: Schedule

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APPENDIX F: Program Code

```c
#include <AccelStepper.h>

// pin definitions:
#define hStep 5
#define hDir 4
#define vStep 3
#define vDir 2
#define tl A2 // Analog input pins: Top Left, Top Right, Bottom Left, and Bottom Right
#define tr A3
#define bl A0
#define br A1

// home switch pin definitions:
#define hHome 10
#define vHome 9

#define motorInterfaceType 1

// Create a new instance of the AccelStepper class:
AccelStepper stepperV = AccelStepper(1, 2, 3);
AccelStepper stepperH = AccelStepper(1, 4, 5);

// LDR Variable Definitions:
int TL;
int TR;
int BL;
int BR;

// Average of Top, Bottom, left, right
int AT;
int AB;
int AL;
int AR;

// horizontal and vertical difference
float DV;
float DH; // horizontal direction according to RHR

// position tracking:
int hPos = 0;
int vPos = 0;
int stepsH = 100;
int stepsV = 100;

// limits
int vMin = 0;
int vMax = 40000;
int hMin = -5000;
int hMax = 5000;

void setup() {
    // put your setup code here, to run once:
    pinMode(hStep, OUTPUT);
    pinMode(hDir, OUTPUT);
    pinMode(vStep, OUTPUT);
    pinMode(vDir, OUTPUT);
}```
pinMode(hHome, INPUT);
pinMode(vHome, INPUT);

Serial.begin(9600);
delay(500);
Serial.println("Serial Init");
Serial.println(digitalRead(hHome));
Serial.println(digitalRead(vHome));

stepperV.setMaxSpeed(40);
stepperH.setMaxSpeed(90);

Serial.println("Home axes");
homeAxes();
    // move horizontal to zero position
    stepn(-9600, 50, 0);
    // set current position (in steps)
    hPos = 0;
    // move vertical to 45 degree position
    stepn(5000, 50, 1);
    // set current position (in steps)
    vPos = 5000;
}

    // bounds of no movement
    int range = 100;

    void loop() {
        // Read voltage dividers
        TL = analogRead(tl);
        TR = analogRead(tr);
        BL = analogRead(bl);
        BR = analogRead(br);
        // average the voltage dividers
        AT = (TL+TR)/2;
        AB = (BL+BR)/2;
        AL = (TL+IL)/2;
        AR = (BR+TR)/2;
        // determine direction the motors need to travel
        DV = AT-AB;
        DH = AR-AL;

        // print out data to serial console
        if(Serial.available() || true) {
            Serial.print("TL:");
            Serial.print(TL);
            Serial.print(" TR:");
            Serial.println(TR);
            Serial.print("BL:");
            Serial.print(BL);
            Serial.print(" BR:");
            Serial.println(BR);
            Serial.print("AT:");
            Serial.print(AT);
            Serial.print(" AB:");
            Serial.println(AB);
Serial.print("AL:");
Serial.print(AL);
Serial.print(" AR:");
Serial.println(AR);
Serial.println();
Serial.print("IV:");
Serial.print(DV);
Serial.print(" DH:");
Serial.print(DH);
Serial.println();
}

// check position before moves
// Horizontal Motor check and movement

if(abs(DH)>range){
  Serial.println("DH out of range");
  if(hMax > (stepsH*(DH/abs(DH))+hFos) > hMin){  //Check the sum of current position and
    stepn(-stepsH*(DH/abs(DH)), 50, 0);  // move Horizontally
    hPos += stepsH*(DH/abs(DH));  // add move to position
  } else{
    Serial.println("New Horizontal position outside limits");
  }
}

if(abs(DV)>range){
  Serial.println("DV out of range");
  if(vMax < (stepsV*(DV/abs(DV))+vFos) > vMin){
    stepn(stepsV*(DV/abs(DV)), 50, 1);  // move
    vPos += stepsV*(DV/abs(DV));  // add move to position
  } else{
    Serial.println("New Vertical position outside limits");
  }
}

delay(600000);  //Wait 10 mins before next check

int stpPin;
int dirPin;

void stepn(int steps, int freq, int motor){
  // steps --> number of steps to move
  // direction --> + = up or left, - = down or right
  // freq --> frequency to step, steps/millisecond
  // motor --> motor to use: 0=horizontal, 1=vertical

  // motor selection
  if(motor==1){
    stpPin = vStep;
stpPin = vStep;
dirPin = vDir;
}
else{
    stpPin = hStep;
dirPin = hDir;
}

// set motor Direction
if(steps > 0) digitalWrite(dirPin, HIGH);
else digitalWrite(dirPin, LOW);

// make steps happen
for(int s; s < abs(steps); s++) {
    digitalWrite(stpPin, HIGH);
delayMicroseconds(50000/freq); // Determining Duty Cycle
digitalWrite(stpPin, LOW);
delayMicroseconds(50000/freq);
}
}

void homeAxes()
{
    int dt=1; // milliseconds
    // home horizontal axis
    Serial.println("Home Horiz");
    // set motor Direction
digitalWrite(hDir, HIGH);
    while(digitalRead(hHcme) == LOW){ // Move Motor
digitalWrite(hStep, HIGH);
delay(1);
digitalWrite(hStep, LOW);
delay(1);
    // Serial.println("hstep");
}
    Serial.println("Home Vert");
    // home vertical axis
    // set motor Direction
digitalWrite(vDir, LOW);
    while(digitalRead(vHcme) == LOW){
        digitalWrite(vStep, HIGH);
delay(dt);
digitalWrite(vStep, LOW);
delay(dt);
        // stepper.setSpeed(100);
        // stepper.runSpeed();
    }
}
APPENDIX G: Annotated Bibliography

Bryan Kennedy – Mechanical and Electronic Engineering

Objective
To better understand the mechanics of complex systems, as well as the controls by which they operate, so that I can thereby develop a means of drastically increasing efficiencies through Factor 10 engineering principles.

