TEAM 7 SOLAR TRACKING SYSTEM PROPOSAL

TO: DR. ACKER

FROM: JOSHUA BELSHEIM, TRAVIS FRANCIS,
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SUBJECT: SOLAR TRACKING SYSTEM PROPOSAL

DATE: DECEMBER 13, 2013

Dr. Acker in the pages below is all the work we have done that led up to our selection of our final concept that we wish to present to you. However, to allow you to save the time of reading our entire report this memo will cover what our final design is as well as the estimated cost of the design. For more detail please see the report attached to this memo.

The final design that we have chosen has come to be called the solar array system. The solar array system is designed to be fixed at slope angle of 36 degrees because the team estimated that the inclusion of dual axis tracking would be too expensive given the cost of designing such a system. The design consists of angled frame with 2 shafts that hold the solar panels with bearings on the end hooked up by a chain to a DC motor which will power the movement of the solar panels. For the cost of the design we found the shipping cost for each of our parts based on the cheapest available shipping from each site which was usually UPS ground or US postal service ground. Our solar array design consists of 8 different parts. The first and most important being the 3”×3”×0.25” Square tubing for the frame of the design which is made out of structural steel and is available from Bobco metals. The steel 2” shafts that the solar panels rest on are made of 1018 cold finished steel and are available at Bobco Metals as well. The aluminum flat sheet metal used for our casing is 12”×48” ×1/16” and is 3003 H4 aluminum which, is also available at Bobco Metals. Our DC motor was originally chosen off of Mcmaster however we found it cheaper at Omega so we will purchase it from there. The gears and chains were also originally chosen from Mcmaster but were found cheaper from ZOROTools and RollerChain4Less. The roller bearings for our design have a bore diameter of 2in and are available from BearingsOn.com. The bolts and waterproof paint we will purchase from Home Depot to save money on shipping. We need the waterproof paint because our design is not made out of stainless steel so to ensure it does not rust the paint is necessary.

So the final cost of all the parts with shipping comes to a grand total of $2,952.04. As for the cost of labor we intend to build the system using the tools available to us from the machine shop on campus. Joshua, Anthony, and Micah all have experience welding so we believe we can do the welding ourselves.

Solar Tracking Structure Design

By: Joshua Belsheim, Travis Francis,
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Team 07

Project Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

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Flagstaff, AZ 86011

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Nomenclature Table

	Symbol
Inside cylinder pressure (piston side) (kPa)	P (Kp)
Piston Diameter	d (m)
Sum of the moment	∑M
Sum of the forces on horizontal axis	∑ Fx
Sum of the forces on vertical axis	∑ Fy
Area	A
The minimum space of two solar panel	L(ft)
The total load of each single solar panel	W(Ib)
Friction factor	μ
Torque required	τ (Ib-in)
force act on the shaft	Fc (Ib)
diameter of the shaft	D(in)
House power	HP
Angular velocity: Revelation per minute	*rpm*

Abstract

To optimize solar efficiency that is collected it is essential follow the position of the sun. This is due to the fact that solar radiation essentially follows a straight line. Current solar tracking systems are costly. In this report several different solar tracking designs were evaluated for feasibility. The early concept designs are called Angled Solar Tracker, Nitinol Solar Tracker, Hydraulic Solar Tracker, Half Cylinder Solar Tracker, Water Clock Solar Tracker and the Solar Panel Array. Using two different decision matrixes the designs were evaluated. The first decision matrix evaluated whether a passive or active design should be used. The second decision matrix evaluated the designs on cost and ability to track the sun. Three highest scoring designs the Angled Solar Tracker, Hydraulic Solar Tracker and Solar Panel Array were then chosen to be analyzed. Each of the designs were analyzed to find the primary area of failure. The Angled Solar Tracker had each of its components broken up and the forces acting along the member were determined. The Hydraulic Solar Tracker analyzed principle stresses throughout the design. The Solar Panel Array analyzed the stresses, gear ratio required and minimum distance to prevent shading from other solar panels. In the analysis the angles that the solar panel will have to be at during certain times of the day were calculated. Using these angles the required torque to move each solar panel was estimated. Using these torque calculation the motor that satisfied these requirements were found. These motors were then added to the overall cost of the product. Then to find the final cost of our design the team made a list of materials required and the cost of shipping. This cost was added up and found to be $2271. The labor was approximated since most of the labor would be handled by members within our team.

Chapter 1: Introduction

Presently, it seems as though there is a great deal of interest in renewable energy. This movement has been the cause of quite a few very innovative devices being developed and implemented. One of these innovative devices deals with capturing solar energy and convert it into useable energy through the use of solar panels. One particular device is couple with a semi-automatic device that tracks the sun throughout the day as the day progresses. This design is intended to maximize the system's efficiency.

Although the current systems may appear to be well thought-out, there is always a need and desire for improvement. Unfortunately, some of the current designs on the market have flaws that could be addressed. Originally, the team perceived this dilemma and noticed that a couple of the areas that need improvement are cost and reliability. After the team acknowledged these points, the team managed to set their sights to design a system that is not only reliable but, cost friendlier than the current ones on the market. The following report will outline the different approaches the team took to address these points.

1.1 Introduction to your client

For this project, Dr. Acker is assigned as the team's client. He is not only a professor at Northern Arizona University (NAU), but is the Director of NAU's Sustainable Energy Solutions Group as well. His field of research is comprised of Renewable Energy Systems, Statistical Thermodynamics and Energy Systems and Integration. Before the team started formulating a design, there needed to be some further clarification about the project in addition to the information that was provided. Consequently, the team decided to set up a meeting time and communicate with the client for the additional information needed.

1.2 Problem Description

The team has been tasked with designing and developing an all-seasonal solar tracking device capable of tracking the sun and maximizing the solar panel's efficiency while being reliable, easily maintainable and inexpensive when compared to other designs that are currently on the market. Throughout the designing process, the team must communicate and cooperate with a client.

1.3 Identification of need

Initially, the team met with Dr. Acker prepared with questions pertaining to the project. During the meeting, the team collected a good amount of information solely based on the questions asked. After the meeting, the team collaborated together and deciphered the information retrieved. In doing so, the team managed to formulate a list of needs that the project required. Based on the information received from the client and on assessing current solar tracking devices, the team decided that the project must be:

- Reliable
- Inexpensive
- Easily maintainable

1.4 Objectives

After identifying the important needs associated with this design, the team further interpreted the information retrieved from the interview. Upon doing so, the team discovered that the client has a set of specific guidelines that must kept in mind and met while designing the solar tracking device. The objectives acknowledged by Dr. Acker consists of the following:

- To design and construct a solar tracking device that will be all-seasonal.
- To design a system that will track the sun as the day progresses.
- To maximize the efficiency of the device to

1.5 Operating Environment

The team is also responsible for testing the model before and during the final construction. In regards to this, the team will utilize MATLAB to run the program that will be linked to the actuators which will transfer motion to the solar panels to test the efficiency of the system. Next, the team will be testing the solar tracking device at the renewable energy station that is located between the Engineering building and the Forestry building. When the team gets to this stage, the use of meters connected to the solar panel's outputs and batteries will determine the actual efficiencies of the system.

1.6 Constraints

Constraints indicate the non-permissible conditions encountered for the solar tracking system and the non-permissible range of the design and performance parameters. The first constraint is the weight of the entire system. The team will design the system with minimizing weight in mind. In reducing weight, the team will reduce amount of material used. Not only will this result in a minimized cost, but it will also reduce the power needed to move for tracking itself. The weight of the tracking system should be within a reasonable range. Another important constraint is the budget. Since current solar tracking systems have a high cost, the team decided to design the new solar tracker needs to be built with a relatively small budget in mind. Also, the working space where the solar tracking system will be housed is fairly small, the solar panels will be placed close to each other. But, this poses another constraint, which is shading. In order to have the maximum efficiency, the panels should not shade each other throughout the day. In order to minimize shading, each panel would have to be adjusted in certain time intervals. Also, weather poses another constraint. Since Flagstaff is a four-seasonal town, the team needs to consider the weather. With this in mine, the team must design a solar tracking system that must function as intended during the winter season as well as survive strong winds.

1.7 State of the Art Research

In order to correctly address the problem, the team performed some state of the art research on this subject. The team researched different designs that were available on the market. The team also used this step to formulate different designs on their own. During this step, the team found the following designs:

Table 1: Research

Manufacturer	Model Number	List Price ($)	Panels Included
Zomeworks [5]	ZOMUTRH-072	$1775.46	No
Suntura [6]	WNN-S400	$4995.95	Yes
Wattsun [7]	AZ-225 WSUNTECH STP240	$7175.00	No
Sonnen Systems [8]	Sonnen_System_3_40	$10725.00	No

The above results illustrated just how expensive these systems can get. So therefore, the team decided to have cost and reliability the two focal points that the team will mainly focus on. From this point, the team managed to generate a few concepts. The concepts that the team originally drew up were then put through a decision matrix to select the final design.

Chapter 2: Concept Generation and Selection

2.1 Concept Generation

The concept generation includes 7 different design concepts with rough sketches. Each team member formulated their own solar tracking design. For each design, pros, cons and how they work will be discussed. The report will describe how the top three designs were chosen to do more analysis in order to find our final design.

Standing Tripod Tracking system

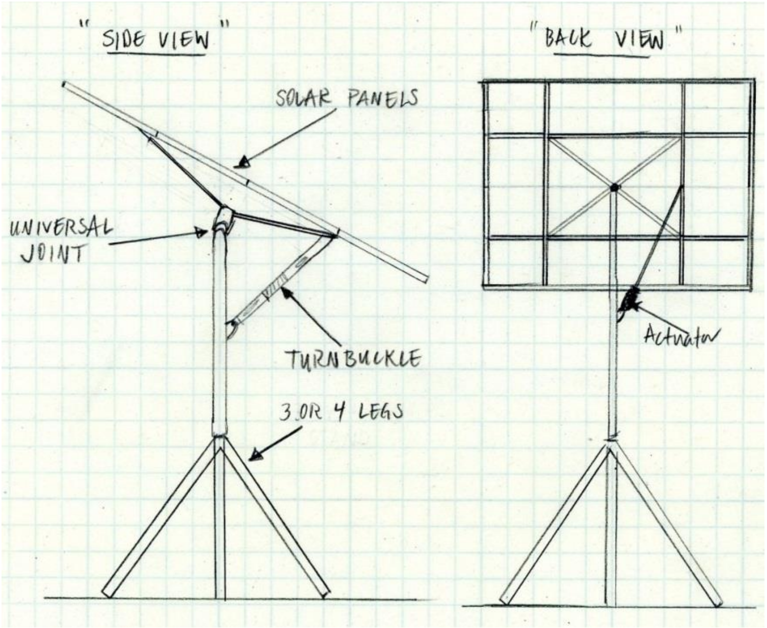


Figure 1. Standing Tripod tracker

The main design aspect was to be very simple and portable. The method of tracking on this design could either be used with a timer or multiple sensors mounted to the system.

The design of the tracking device is that the four solar panels are mounted into a tray. The panels all mounted together, will track the sun as a whole throughout the day. This setup, will hopefully keep the panels from shading each other in the morning and evening hours. This design doubtful to be able to hold up to inclement weather, such as snow and wind but not fully known until more analysis and testing can be done. Therefore, there is a lot of uncertainty about the survivability aspect. To adjust the panels north-south there is a manual turnbuckle which would need to be changed with the seasons. The turnbuckle would be tightened to aim it to the south and loosened to aim it to the north. For the east-west setting, it would be connected to an actuator that would automatically set the angle for the best efficiency. The tray apparatus will be mounted to a pipe then onto a universal joint. The universal joint would not have to be designed but rather selected because of the large variety and availability of universal joints. The purpose of the tripod-base system is for stability on level ground so that the tracking device will stay upright. The problem with the tripod design is that it could be unsafe in bad weather.

Advantages:

- Inexpensive
- Portable
- No Shading

Disadvantages:

- Needs external power source
- Unsafe due to elevated design
- Can only with stand some inclement weather
- Manual setting on north-south axis

The half-cylinder design

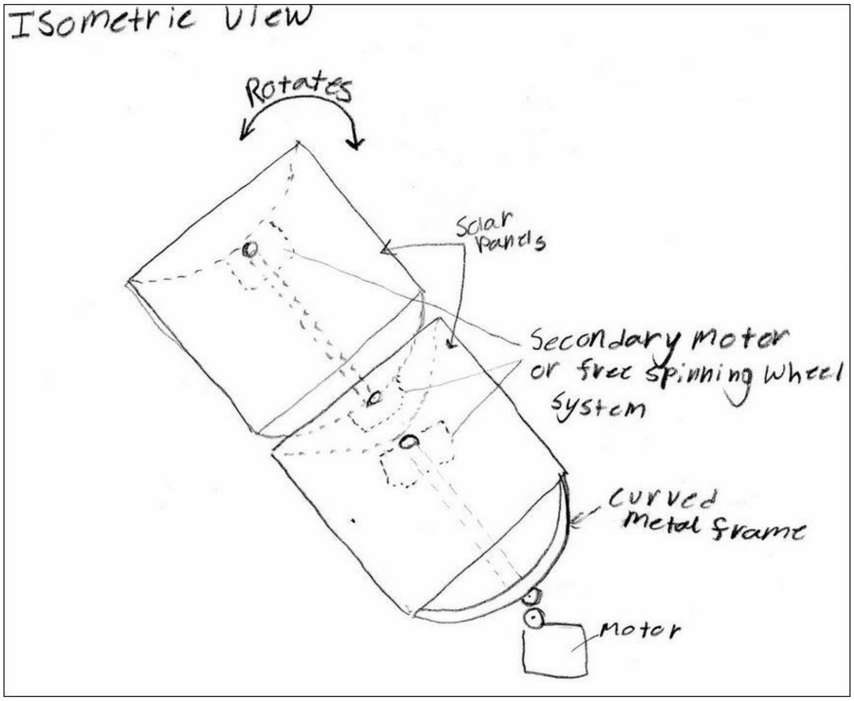


Figure 2. Half-cylinder design

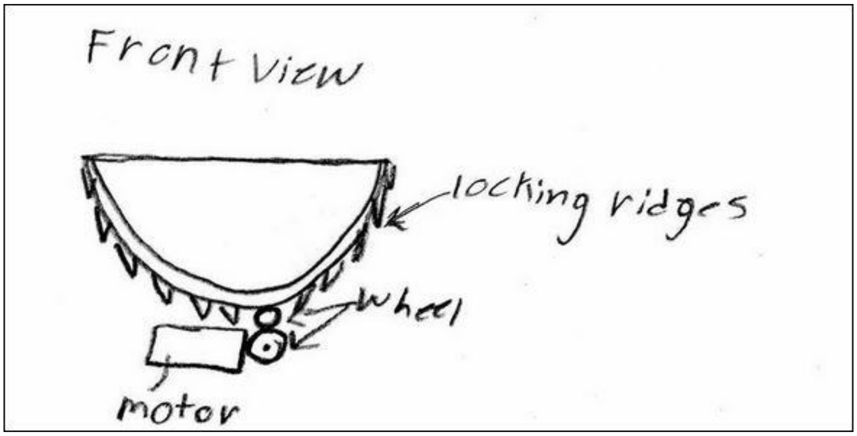


Figure 3. Wheel-assembly

The half-cylinder design is set to turn on a motor at a specific time thus rotating a specially designed wheel as seen in Figure 2. The wheel will spin a certain amount thus turning the half cylinder frame. The wheel will lock into preset grooves along the frame as seen in Figure 3. The frame will be made out of a material that can be bent easily and is should be relatively cheap. The solar panels will be mounted to the half-circular frame that has wedges cut into it to allow for a controlled movement of the half cylinder. The design calls for one powerful motor that rotates a specialized wheel seen below in Figure 4. The wheel will be attached to a drive shaft rotating the solar panels all at once.

Figure 4: Specialized Wheel

Advantages:

- It is a unique design thus marketable
- Can have multiple solar panels connected

Disadvantages:

- A difficult to manufacture frame
- It would require a powerful motor
- It would require a costly specialized wheel
- The design would be costly

The low-tech water clock design

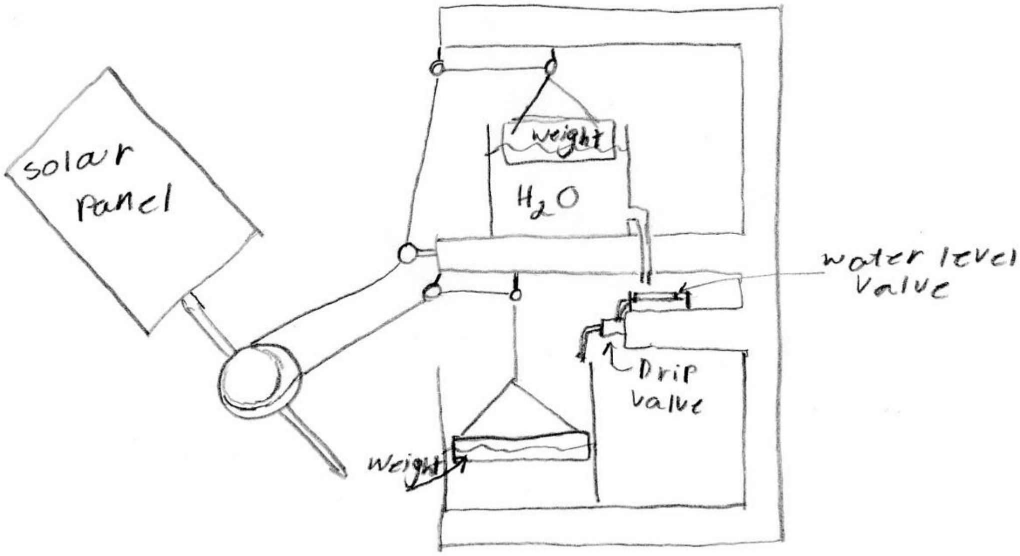


Figure 5: Low-tech water clock design

The solar panel are tilted so that it can be rotated via a cable and pulleys as seen in Figure 5. Weights that have buoyancy will be tied to cables and lowered until they float in liquid. The fluid will drain from the top tank into the bottom tank. This will cause the solar panel to rotate and follow the sun as it rises and sets each day. The tanks would need to be emptied and refilled the following day. The liquid would also have to be something that does not freeze in winter weather. With these huge disadvantages the group did not further develop the design at the concept generation stage such as type of pulleys, cables and material selection.

Advantages:

- Does not require power
- It is a unique design thus marketable

Disadvantages:

- Requires constant maintenance
- Would require a liquid that would not freeze in the winter time
- Only works for one solar panel

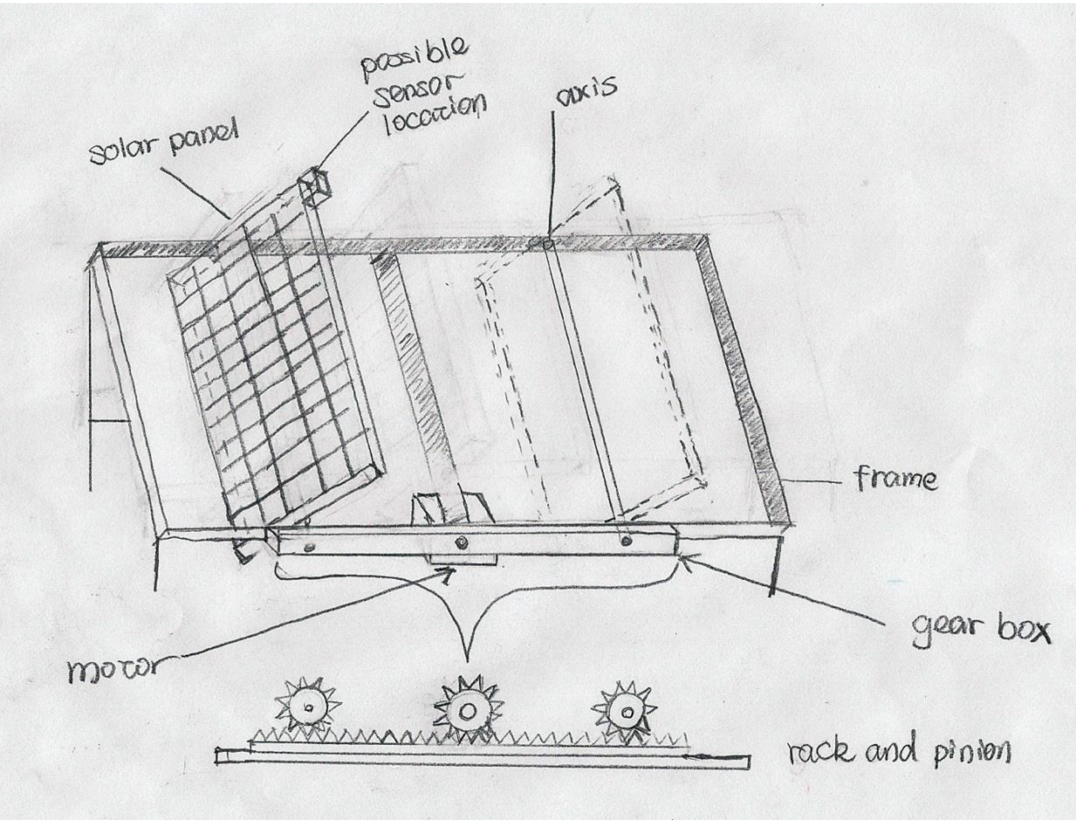


Figure 6: Solar Panel Array

The Solar Panel Array has a single tracking system which can adjust all the solar panels in the system simultaneously. This aspect would increase efficiently and reduce the cost of the design. The sketch shows a design using rack and pinion to pivot the solar panels. A rack and pinion is a type of linear actuator that comprises a pair of gears which convert rotational motion into linear motion. In the design, a solar panel is attached on an axis, which can rotate on the frame. All the axes are connected through the rack and pinion. Since all solar panels in the system have the same motion, only one sensor and motor are needed to pivot all solar panels. This design is setup for East-West rotation of the solar panel. The spacing of the panels will be an important part of this design. If the spacing is too large it will not fit in shack and increase the moment arm while if the spacing is to close the panels will shade each other.

Advantages:

- Similar design has been done before.

- Only one sensor and motor are needed to pivot all solar panels, which can reduce the cost.

Disadvantages:

- Large amounts of torque are needed since the single motor has to rotate all the solar panels in the system.
- This design is not new so it would be unlikely that we could market the design outside of NAU.
- Need a large space to avoid solar panels shading each other once they are being rotated.
- There is a potential for high maintenance because of the rack and pinion gear system

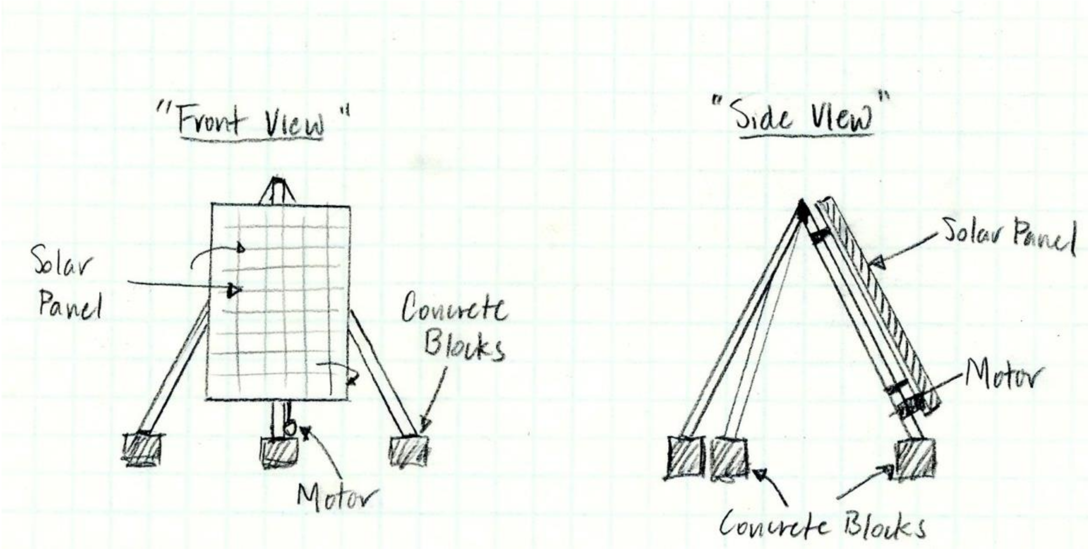


Figure 7: Angled tracker design

The general concept of this design is to have the solar panel at an angle that is capable of allowing the solar panel to track the sun in an east-west direction through the sky. The solar panel being permanently angled north and south only requires a simple tripod design to support the solar panel. The panels sit on the front leg instead of on top of the tripod for more stability. The poles of the tripod can either be semi-permanent with sandbags, or permanent with the poles being cemented into the ground. The actuator is below the panels and pushes or pulls the panels around the front leg.

Advantages:

- Similar design has been done before.
- Simple design.
- Relative low cost depending on the materials used for the supports and motor/actuator systems.
- Only moving parts is the motor/actuator
- Could be designed as either an active or passive tracking system.

Disadvantages:

- This design is not new so it would be unlikely that we could market the design outside of NAU.
- Requires external power to power the motor/actuator system depending on what we choose.
- Only works for one solar panel.
- Takes up space

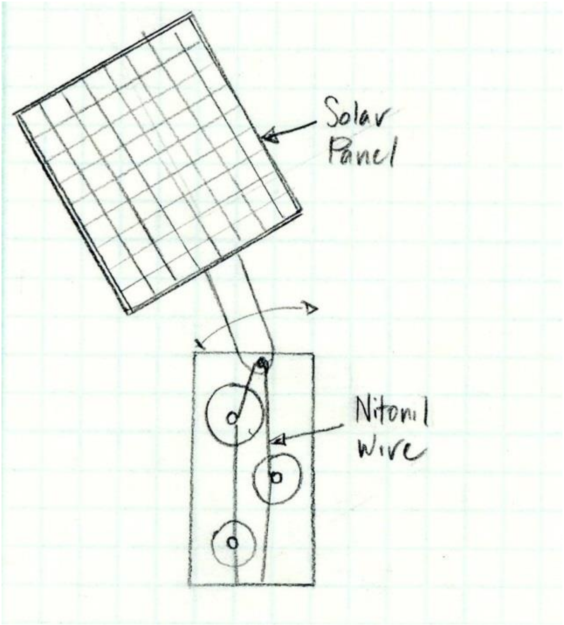


Figure 8: Side view Nitinol tracker

To understand how this design works a background of Nitinol is need. Nitinol, is nickel-titanium (NiTi), and is one of the more common types of SMAs (Shape Memory Alloys). SMAs have two important characteristics known as the "*shape memory effect*" and the "*pseudoelastic effect*". The "*shape memory effect*" is a property by which very large mechanical strains can be recovered above a critical temperature. The "*pseudoelastic effect*" is a property by which the material exhibits a very large strain upon loading that is fully recovered fully when the material is unloaded. [2]

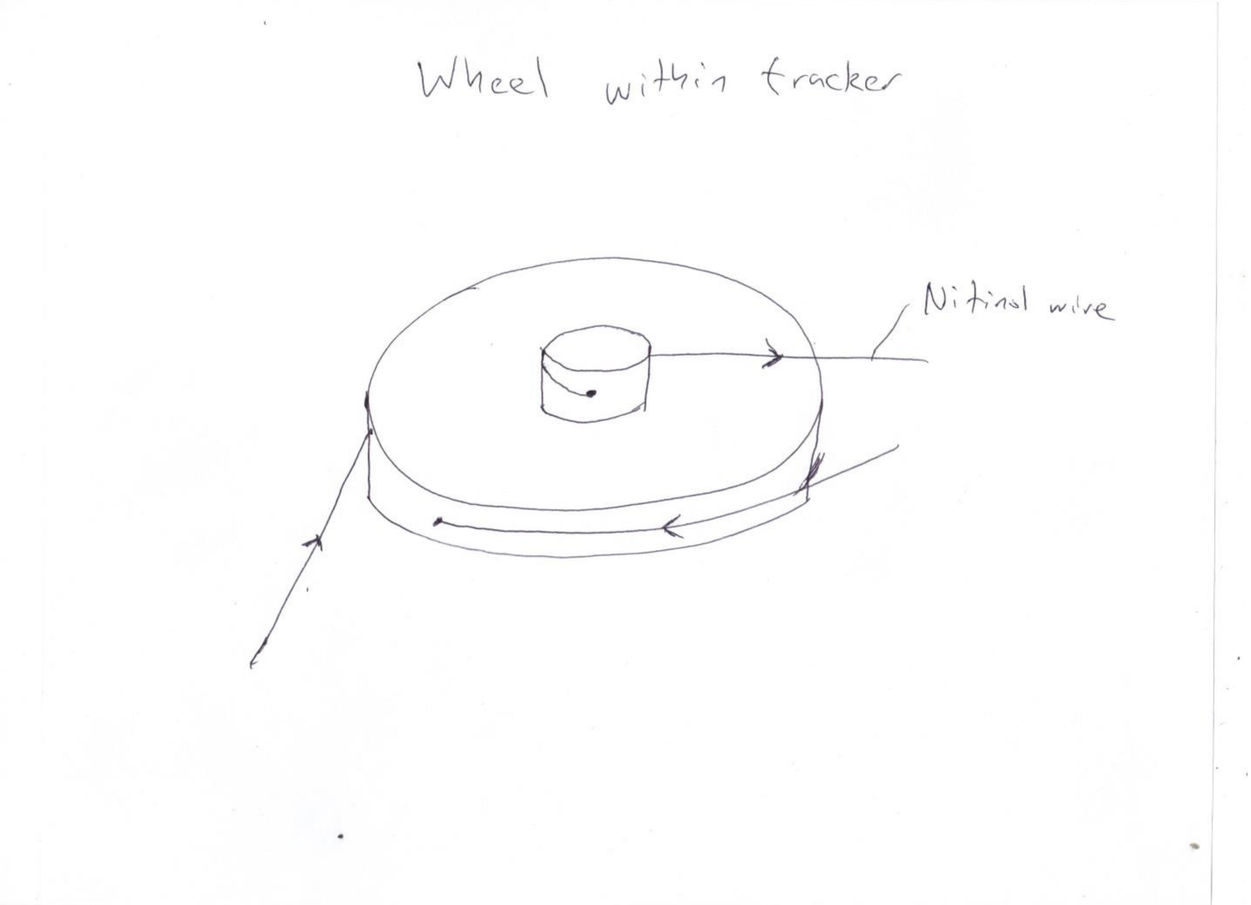


Figure 9: Nitinol tracker wheel close up

The Nitinol Tracker design is alteration to the Angled Tracker design. The alteration is the replacement of the actuator with a Nitinol pulley system. Nitinol tracker design will achieve the shape memory effect by passing a current through the lengths of the Nitinol wire to move the pulleys that would then pull the solar panel in an east-west tracking pattern. Figure 9 displays how the Nitinol wire moves the solar panel and wheels. The wires are connected to the wheels sides and top so that when the wire under goes the "*shape memory effect*" the wires will contract and pull the wheel in one way or another as the figure above shows.