Experience
Internship – Rosemount Specialty Products, Emerson Inc., Wenatchee, WA June 18-Sept 14, 2018
- Worked on several engineering projects oriented around product development
- Conducted R&D experiments to determine feasibility of new product
- Dealt closely with other engineers on collaborative projects

Internship – Exotic Metals Forming Company, Kent, WA June 19-Sept 8, 2017
- Utilized Lean Manufacturing principles to increase production flow, efficiency
- Improved and taught new job operation and production processes to employees
- Learned machining, design practices used in Tool and Die dept.

Facilitator / Trip-Leader – Outdoor Pursuits and Rentals, CWU March 2015-Current
- Certifications: Wilderness First Responder, Swift Water Rescue, and Professional Climbing Instructor
- Facilitated and led outdoor trips throughout WA

Grip – Vangard Inc., Tacoma, WA 2008 – Current
- Assembled CNC router, developed production processes and procedures
- Designed / built mechanical systems for large corporate events (ie: Air cannon target range)
- Helped set up and breakdown events
• Setup CNC Mills to run production aerospace parts

**Education**

Mechanical Engineering Technology - CWU, ABET Accredited  
Fall 2014-2019
• Completed Beginning, Advanced, and CAD / CAM Machining classes
• Experience with Welding, Forging
• Concentrated on Advanced Energy Systems, Manufacturing Processes

Electronic Engineering Technology - CWU, ABET Accredited  
Fall 2017-2020
• Focus on Robotics, Power Generation / Motors, and Electrical Power Transmission

Entrepreneurship Minor – CWU, AASCB Accredited  
Fall 2018-2020

**Extracurricular**

Cross-Cultural Leadership Program, 3 years
• Studied leadership aspects from a multicultural perspective
• Fostered effective communication skills
• Immersion into foreign cultures to gain real-world experience

Society of Manufacturing Engineers (SME) Member
• Club Senator (2017-18)

American Society of Mechanical Engineers (ASME) Member

Institute of Electrical and Electronics Engineers (IEEE) Member

**References**

Steven Anderson  
Vangard Inc.  
253-682-7044
Greg Lyman
CWU Electronics Engineering Professor
glyman@cwu.edu
509-963-1760

More references available upon request
APPENDIX J: Job Hazard Analysis

JOB HAZARD ANALYSIS
{Insert description of work task here}

<table>
<thead>
<tr>
<th>Prepared by: Bryan Kennedy</th>
<th>Reviewed by: Charles Pringle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Approved by: Charles Pringle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location of Task:</th>
<th>Somewhere with a welder that can be used, Machining Lab, Electronics Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required Equipment / Training for Task:</td>
<td>Welding training, welding protection, shop-acceptable clothing, machining training</td>
</tr>
<tr>
<td>Reference Materials as appropriate:</td>
<td>Emergency eyewash station, fire extinguisher</td>
</tr>
</tbody>
</table>

**Personal Protective Equipment (PPE) Required**
*(Check the box for required PPE and list any additional/specific PPE to be used in “Controls” section)*

<table>
<thead>
<tr>
<th>Gloves</th>
<th>Dust Mask</th>
<th>Eye Protection</th>
<th>Welding Mask</th>
<th>Appropriate Footwear</th>
<th>Hearing Protection</th>
<th>Protective Clothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑</td>
<td>☑</td>
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</tr>
</tbody>
</table>

Use of any respiratory protective device beyond a filtering facepiece respirator (dust mask) is voluntary by the user.

**TASK DESCRIPTION**

<table>
<thead>
<tr>
<th>TASK DESCRIPTION</th>
<th>HAZARDS</th>
<th>CONTROLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding</td>
<td>Toxic gasses, Intense UV radiation, Slag Spray, Debris, Intense Light Emissions</td>
<td>Proper welding training, and protective equipment. Well-ventilated area.</td>
</tr>
<tr>
<td>Cutting Aluminum</td>
<td>Debris/particulate inhalation or penetration</td>
<td>Wear proper mask and eye protection. Use gloves if needed</td>
</tr>
<tr>
<td>Testing Device</td>
<td>Electrical Shock, pinch points</td>
<td>Make sure project is properly wired and grounded. Keep fingers and other appendages away from device while in operation or powered on.</td>
</tr>
</tbody>
</table>