Advantages:

- The only moving parts are the wheels that move the solar panel.
- Could be marketed to other customers besides NAU.
- The housing structure of the Nitinol pulley system could be setup horizontally or vertically to save space
- A system of this design could be used to move all four solar panels

Disadvantages:

- Design has not been used before little research done
- Due the large amount of Nitinol wire that is needed to pull and push the panels the price would be high.
- Nitinol as well as other smart materials are still being heavily researched and many unknowns of the properties of Nitinol.

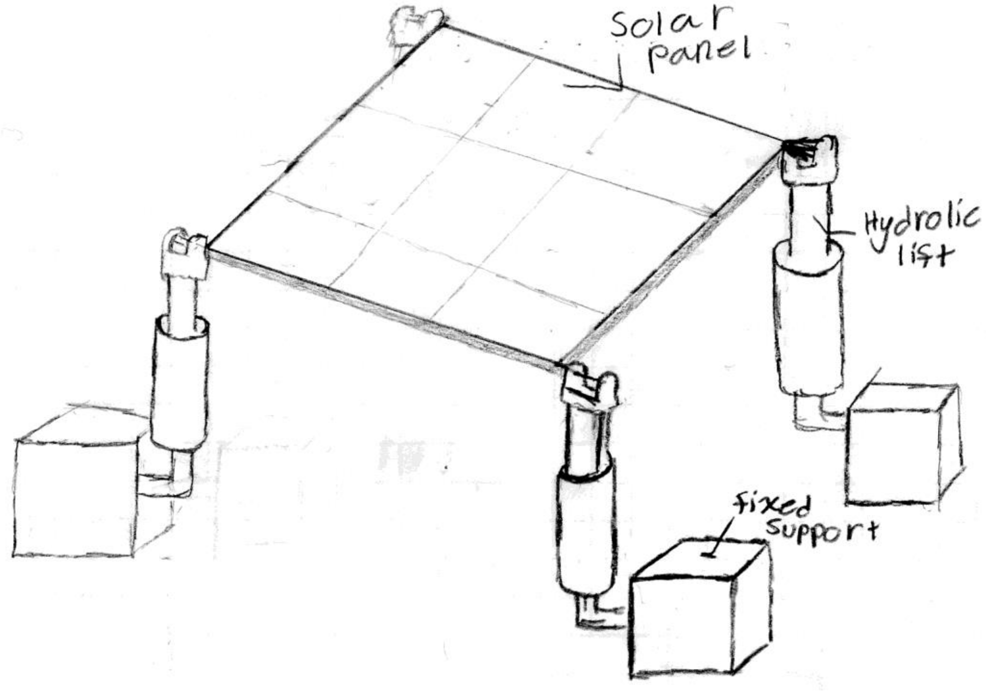


Figure 10: Hydraulic tracker design

The hydraulic design uses hydraulics to move the solar panels and a ball joint to hold the weight. With hydraulics on each corner this allows for dual axial tracking, which tracks the sun north and south over the year and east to west during the day. The design could be passive or active tracking depending on the hydraulics. Passive hydraulics would have a low boiling point fluid in the hydraulics and would be heated up with solar rays. The active hydraulics would be magneto rheological hydraulics. This hydraulics could use a magnetostrictive fluid when coupled with a magnetic field they become useful in controlling motion[2]. This system would be controlled with an electric pulse. The passive does not use any power from the solar panels but won't be as accurate as the active tracking. The reason being it takes it takes time to heat up the fluid and with cloud coverage it could throw off the tracking for the whole day. The active tracking takes some energy but increases the efficiency of the tracking. It would also increase the price of the design.

Advantages:

- There are no gears or motor needed.
- Uses either passive or active components.

Disadvantages:

- A tall ball and joint.
- The uses of smart materials can be costly.
- The design is an untested.

2.2 Concept Selection and Decision Matrices

To decide between the seven concepts that our team generated we decided to come up with seven categories to judge our designs:

- Reliability
  - ➢ Does the design work consistently?
  - ➢ How often does it break down?
- Cost
  - ➢ The price of the design all together.

- Safety
    - Does the design present a danger to anyone in operation or when it fails?
- Maintenance
    - How many man hours and parts are needed to repair the tracking system?
    - How often maintenance is need
- Survivability
    - Can the tracking system operate effectively in the weather of Flagstaff and other potential market areas?
    - For Flagstaff pacifically, can the tracking system withstand snow?
- Efficiency
    - How much energy does the tracking system allow the solar panels to absorb?
    - How much net energy is gained by the tracking system?
- Light weight
    - How heavy is the design?
    - The lighter the design the easier it will be to install and move the design if necessary.

As well as coming up with these seven categories to judge our designs, added weights to each category ranking them from one to seven, seven being the most important and one being the least important.

Lightweight (1): lightweight was assigned the value of one because it was a self-imposed objective by the group and not an actual requirement of the client. Also the only benefit that being lightweight gives is that it is easy to move around and install if necessary.

Survivability (2): We gave survivability a two because most solar tracking systems available today are capable of being implanted in the flagstaff area. However survivability is more important than being light weight because of the added secondary objective by our client and team that the tracking system be able to remove snow from the solar panels.

Maintenance (3): Received a three because simple maintenance was one of the objectives stated by our client that he would like us to consider in our design. However it is only a three because all designs have some maintenance. So it is acceptable to have some increase maintenance if the tracking system improves upon the efficiency, reliability, and cost of current designs which are weighted more heavily in our decision matrix.

Safety (4): We gave safety a four because anything that engineers design should be considered safe to operate around people or during maintenance. Safety is important as well due to the fact that Dr. Acker wants the systems to be used for his renewable energy classes to demonstrate ideas from the class in real life. However these systems are not as important safety wise as say bridge so that is why it received a 4 instead of a higher score.

Efficiency (5): Efficiency received five out of seven because current solar tracking system designs are pretty efficient and significantly increasing the efficiency of the solar panel is beyond the scope of this project. However the solar tracking should be more efficient than the current stationary rack system that the solar panels are sitting on now or there would be no point to designing the solar tracking systems.

Cost (6): Cost was the second most important factor in our design matrix because the cost of current solar tracking systems is too expensive for Dr. Acker to purchase for the school. We also want our design to be competitive if the design were to be marketed.

Reliability (7): Reliability is the most important category in our decision matrix because current solar tracking systems are unreliable in that they break down often and require replacement. Current solar tracking systems are also unreliable in that their ability to be a consistent energy source. Dr. Acker also emphasized to our team that this was the biggest reason he gave this project to our capstone group.

For both of our decision matrices we went with a simple system of grading each design according the each category with 1, 0,-1. 1 being good or achieving the necessary goal, 0 being neutral and -1 for not achieving the goal. We decided to go with this system for our decision matrices because of advice we received from Dr. Nelson. Basically the 1 to 10 scale normally used in most decision matrices however Dr. Nelson said that this method is often used by engineers who have lots of knowledge or experience in design. However, us as students do not have a large amount of experience in design and we do not have a lot of experience in solar energy. It is easier for us to decide if a design fully meets or doesn’t meet the goal compared to saying it received 5 out of 10.

Table 2: Concept decision matrix

	Safety	Cost	Light weight	Efficiency	Maintenance	Reliability	Survivability	
Weighted Importance	4	6	1	5	3	7	2	Total
Designs								
Half Cylinder	0	-1	-1	1	0	0	1	0
angled tracker	1	1	0	1	1	1	1	27
Solar array	1	1	0	1	0	1	1	24
ball joint	1	0	1	1	1	1	1	22
Nitinol tracker	1	-1	1	0	1	1	1	11
Water low tech	0	1	-1	0	-1	0	1	4
Standing tripod	0	1	1	1	1	1	0	22

With the results from the decision matrix we moved forward with three designs. The three designs being the angled tracker, solar array, and ball joint systems. The three designs all came relatively close to each other with scores of 27, 24, and 22 respectively. The team placed two members on each design to analysis.

Passive and Active Tracking Selection:

There are three factors to decide between active or passive tracking. The factors are:

- Cost
  - ➢ The price advantage of the type of tracking

- Efficiency
    - ➢ The ratio of energy gained for tracking over the energy loss because of tracking
- Reliable
    - ➢ The maintenance of the design

Each factor was also given a multiplier weight by the ranking of importance. The value of the multipliers on the passive and active tracking is different than the design matrix because this matrix is about finding which type of tracking is better not better design.

Cost (1): Cost was rated the lowest at one because the costs depend on the design rather than passive and active but passive has a built in advantage in cost over time so it need to be included on the decision.

Reliable (2): The weighted value of reliability was a two because once again depends on the design but active has a clear advantage in withstanding weather conditions

Efficiency (3): Efficiency was rated the highest value with three because active tracking is overall more efficient than passive tracking

Table 3: Passive vs. active systems

	Cost	Efficiency	Reliable	
Weighted Importance	1	3	2	Total
Active	-1	1	1	4
Passive	0	0	1	2

Passive:

Passive tracking uses methods that do not require the conversion of energy to electricity in order to track the sun. The most common is a low boiling point fluid hydraulic. This is a non-precision technique but does not require any additional power from the solar panels. The reliability of the hydraulics in the weather is subpar. These reasons are why passive tracking is less common than active tracking.

Active:

Active tracking uses motors and gears to track the sun. There are many more designs and tested designs with active tracking. The additional small load on the solar panels adds a tremendous amount of efficiency in tracking these are the reason why active tracking is more common.

Dual and Single Axial:

The two types of axial rotation are north south and east west. North south tracks with the change of the season and the height of the sun. East west tracks the sun from sunrise to sunset from day to day. A single axial design can have only one or the other type of rotation. A dual axial rotates both north south and east west. Since the height position of the sun does not have a large range in Flagstaff the value of energy of single axial produce in a year is $727.09 and dual axial is $776.56 with a difference of $49.47. To design a tracking system that can do both north-south and east-west is waste of time and money. [3]

Chapter 3: Engineering Analysis

In this portion of the report our team did static structural analysis on all three of designs selected from the concept generation. With this information we selected some material and motors for each design. In addition to the structural analysis we also did analysis of the angles required to track sun.

3.1 Angled Solar Tracker

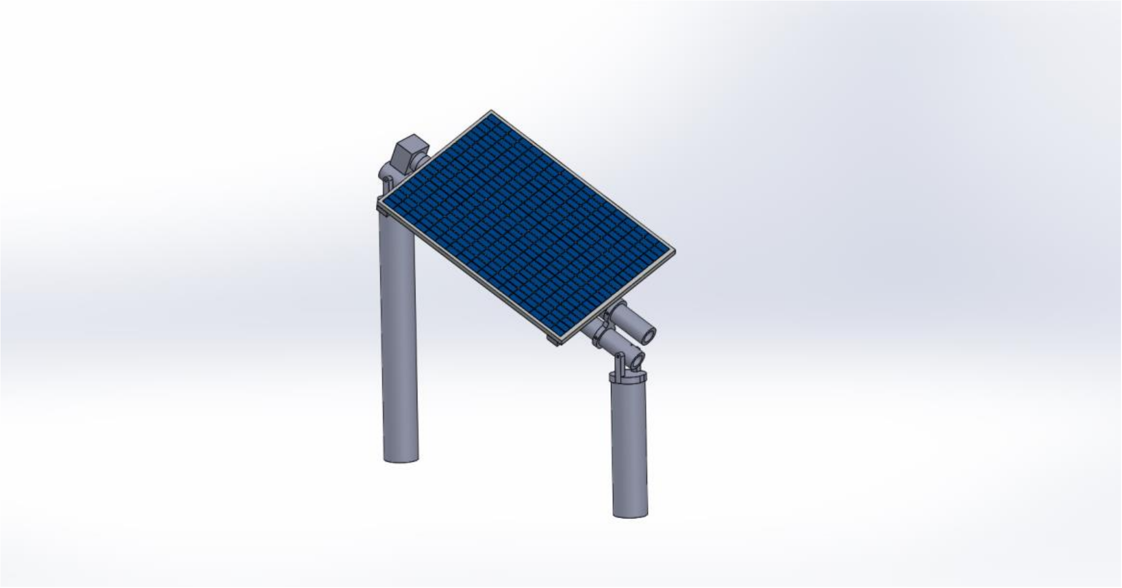


Figure 11: Isometric view of Angled tracker

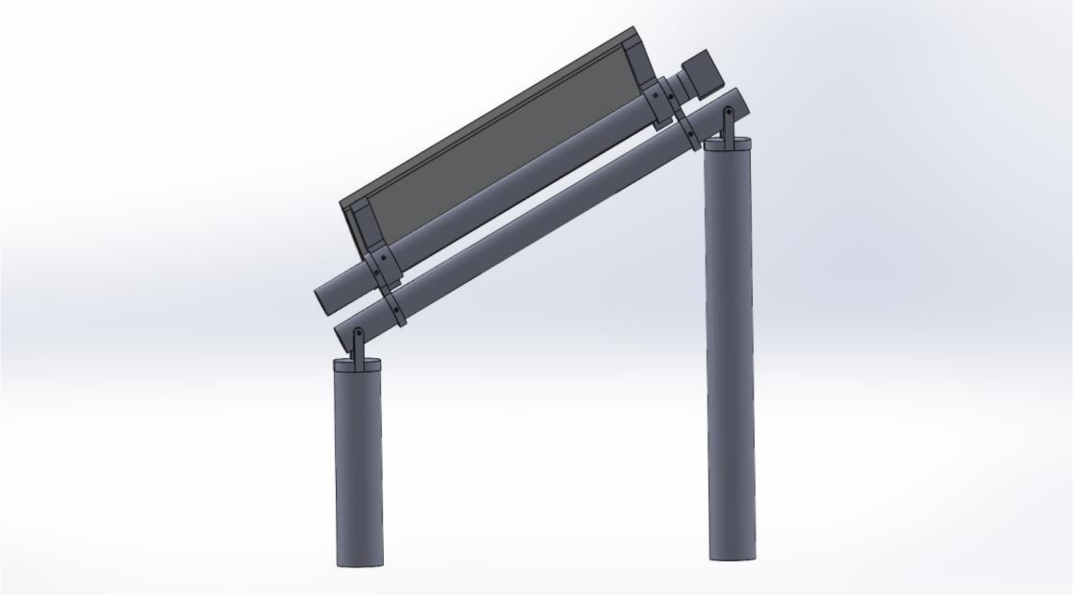


Figure 12: Side view of Angled tracker

In the last report of concept generation this design originally consisted of one support with the upper part of the solar panel resting on a triangular support of two shafts. However, to save space and to make the analysis of the design easier we decided to go with only one support on the back.

The Angled Solar Tracker frame using statistical equations. The frame was broken up into segments and analyzed. Starting with Component A seen in figure 3, the component that is attached directly to the solar panel experiences a distributed load over the width of the solar panel. The general equation is listed below.

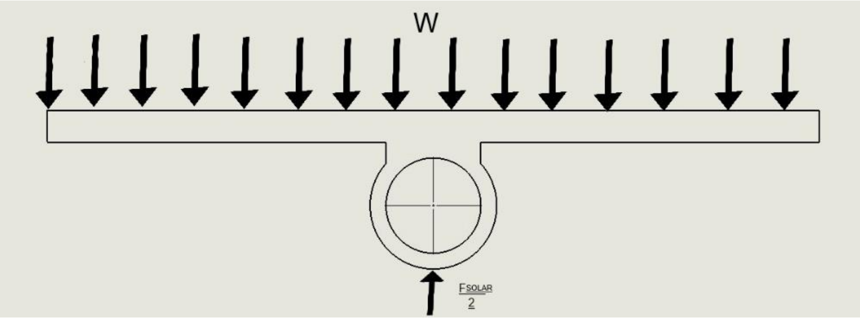


Figure 13: Component A

$$\sum Fy \ = \ 0 \ = F_{solar} - F \times W$$

$$\sum Fx \ = \ 0 \ = \ A_{x_1}$$

Where A1 is the reaction at the A joint, W is the width of the solar panel and F_{solar} is the normal force exerted to the solar panel. F is the force of the whole solar panel.

For Component B, seen in Figure 4. The general equations come out to be

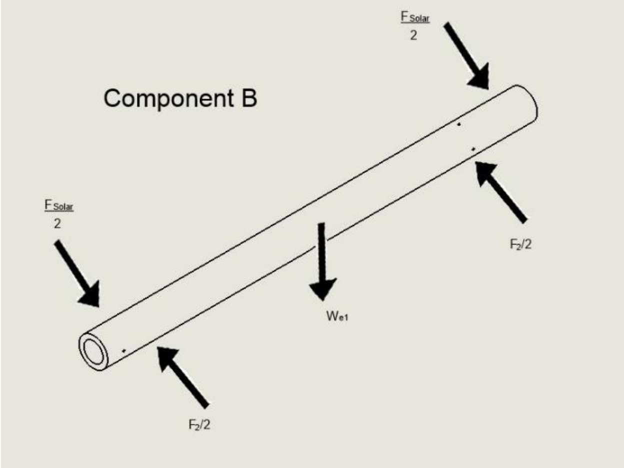


Figure 14: Component B

$$\sum F_y = 0 = -F_{solar} \ + \ F_2 - We_1 \ \times \ sin(\theta_1)$$

$$\sum F_y = \ 0 = -We_1 \ \times cos(\theta_1)$$

Where W_{e1} is the weight of the component B bar. Component B is attached to Component C. Calculating the force in Component C seen in Figure 5 the general equations are shown below.

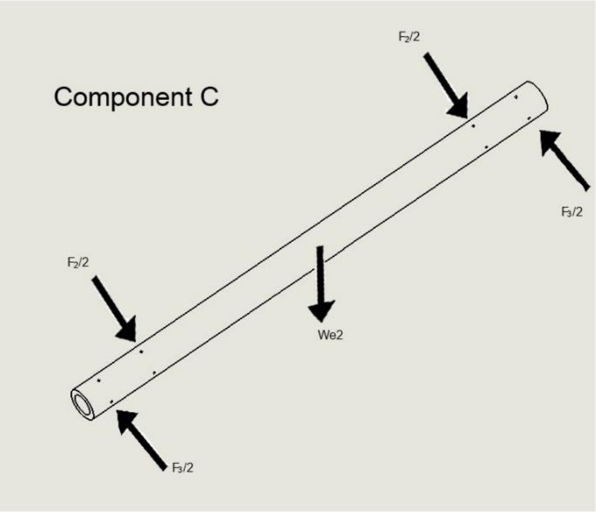


Figure 15: Component C

$$\sum Fy = 0 = -F2 + F3 - W_{e_2} \times sin(\theta 1)$$

$$\sum Fx = 0 = -W_{e_2} * cos(\theta 1)$$

Component C rest upon two bars are perpendicular to the ground, which have been labeled Component D seen in Figure 6 and Component E seen in Figure 7. Calculating the forces in each component the general equations become.

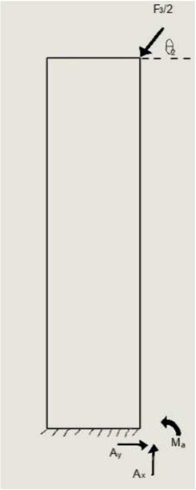


Figure 16: Component D

$$\sum F_y = 0 = A_y - \left(\frac{F_3}{2}\right) \times sin(\theta_2)$$

$$\sum F_x = 0 = A_x - \left(\frac{F_3}{2}\right) \times cos(\theta_2)$$

$$\sum M_a = L \times \frac{F_3}{2} \times cos(\theta_2)$$

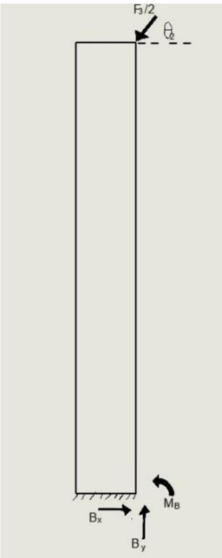


Figure 17: Component E

$$\sum Fy \;=\; 0 \;=\; Ay - \left(\frac{F_3}{2}\right) \times sin(\theta_2)$$

$$\sum Fx \;=\; 0 \;=\; Ax - \left(\frac{F_3}{2}\right) \;\times cos(\theta_2)$$

$$\sum Ma \;=\; L \;\times \left(\frac{F_3}{2}\right) \times cos(\theta_2)$$

Torque

The Torque was calculated by taking the Force that the solar panels apply times a frictional coefficient of 0.48 times the diameter of 5cm

$$T \;=\; (F \times 0.48) \;\times D$$

The Torque is calculated to be 6.5079 N*m. Then taking this Torque the ratio between horsepower (HP) and Revolutions per Minute (rpm) was found using the Full-load Torque equation.

$$T \;=\; \frac{(HP \times 5252)}{rpm}$$

The ratio of HP/rpm was found to be 0.001239, using the DC Motor, NEMA 56 C-Face with Base, 12 VDC, 1/4 hp, 1800 rpm[1]

Solving the General equations

<u>Given</u>

Width = 4’ = 1.2192m

Length of Component D = 1.9m

Length of Component E = 1m

Weight of Component B = 10lbs = 44.5 N

Weight of Component C = 10lbs = 44.5 N

$\Theta = 21.1$

Raw Data

$F_{solar} = 325.4$ N

$F_2 = 341.42$ N

$F_3 = 357.44$ N

$A_y = 64.34$

$A_x = 166.737$

$B_y = 64.34$

$B_x = 166.737$

Material Selection

The material that satisfies the stresses at these points is AISI 1020 steel. AISI 1020 steel has a Ultimate Tensile Strength (UTS) of 394.72 MPa and a modulus of Elasticity of 200 GPa which easily satisfies the design requirements. This steal was chosen over other grade steal since it is cheap and easy to manufacture.

3.2 Hydraulic Tracker - Analysis

The team decided to design a light weight, yet reliable solar tracking system that not only meets the objectives and needs but is to perform in a safe and efficient manner. After applying the decision matrix, the team decided to pursue three potential designs since the tracking system will be utilized in an environment where there is plenty of sunshine during the midday and shady in the mornings and evenings. The team figured that in order to maximize the system's efficiency, the system and its components would have to be designed and chosen with reliability in mind. The following is the analysis of the Hydraulic Tracker.

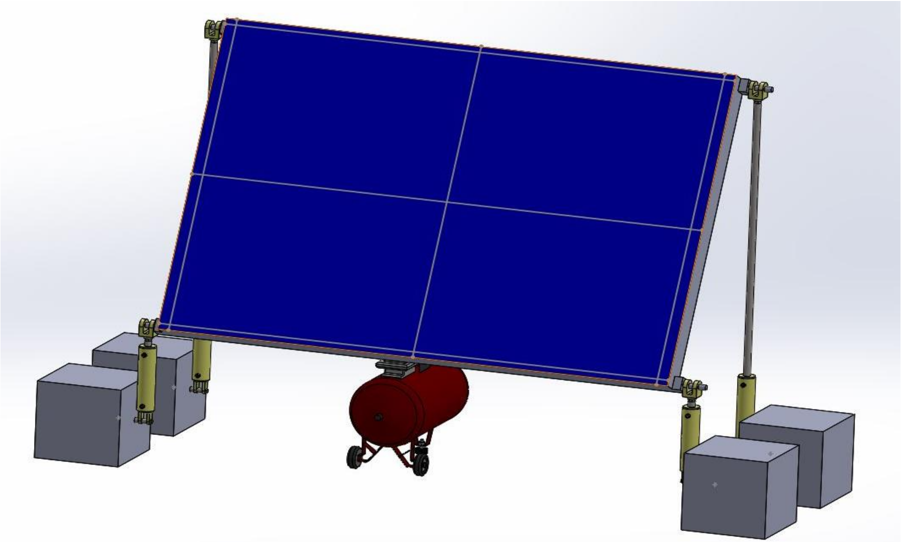


Figure 18: Isometric View Hydraulic

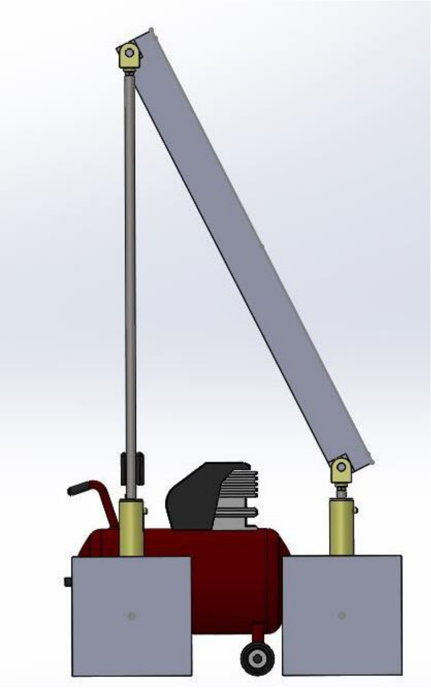


Figure 19: Hydraulic side view

The original plan was for the design to include a ball joint in the center of each panel for support it also had magneto-rheological (MR) fluids in the hydraulics. Since the panels do not weigh more than the team originally estimated, and it is hard to find a ball joint with our needed dimensions. So we will not be using a ball joint in this design. The MR fluid is used in damper hydraulics and thus does not provide the necessary lifting force. There have been a couple modifications done to the design due to the facts stated above. These modifications include moving from MR hydraulic fluid to air and no ball joint.

So for this new design, the team decided to do a stress analysis of a few particular points. The stress analysis calculated on the system will be located at the points where the rods are inserted into the upper and lower eyelets of the hydraulic cylinder.

The weight of each solar panel is 266.9 Newton (N) and the weight of each hydraulic cylinder is approximately 22.24 N. The minimum length of the connecting rods should be 0.06 meters (m) to fit the eyelets of the hydraulic cylinder, nuts, and bolts used to secure it. The eyelets of the hydraulics have a diameter of 0.02 m. The material that the team chose for the rods will be AISI 1020 Steel because it is relatively inexpensive and readily available. The Ultimate Tensile Strength (UTS) for the material chosen is 394.72 MPa. The Modulus of Elasticity of AISI 1020 Steel is 200 GPa. With these known values and assumptions, the basic hand calculations of the prototype are as follows:

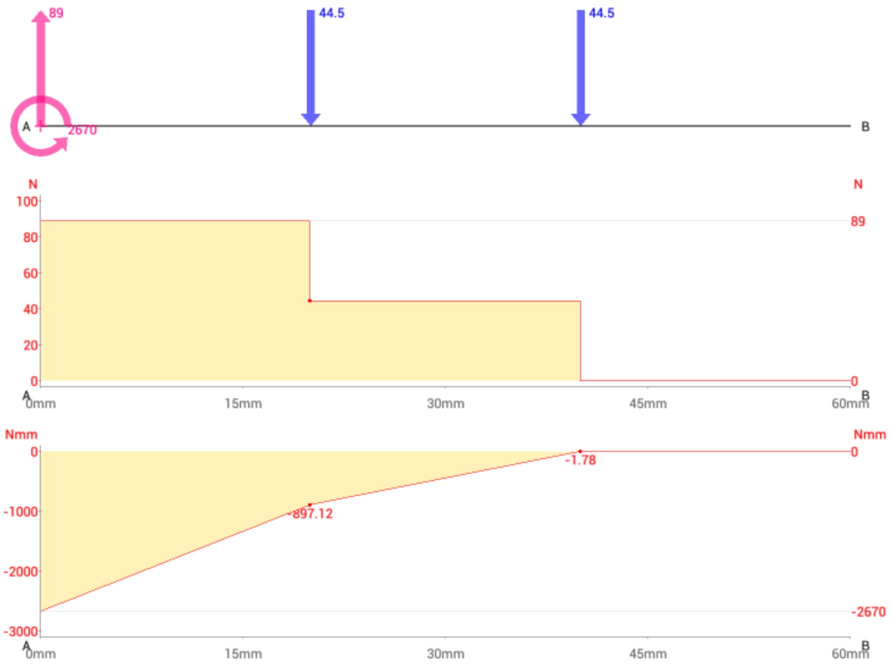


Figure 20: Shear and Bending Moment Diagram Section AB

This analysis was performed for the lower hydraulic eyelet. This location is to be connected to the concrete blocks for support and stability. The reaction force acting on the connecting rods are the ¼ of the weight of each assembly, panel and 4 hydraulic cylinders, because there are four supports for each system. For this calculation, the team assumes static equilibrium because the acceleration of the panels will be slow. Thus, calculating at static equilibrium, the shear force is 88.97 N and the moment at Point A turned out to be 5.34 N-m. According to these values, the team did not calculate the forces that the hydraulic cylinders can withstand because each cylinder will have to withstand greater values of force due to the high internal pressures that each assembly must have to move each panel.

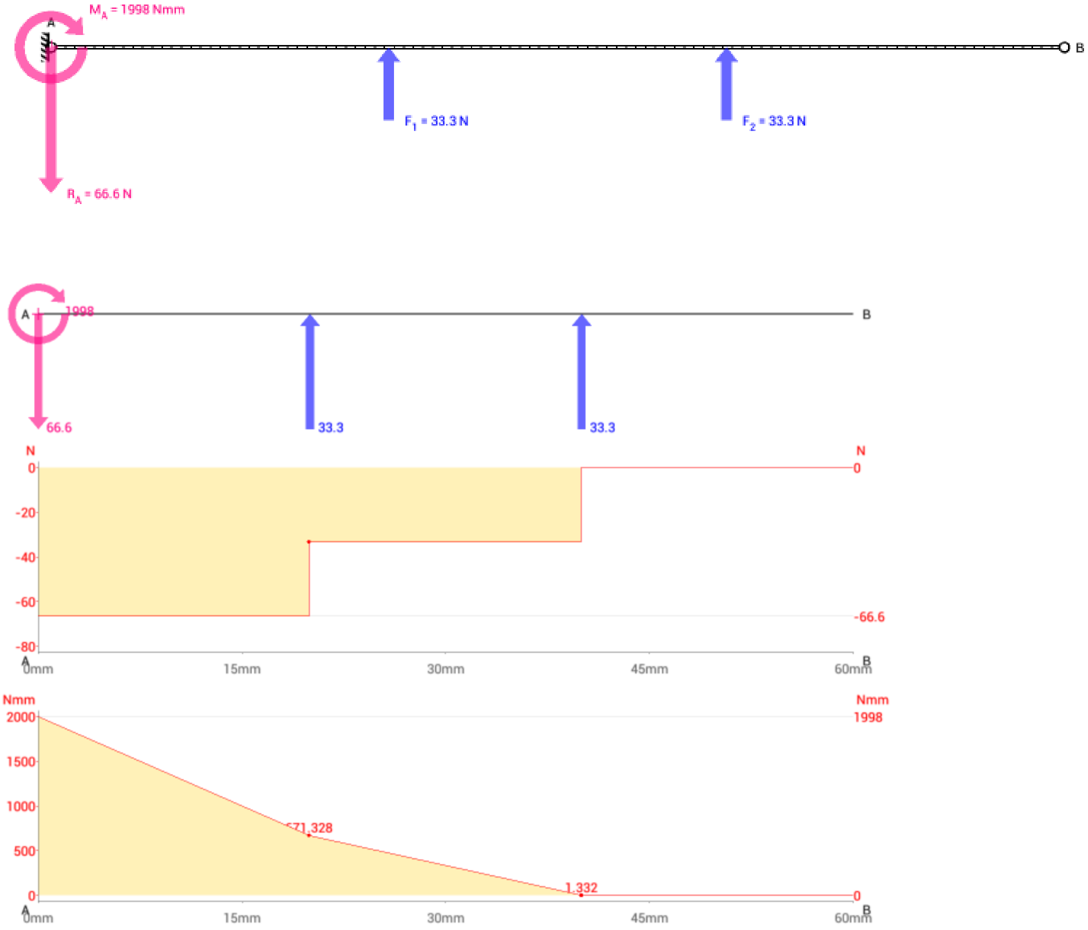


Figure 21: Shear and Bending Moment Diagram Section CD

The following analysis was of the connecting rods mounted to the solar panels. The weight applied to this area is ¼ of the weight of each panel. The team made the same assumptions for static equilibrium case. The shear force is 66.73 N and moment is 4 N-m. These values are less than the shear and moment in section AB. The driving values of this shear and moment diagram are 88.97 N and 5.34 N-m.

The determining factor of each connecting rod is the diameter or the cross sectional area of each rod so it can match the diameter of the hydraulic. We choose AISI 1020 steel because it is inexpensive and readily available. Using equation UTS=FL/EA the maximum length that each rod can withstand before failure is 11914 m. Since the length of the rod we are using is 0.06 m, there is no concern about the rods failing.

After doing some further research, the team found that using a Standard Double-Acting Hydraulic Cylinder makes the most sense. This system would be the best fit since it can deliver both, a pulling and pushing motion. These pistons are relatively cost-effective when compared to other systems such as Double-Rod Cylinders, Spring Return Single-Acting Cylinders, Tandem, Telescoping Cylinders and so forth.

The next set of analyses performed was on the hydraulic cylinders. The hydraulic cylinders were analyzed to determine the force needed to lift and lower the panel throughout the day. The hydraulic cylinders are permanently set on the North-South axis, but most move on the East-West axis. As a part of this analysis, the team did manage to calculate forces needed to move the panels to effectively track the sun. The following calculations were completed using Microsoft Excel program. The program was utilized to calculate forces required to successfully move the solar panels. There were some constant variables that were used, such as:

- Panel weight = 60 lbs or 266.9 N each (approximately)
- Number of Supports = 4
- Weight at each support = 15 lbs or 66.725 N

After determining the essential constants, the following equation was used to determine the pushing force that each double acting hydraulic piston would produce:

- $F = P \times \left(\frac{\pi d^2}{4}\right)$ [1]
    - F = rod pull force (kN)
    - d = piston diameter (m)
    - P = inside cylinder pressure (piston side) (kPa) [1]

Using an excel spreadsheet; numerous iterations were performed of this equation. The program did supply a large quantity of possible combinations that would be sufficient for this application. In order to keep the energy consumption down to a minimum, the team decided to keep the air pressure as low as possible within the cylinder so that the air compressor would not have to be operating constantly.

After reviewing the calculations found within the spreadsheet [Table 1], which is available in the appendix, in the and comparing them to the options listed within the Parker Cylinder Catalog, the team found that the best option would be to utilize a cylinder with a piston diameter of 0.125 m [2]. The reason why we compared results to the catalog was to order an off-the-shelf part rather than a custom made one because this would lead to money saved. The team found an assembly that would allow us to use the least power possible and still have a functioning tracking system. This choice was made by assuming that when the hydraulics located on the east side would be pulling while the ones located on the west side would be pushing in the morning. Then the hydraulics would operate in an opposite manner in the afternoon. The reason why the team chose to perform the analysis in this manner is because it would keep the hydraulics from conflicting with each other and causing damage to the design. Plus, the hydraulics will be assisting each other in moving the solar panel. This in return would help save the power required to move each solar panel. In reference to this idea, the pressure required to pump each hydraulic included within each system that would need to produce and hold 80 bars of pressure. Therefore, when the system is not in operation, the pressure inside the hydraulic cylinders will be large enough to hold the solar panel in place until it is ready to move again. This will help cut down on the power consumption during operation.

In conclusion to the analysis of this design, the team concluded that it would be rather expensive to assemble this design. The original plan was to include a ball joint in the design. The ball joint idea was dismissed due to weight issues, because the panels do not weigh as much as the team thought. Also, the team chose to utilize a different fluid within the cylinders due to the cost constraint. Lastly, the team believes this design would rank closer to last than the other two designs.

3.3 SOLAR PANEL ARRAY

The solar panel array can adjust all the solar panels in the system simultaneously through a pulley and belt system. The design can efficiently reduce the cost and increase efficiency of the tracking system, since only one motor and one sensor are used in the system. The design consists of

- a frame made of 3”×3”×0.25” square hollow tube
- four 2” diameter partially keyed drive shafts
- several mounted bearings
- a pulley belt system
- a powerful DC motor
- a light sensor and control system

Most of the components will be made from AISI 1020 carbon steel.

The overall system is shown in figure 12. As mentioned in the next section, the angle between the shaft and the ground is 36 degrees. Four solar panels are fixed on the rotating shafts. And a pulley-belt system is installed on the lower end of the shafts.

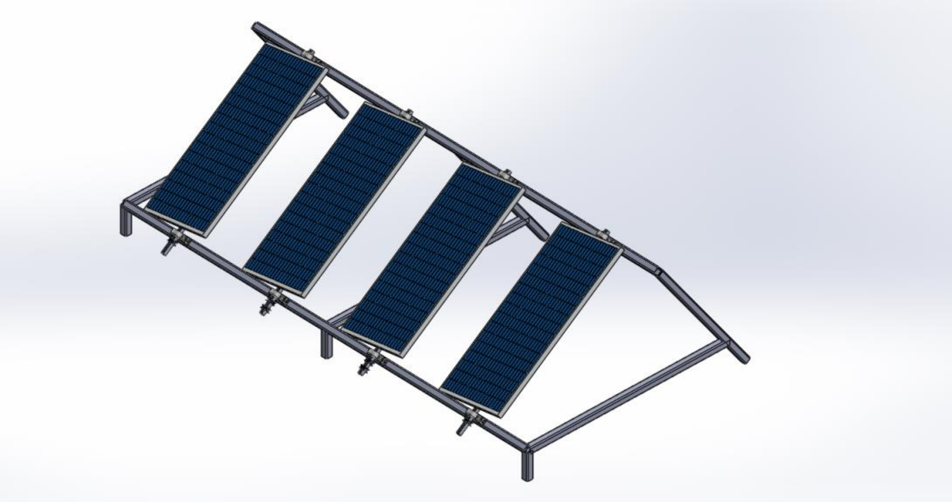


Figure 21: Isometric View of Solar Panel Array

Figure 22: Side View of the Solar Panel Array

The presented sketch was used to conduct the analysis on each member of the design. No sensor and motor is included since more calculations need to be done to determine the locations of the motor and the light sensor.

Shading analysis:

The solar panels will be installed on the frame as shown in figure 16. To avoid the solar panel shading each other, the distance between two adjacent solar panels needs to be at least 8 ft. The calculation is shown below. Usually, solar panels absorb the sun light from 7:00 am to 6:00 pm. and the sun light has the incident angle about 30 degrees and the solar panels will always be perpendicular to the sun light. The minimum space of the solar panel L can be calculated with the following function:

$$L = \frac{0.5 * a}{\sin 30} * 2$$

Where:

L: the minimum space between solar panel;

a: short side length of the solar panel;

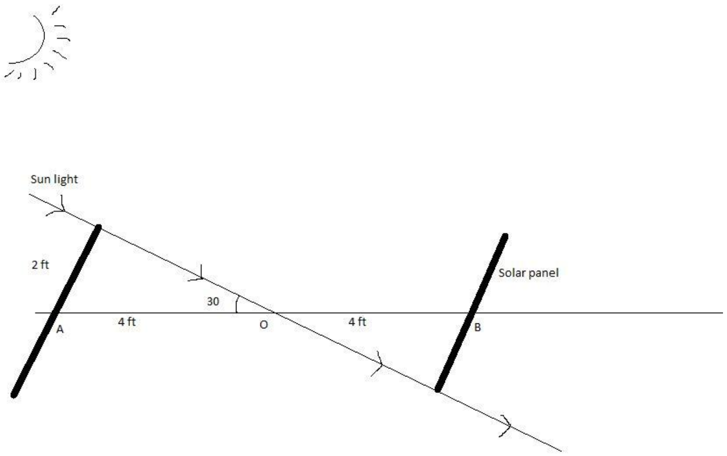


Figure 24: The geometric sketch of the space analysis

Structural Analysis:

As shown above in figure 15, the shaft will be welded with a solar panel at two points and the distances between each point are same, assuming the weight of each solar panel is 60-lbs, the maximum snow load is 127-lbs, and the maximum wind load is about 75-lbs, and self-weight of the steel bar is 10-lbs, the total load can be treated as the concentrated load of 272-lbs for each solar panel. The reactioin forces and shear moment diagram are provided below.

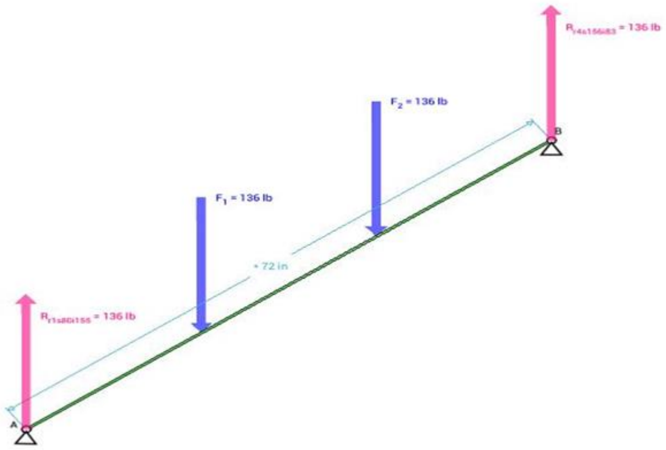


Figure 25: Free body diagram for shaft

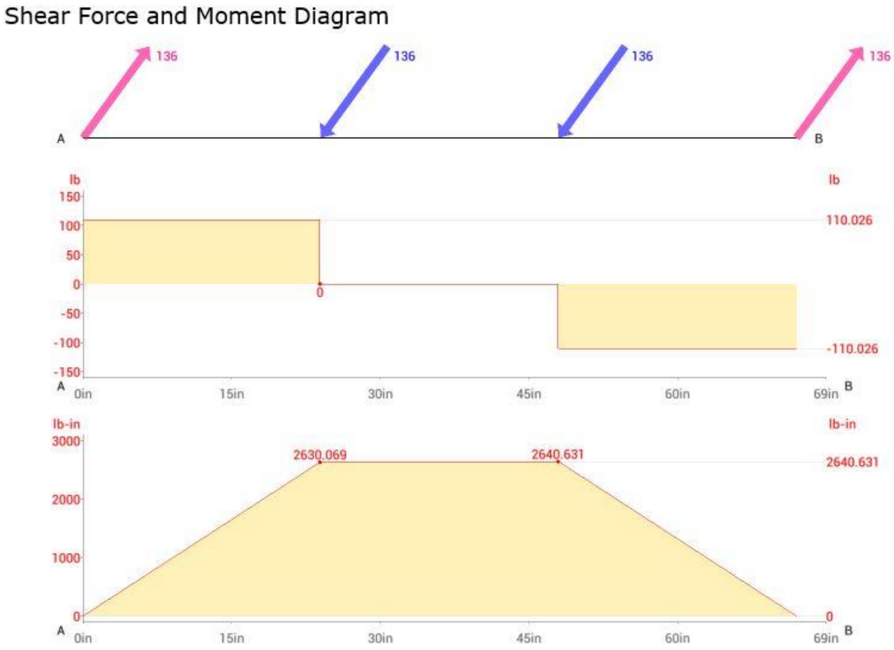


Figure 26: Moment diagram for the shaft

Based on the shear moment diagram above, the maximum moment occurred between the two supports, which is the most likely region of failure. The maximum shear force is 110 lbs. The diameter of the shaft is 2 in. The equation below is used to calculate the shear stress of the shaft:

$$\text{Shear Stress} = \frac{Forces}{Area}$$

Area=1/4*π*D^2

Raw data:

Maximum shear forces: 110 lb;

Maximum moment: 2640 lb-in;

Maximum shear stress: 35 lb/in^2

There are four shafts which will be connected and supported by two parallel beams. The distances between each shaft are equal. The free body diagram and shear moment diagram are provided below:

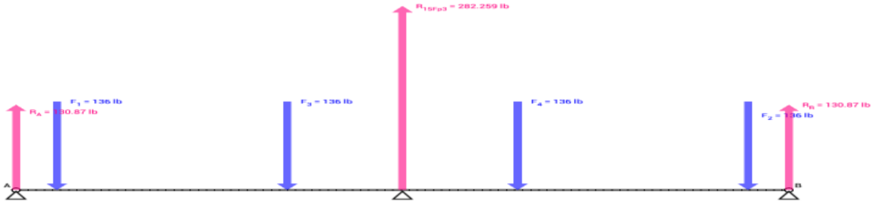


Figure 27: Free body diagram for beams

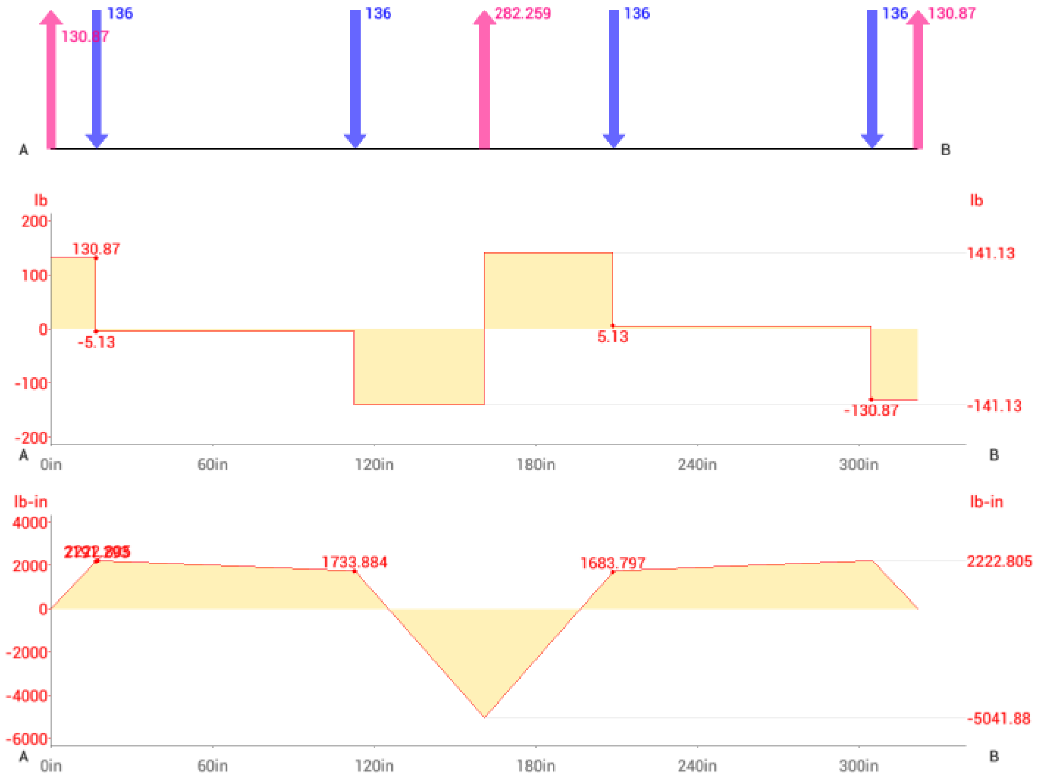


Figure 28: Shear moment diagram for the beam

Based on the shear moment diagram above, the maximum moment occurred at the mid-point of the beam between the two supports, which is the most likely region of failure. The maximum shear force is 116 lb on the beam made of 3”×3”×0.25” square hollow tube. The equations below are used to calculate the shear stress of the shaft:

$$\text{Shear Stress} = \frac{Forces}{Area}$$

Area=L^2-(L-2t)^2

$$A = L^2 - (L - 2 * t)^2$$

Raw data:

Maximum shear forces: 141 Ib;

Maximum moment: 5041 Ib-in;

Maximum shear stress: 51.273Ib/in^2

The shear moment diagrams indicate the possible failure point and region so that group can choose the appropriate material for the solar tracker to avoid fracture.

Torque

Assuming that the forces calculated above are used to drive a single shaft of 300lb, and the shaft diameter is 2 in, The Torque can be calculated by using the equation below:

$$\tau = Fc*D/2$$

Where:

τ: the torque required to drive the shaft for rotating solar panel.

Fc: forcing act on the shaft.

D: diameter of the shaft.

The Torque for a single shaft is calculated to be 300lb-in. Once the torque for a single shaft is known, the sum of the torque for 4 shafts is 1200lb-in. we can select the appropriate motor by using the equation below

$$T = (HP \times 5252 \times 8.851)/rpm$$

$$HP/rpm = 0.026$$

3.4 Tracking Angle Analysis

To understand the analysis we did for the tracking angles of our design some basic solar engineering concepts must be introduced. The first being beam radiation which is defined as the solar radiation received from the sun without having been scattered by the atmosphere, also referred to as direct radiation. [1] There are two parts of the total solar radiation that solar panels receive the first being beam radiation the second being diffuse radiation. Diffuse radiation is defined as the solar radiation received from the sun that is scattered by the atmosphere. For the purpose of our analysis however regarding angles of tracking for our solar panels all calculations are done with respect only to beam radiation due to the nature of diffuse radiation being a value that requires extensive modeling outside of what is necessary to get the tracking angles for a solar panel. The next important term is Irradiance, which is defined as the rate which radiant energy is incident on a surface per unit area of the surface. [1] This term is relevant to the irradiance angle which will be covered later. The last term to go over is the Solar time which is the time based on the apparent angular motion of the sun across the sky, with solar noon being the time that the sun crosses the meridian of the observer.

In sections 1.6 and 1.7 of the Solar Engineering of Thermal Processes book provided to our team by Dr. Acker the topic of “Direction of beam radiation” and “Angles for Tracking surfaces” the concepts required to analyze the angles of tracking for our designs is gone over. The goal of any solar tracking system is to minimize the angle of incidence of beam radiation and thus maximize the incident beam radiation on the surface of you tracking system which should increase the amount of energy collected by the tracking system. The book goes over methodology of analysis for North-South and East-West solar tracking in these sections as well. However, due to the location of Flagstaff not being in the Arctic Circle the variation of the sun in the North-South axis is very small our team has decided that all three designs should be fixed in North-South direction, the slope angle between the solar panel and the ground needs to be calculated to maximize the energy absorption. As shown in Figure ##, the slope angle (h) in North-South direction is related to the solar elevation angle.

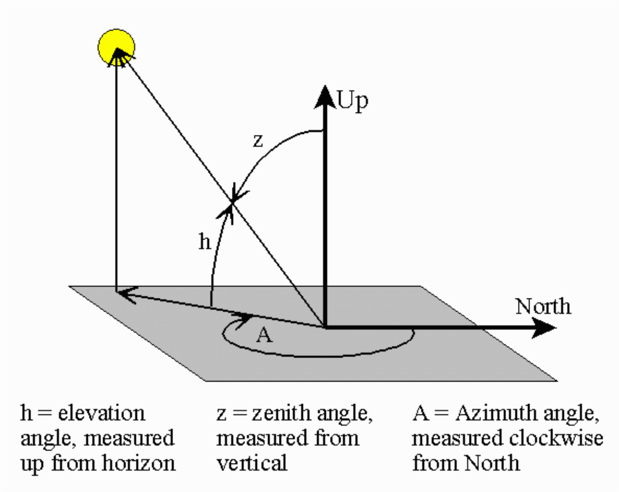


Figure 29: Solar Angle Diagram

The maximum solar elevation angle in Flagstaff occurs at 12:30pm on June 21 (Summer solstice), which is about 78 degrees above the ground. The minimum solar elevation angle in Flagstaff occurs at 12:27pm on December 21 (Winter solstice), which is about 31 degrees. Azimuth angles are 180° for both cases. The average of the maximum angle and the minimum angle is 54 degree, which is the average angle between the sunlight and the ground in North-South direction over a year. Therefore, the angle between the frame and the ground is 36 degree (without considering the shading), which is shown in Figure ##.

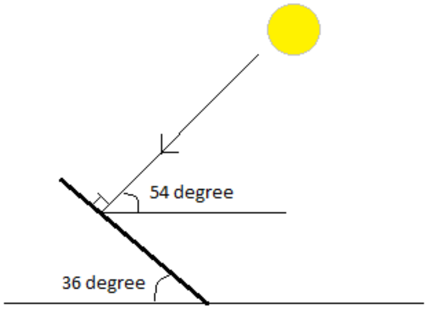


Figure 30: Angle between the Ground and the Solar Panel

So the main focus of our analysis relates to the angles required to accurately track the sun east-west with figures 24 and 25 below from the book you get an accurate picture of what angles are needed to properly analyze our tracking angles as well as what the variables mean.

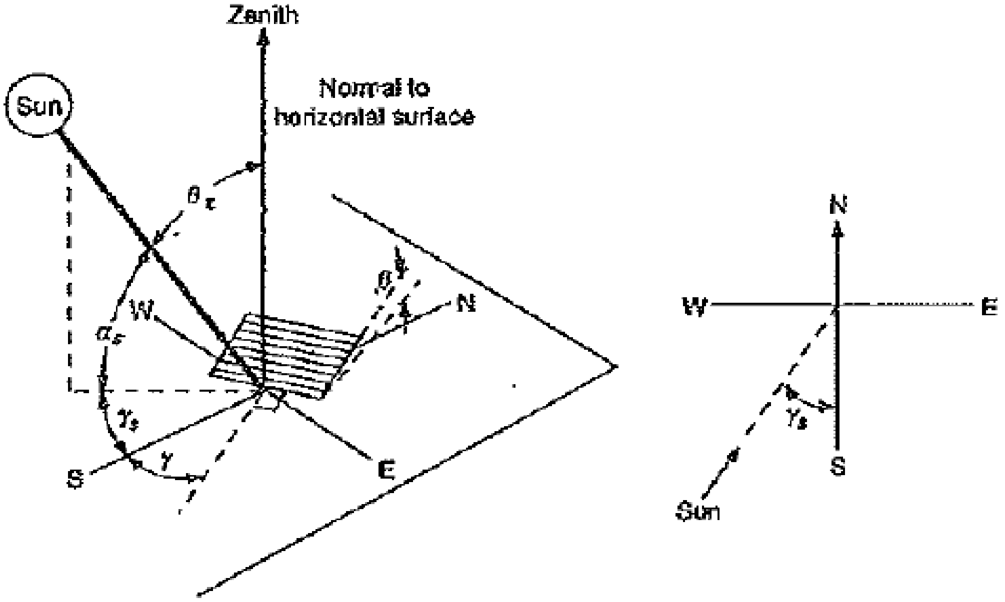
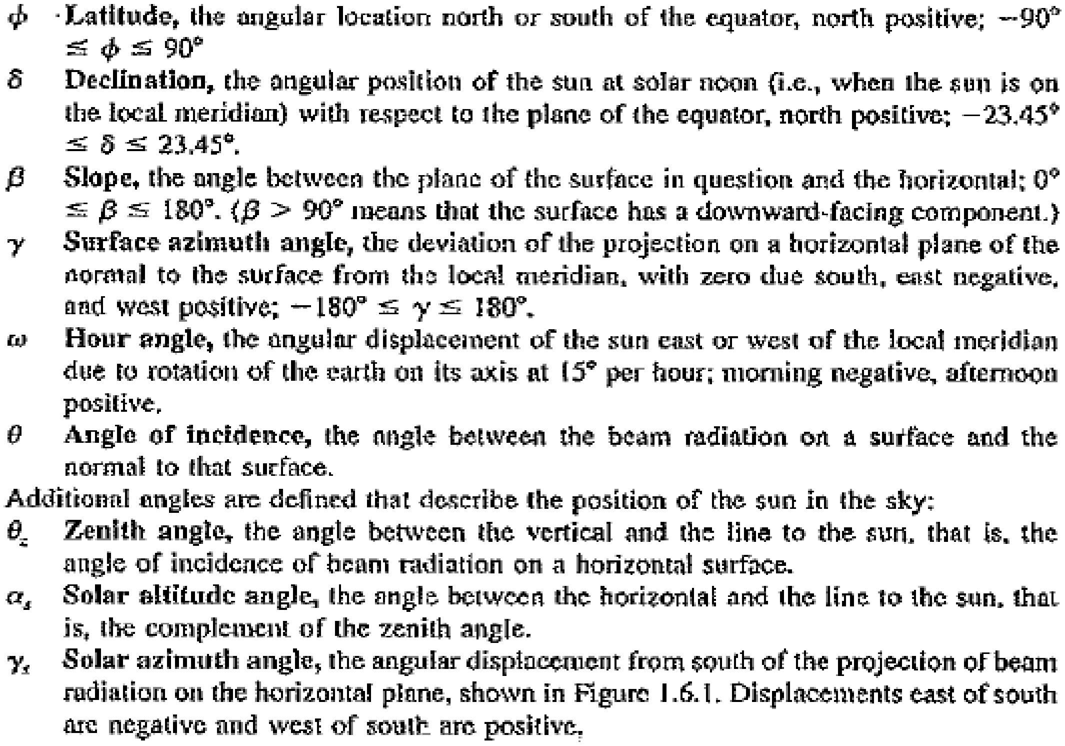


Figure 31: Important angles for analysis



ϕ	**Latitude,** the angular location north or south of the equator, north positive; $-90° \leq \phi \leq 90°$
δ	**Declination,** the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive; $-23.45° \leq \delta \leq 23.45°$.
β	**Slope,** the angle between the plane of the surface in question and the horizontal; $0° \leq \beta \leq 180°$. ($\beta > 90°$ means that the surface has a downward-facing component.)
γ	**Surface azimuth angle,** the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180° \leq \gamma \leq 180°$.
ω	**Hour angle,** the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.
θ	**Angle of incidence,** the angle between the beam radiation on a surface and the normal to that surface.

Additional angles are defined that describe the position of the sun in the sky:

θ_z	**Zenith angle,** the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.
α_s	**Solar altitude angle,** the angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.
γ_s	**Solar azimuth angle,** the angular displacement from south of the projection of beam radiation on the horizontal plane, shown in Figure 1.6.1. Displacements east of south are negative and west of south are positive.

Figure 32: Definitions of all variables required for analysis

Given that the latitude of Flagstaff is 35^{o} and that slope of our solar panels does not change based on no North-South axis tracking the most important angles for analysis are the Angle of incidence (Θ), the Zenith angle (Θ_z), and the Solar azimuth angle ($ϓ_s$). The incidence angle is important because it should be minimized to increase the amount of beam radiation that the solar panel absorbs. The Zenith angle is important because it is the angle that should be maximized to allow for the most absorption of beam radiation. Finally the azimuth angle is important because it relates to rotation of panel from east to west to track the sun.

The first things needed for solar angle tracking calculations are the Solar hour angles (w) in either the North-South axis or East-West axis. Since our design focuses on East-West tracking in the table below contains the corresponding solar hour angles. One thing to keep in mind though is that for this analysis per the books recommendation as seen figure xx (w) must be in increments of 5^{o} which means that the solar panel makes a tracking correction three times every solar hour.

Table 4: Solar Hour angle for east west tracking

Solar hour angle (w) in degrees	True solar time
-90	6 hours before solar noon
-75	5 hours before solar noon
-60	4 hours before solar noon
-45	3 hours before solar noon
-30	2 hours before solar noon
-15	1 hour before solar noon
0	Sun overhead (Solar Noon)
15	1 hour after solar noon
30	2 hours after solar noon
45	3 hours after solar noon
60	4 hours after solar noon
75	5 hours after solar noon
90	6 hours after solar noon

The first equation needed to analyze these angles relates to the day of the year that you wish to analyze the angles for.

$$B = (n - 1)\left(\frac{360}{365}\right) \quad eqn\ 1$$

Where:

n= day of the year 1-365

Once you have B you must calculate the angle of declination (δ) to be able to calculate the incidence angle, zenith angle, and the azimuth angle. The equation we used for calculating the declination is seen below

$$\delta = 23.45 sin\left[360\left(\frac{284 + n}{365}\right)\right] \quad eqn\ 2$$

Where:

n= day of the year 1-365

With the variable B and declination (δ) calculated you can then calculate the angle of incidence for a plane about a horizontal east-west axis with continuous adjustment using the equation below

$$\theta = cos^{-1}[1 - cos^2(\delta) sin^2(w)] \quad eqn\ 3$$

Where:

δ= the declination angle

w=sun hour angle from -90° to 90° in increments of 5°

After calculating the angle of incidence (Θ) to see if the device minimizes the angle of incidence between 90 and -90 degrees. The zenith angle should be calculated using this equation

$$\theta_Z = cos^{-1}[cos(\emptyset)\cos(\delta)\cos(w) + \sin(\emptyset)\sin(\delta)] \quad eqn\ 4$$

Where:

Ø= Latitude

δ= the declination angle

w=sun hour angle from -90^o to 90^o in increments of 5^o

Finally when rotating about the East-West axis it is necessary to know the azimuth angle to rotate the solar panel to properly track the sun which, can be done using the equation below

$$\gamma_s = sign(w)\left|cos^{-1}\left(\frac{\cos(\theta_z)\sin(\emptyset) - \sin(\delta)}{\sin(\theta_z)\cos(\emptyset)}\right)\right| \quad eqn\ 5$$

To effectively analyze the angle of incidence, zenith angle, and azimuth angle we wrote a Matlab code that calculates all of these angles for any day specified from 1-365. With the angles calculated for each day this will be useful for the eventual programming of sensor and tracking system to run on its own further down the line. To demonstrate how the program works we will display the data for the incidence angle, zenith angle, and azimuth angle for n=180 which is about half way through the year and about half way through the earth's rotation around the sun.

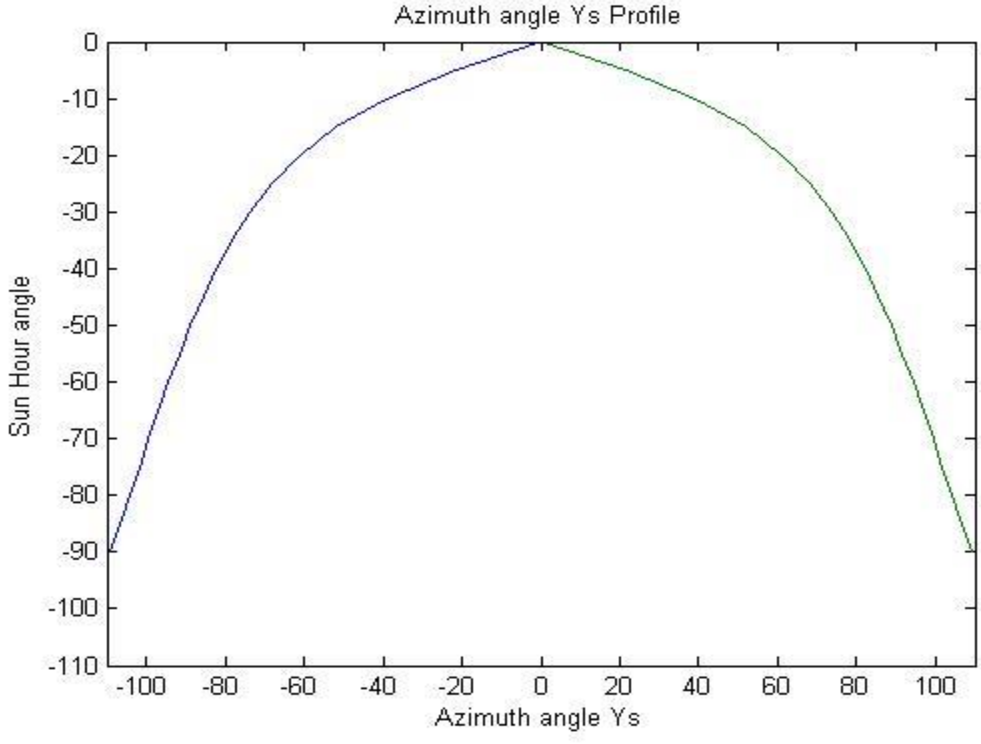


Figure 33: Azimuth angle profile for the 180th day of the year

What figure 24 shows is the angle that the solar panel will rotate from East-West during the 180th day of the year. This angle is most important to East-West tracking due to the fact that our solar panel will only be tracking in the East-West axis.

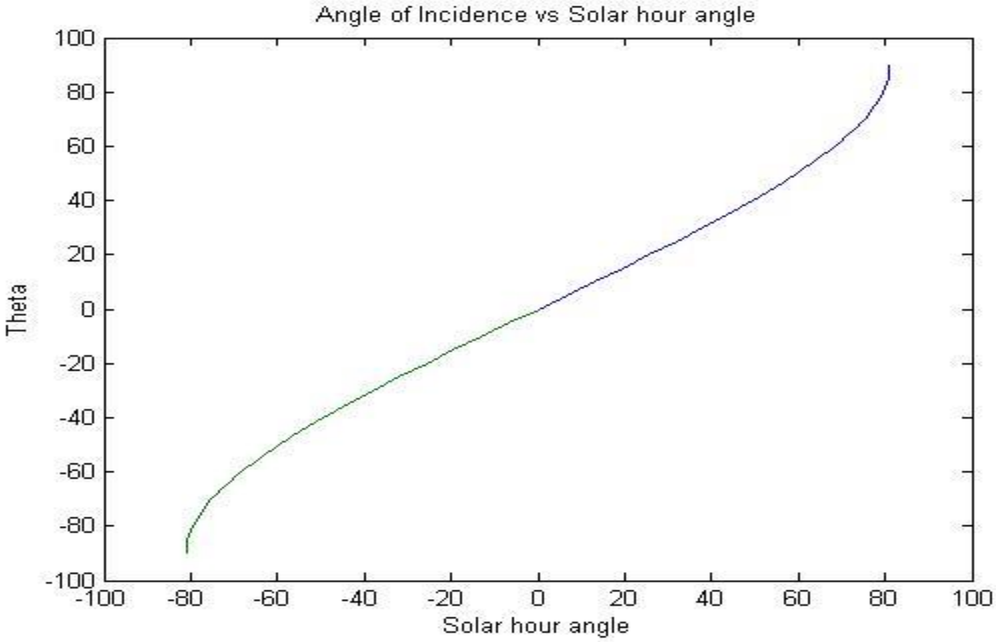


Figure 34: Angle of incidence for 180th day of the year

What this graph shows for the 180th day of the year is that the angle of incidence will be not exceed -90° or 90° which is necessary for the solar panel to receive the most beam radiation during the day.

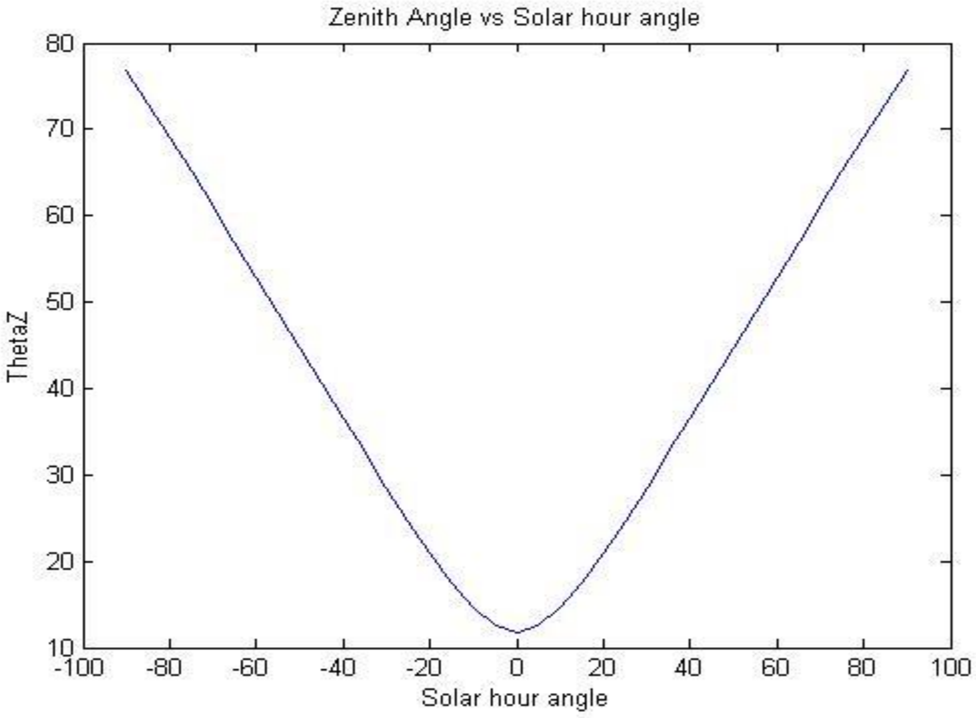


Figure 35: Zenith angle for the 180th day of the year

What this graph shows is the Zenith angle of panel which once again should not exceed 90° to ensure that the solar panel receives the most beam radiation absorption.

The Matlab program also calculates the available hours of sunlight for the day specified by using this equation where N=number of daylight hours in a day which comes out most of the time to 12 hours of sunlight per day.

$$N = \left(\frac{2}{15}\right) cos^{-1}[-\tan(\emptyset)\tan(\delta)]\ eqn\ 6$$

The last thing the Matlab program does is calculate the Geometric ratio (R_b) of a tilted solar panel to a horizontal solar panel using this equation which results in a number ranging from 0 to 2

$$R_b = \frac{\cos(\theta)}{cos(\theta_z)} \quad eqn\ 7$$

In conclusion for the solar angle tracking analysis the Matlab program, which is available in the appendix of this report, calculates the incidence angle, zenith angle, and azimuth angle based on the known variables for each day of the year from 1 to 365. The program itself only produces data for the day specified by the user. As the project nears completion this program will have to be changed to graph data for every day onto one graph but for this engineering analysis it is sufficient to only calculate the data based on the day of the year that you want to know about in question.

Final Concept Selection

Based upon the analysis of the hydraulic tracker, angled tracker, and solar array we made a decision what the final concept should be that we present to our client Dr. Acker. The final concept that we have chosen to present to Dr. Acker is the solar array design because it is able to hold more than one solar panel and has the best load distribution to the simple frame that the solar panels rest upon. We did not choose the hydraulic tracker because its power requirements and are too high and would require purchasing very expensive hydraulic units and a very expensive compressor to create the force necessary to lift the solar panel. We also did not choose the angled tracker because it only holds one solar panel which is less efficient then the solar array and the spacing of 4 of these units would not fit within the shacks area for the solar panels do to shading between the angled tracker units. However, after choosing the solar array we realized the solar array with 4 panels is also too large for the area up at the shack so we decided to cut the array in half leaving two solar panels and a distance of only 8 feet in between each panel to ensure that they would not shade each other. So after cutting the solar array in half we had to redo our analysis of the solar tracking based on there being only 2 solar panels instead of 4 solar panels.

Shading analysis:

The solar panels will be installed on the frame as shown in figure 16. To avoid the solar panel shading each other, the distance between two adjacent solar panels needs to be at least 8 ft. The calculation is shown below. Usually, solar panels absorb the sun light from 7:00 am to 6:00 pm. and the sun light has the incident angle about 30 degrees and the solar panels will always be perpendicular to the sun light. The minimum space of the solar panel L can be calculated with the following function:

$$L = \frac{0.5 \times a}{\sin 30} \times 2$$

Where:

L: the minimum space between solar panel;

a: short side length of the solar panel;

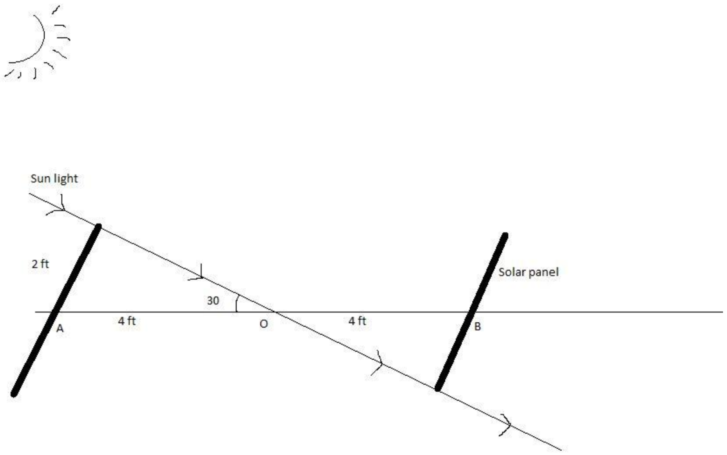


Figure 36: **The geometric sketch of shading by solar panel on single solar tracker**

Two solar trackers will be placed in parallel, as showing in Figure-xx, it is likely that the front solar tracker will shade the incidence sunlight. The follow steps are going to find the space to avoid shading. The team figured out that on December 21st, the solar elevation will reach the minimum value, about 30 degree, which will cause the maximum shading area. This situation are showing in figure below:

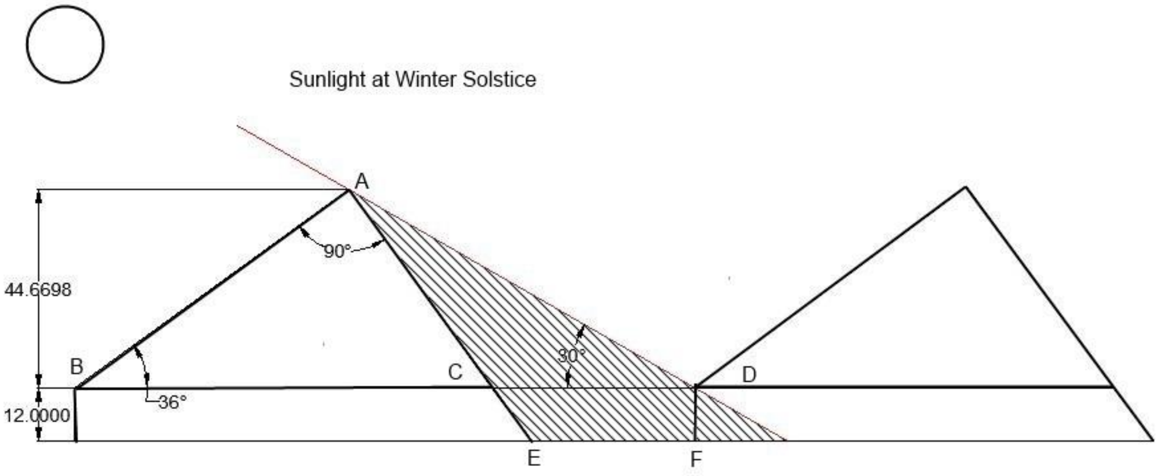


Figure 37: **The geometric sketch of shading by two solar trackers**

The segment EF is the minimum space between, according to our team calculation, two adjacent solar tracker must a little greater than segment EF that is equal to 37 inches, so that we will place two solar tracker with the space of 3.5 ft.

Structural Analysis:

As shown above in figure 15, the shaft will be welded with a solar panel at two points and the distances between each point are the same, assuming the weight of each solar panel is 60-lbs, the maximum snow load is 127-lbs, and the maximum wind load is about 75-lbs, and the weight of the steel bar is 10-lbs, the total load can be treated as the concentrated load of 272-lbs for each solar panel. The reactioin forces and shear moment diagram are provided below.

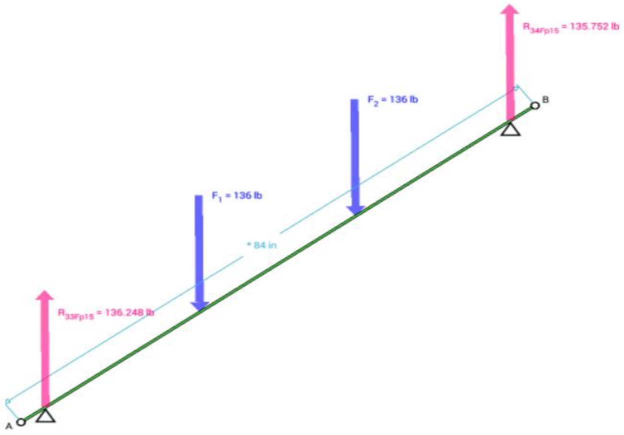


Figure 38: **Free body diagram for shaft**

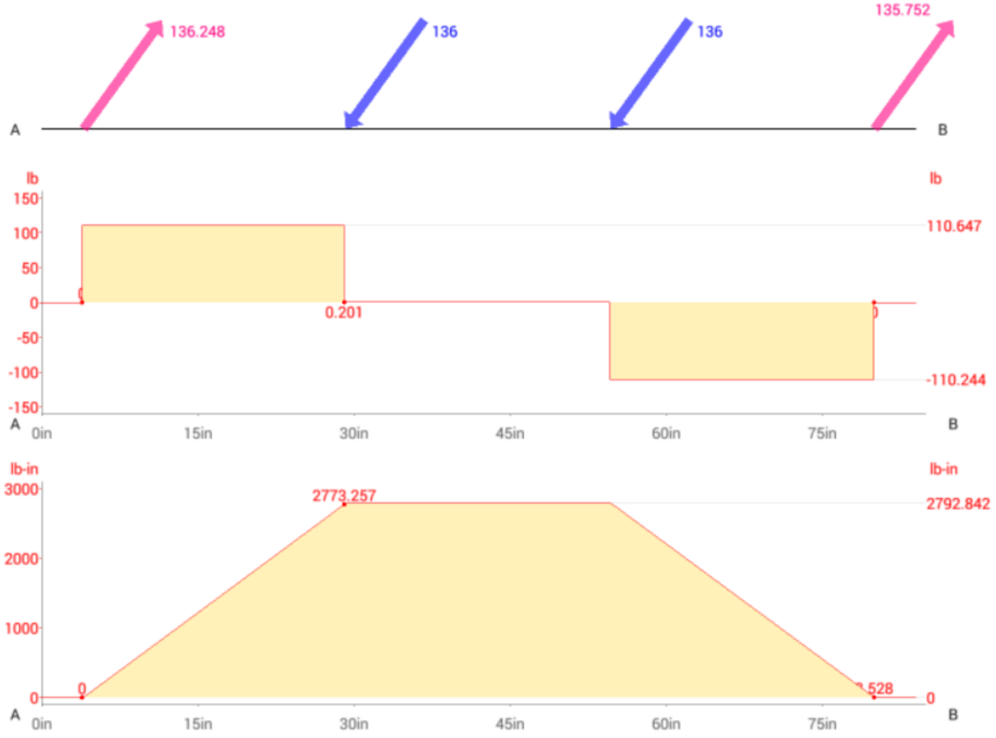


Figure 39: **Shear moment diagram for the shaft**

Based on the shear moment diagram above, the maximum moment occurred between the two supports, which is the most likely region of failure. The maximum shear force is 110 lbs. The diameter of the shaft is 2 in. The equation below is used to calculate the shear stress of the shaft:

$$\text{Shear Stress} = \frac{Forces}{Area}$$

$$Area = \frac{1}{4} \times \pi \times (D^2)$$

Raw data:

Maximum shear forces: 110 lb;

Maximum moment: 2773 lb-in;

Maximum shear stress: 35 lb/in^2

There are two shafts which will be connected and supported by two parallel beams. The free body diagram is provided below:

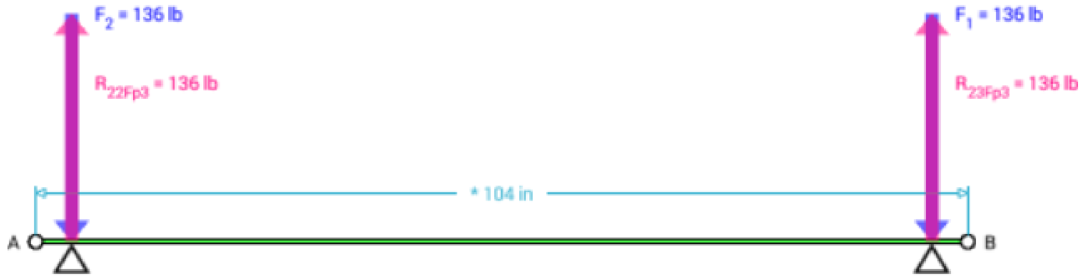


Figure 40: **Free body diagram for beams**

The free body diagram indicated that there is no shear force on this beam; in other words, Fracture will not occur due to moment created by shear force.

Torque

The shaft diameter is 2 in, the force acts on the shaft can be calculated by equation below:

$$Fc = \mu \times 0.5 \times W$$

$$\text{Fc} = 21.76 \text{ Ib}$$

The Torque can be calculated by using the equation below:

$$\tau = Fc \times \frac{D}{2}$$

$$\tau = 21.76 \text{lb-in}$$

Where:

W: the total load of each single solar panel.

μ=0.16: the friction factor

τ: the torque required to drive the shaft for rotating solar panel.

Fc: force act on the shaft.

D: diameter of the shaft.

The Torque for a single shaft is calculated to be 21.76lb-in. Once the torque for a single shaft is known, the sum of the torque for 2 shafts is 43.52lb-in. We can select the appropriate motor by using the equation below

$$\tau = \frac{(HP \times 5252 \times 8.851)}{rpm}$$

$$\frac{\mathrm{HP}}{\mathrm{rpm}} = 0.000936$$

Which is a NEMA 56C with a power ratio of ¾ HP and rpm of 1750.

Chapter 4: Cost Analysis

For our cost analysis we tried to look for the cheapest prices for the parts that we needed for our design. We also found the shipping cost for each of the parts based on the cheapest available shipping from each site which was usually UPS ground or US postal service ground. Our solar array design consists of 8 different parts that we needed. The first and most important being the 3”×3”×0.25” Square tubing of the frame of the design which is made out of structural steel and is available from bobco metals. The steel 2” shafts that the solar panels rest on are made of 1018 cold finished steel and are available at Bobco Metals as well. The aluminum flat sheet metal used for our casing is 12”×48” ×1//16” and is 3003 H4 aluminum which, is also available at Bobco Metals. Our DC motor was originally chosen off of Mcmaster however we found it cheaper at Omega so we will purchase it from there. The gears and chains were also originally chosen from Mcmaster but were found cheaper from ZOROTools and RollerChain4Less. The roller bearings for our design have a bore diameter of 2in and are available from BearingsOn.com. The bolts and waterproofing paint we will purchase from Home Depot to save money on shipping. We need the waterproof paint because our design is not made out of stainless steel so to ensure it does not rust the paint is necessary.

Table 5: Bill of Materials

Parts	**Company**	**Unit price**	**Amount**	**Total Cost**	**Shipping Cost (Ground)**
3”×3”×0.25” Square tube	Bobco Metals	73.29/8ft	64ft	$897.87	$420.11
2” Shaft	Bobco Metals	110.91/8ft	2	$221.82	$132.42
2 pillow block bearings	BearingsOn.com	29.98	4	$119.92	$9.00
Gears	ZOROTools	36.05	4	$144.20	$8.00
Chain	RollerChain4Less	184.65/10ft	2	$369.30	$83.26
DC Motor, NEMA 56C, 3/4 hp, 1750 rpm	Omega	318.00	1	$318.00	$8.00
Aluminum Flat sheet 12”×48” ×1//16”	Bobco Metals	21.21	4	$84.84	$20.27

Waterproofing Paint	Home Depot	114.98	5 gallons	$114.98	$0.00
Bolts	Home Depot	0.14	20	$2.80	$0.00
				$2270.98	**$681.06**

Manpower/Production cost

For manpower and production cost we have no cost associated with our design because we will building the array at NAU due to the fact that members of the team have experience welding. Joshua and Anthony both have some experience welding and Micah has taken a yearlong course that covers welding methods. So Micah would be the main welder on this job and would be able to provide assistance to both Anthony and Joshua to ensure that all the welds on the frame of the design were structurally sound. If however we had to source out the welding to someone else we would either have students at the machine on campus do it or get a cost estimate from Mayorga's Welding which is a local welding shop in here in Flagstaff. For production the team will be assembling the design with the help of the tools available at the machine shop on campus. This design is currently not being considered for production so we did not do any cost analysis on the payback period for this design.

Chapter 5: Conclusions

5.1 Problem description

Solar tracking systems are costly and could use improvements in energy efficiency. The solar panels are limited to the set angle they are placed at. This project should be energy efficient with low maintenance requirements. The solar tracking system should be operational even in any weather condition this is especially true for flagstaff snowy weather. The solar panel should be made within our budget, fit within the space provided and must be able to move the solar panels. The solar tracking device will track the movement of the sun such that it optimizes the efficiency of the solar panels and must be able to operate in varying weather conditions.

5.2 Concept Generation and Selection

Our group came up with seven different concepts for the design of the solar tracking system. Each concept ether used passive or active tracking systems. To decide which design concepts were the most appropriate our group created a decision matrix to evaluate the benefits of passive or active solar tracking units. Using this decision matrix it was found that an active system was the preferred method for our solar tracking unit. Another decision matrix was made for the design concepts. From that decision matrix we came up with three final designs that will be investigated in further detail in the engineering analysis portion of the report. These include the angled tracker, ball joint, and solar panel array.

5.3 Engineering Analysis

Each of the designs were analyzed based upon what would be the determining failure for each design. First, the team analyzed the Angled Tracker design. The team performed a structural analysis of the power, torque, and motor required to move the solar panels to effectively track the sun. The material was chosen then analysis of each design was calculated. Our group analyzed the Hydraulic Tracker. For this design, the team found the stresses at various locations throughout the design. The pushing force that is required to move the solar panel was calculated for the Hydraulic Tracker. Third, the last design, the Solar Panel Array design was analyzed for shading, structurally, and for tracking. The analyses for the three designs were all completed using a combination of hand calculations, Matlab programming, and using Excel spreadsheets.

5.4 Cost Analysis

Through the cost analysis of the design a table that held the bill of materials which listed what each part was, the company that produced it, unit price of each part and the amount required to build our design. Several of the companies that were originally investigated proved to be too expensive compared to leading competitor prices so the cheapest company was chosen. The method of shipping the material was found to be ether USP ground or US Postal Service ground. The cost of labor was not added to the final cost since it was assumed that most of the labor would be done by our group using equipment provided by Northern Arizona University.

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Appendix A

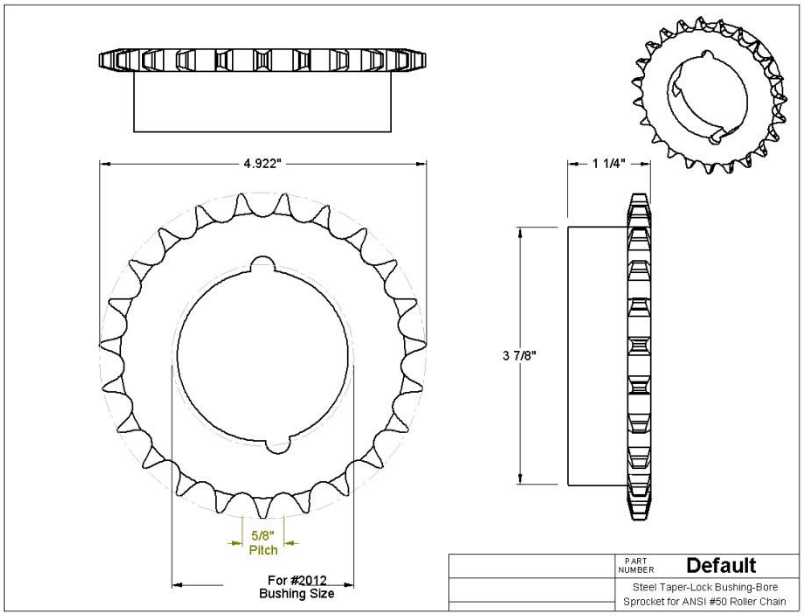


Figure 41: Gear dimensions

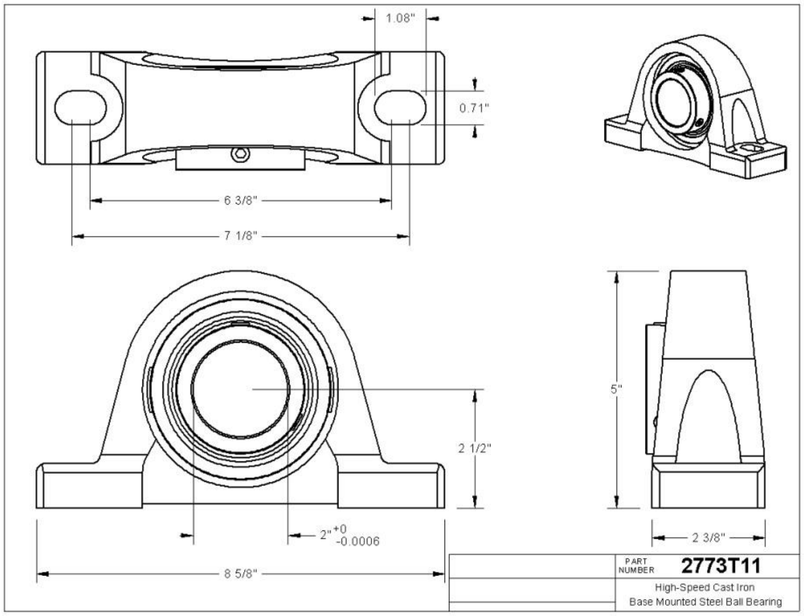


Figure 42: Bearing Dimensions

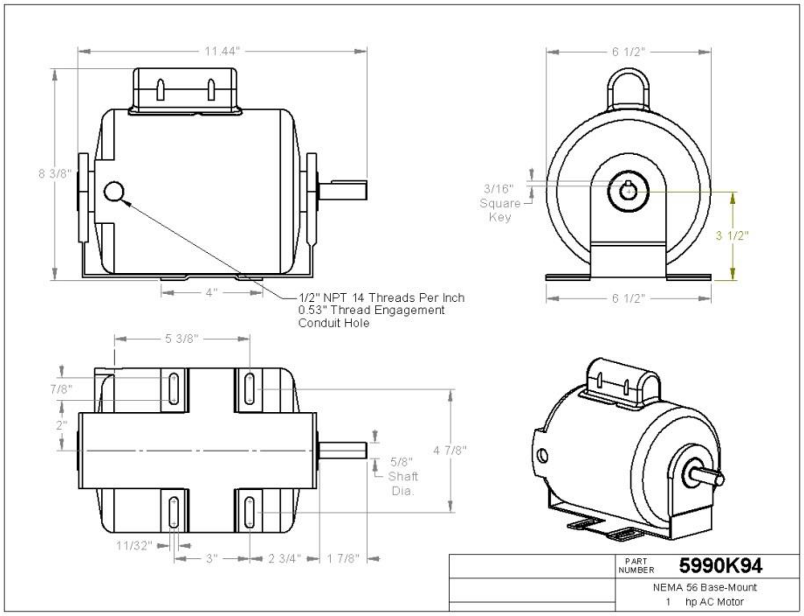


Figure 43: DC Motor, NEMA 56C, 90 VDC, 3/4 hp, 1750 rpm

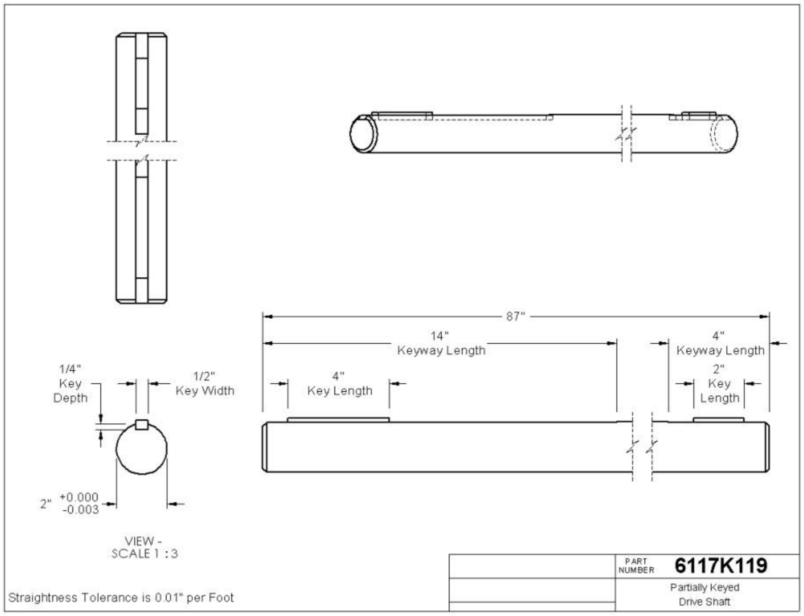


Figure 44: 2” shaft dimensions

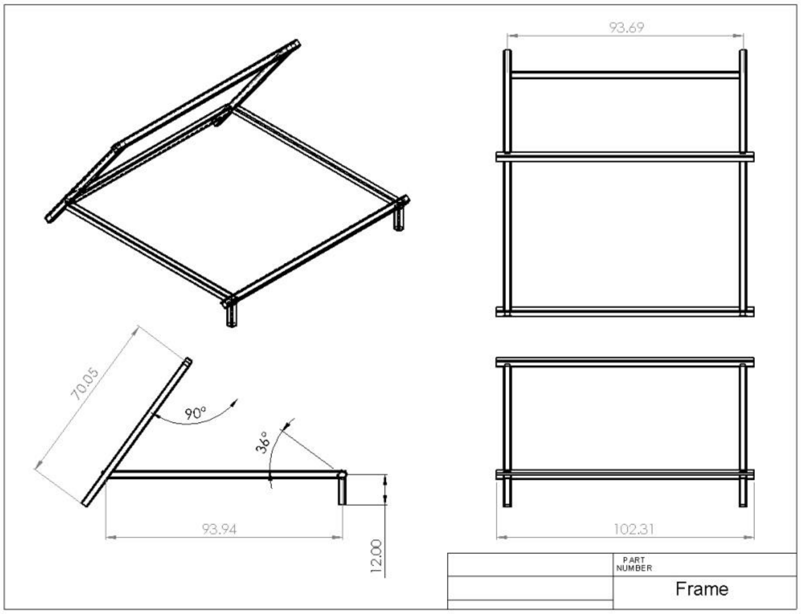


Figure 45: Frame dimensions

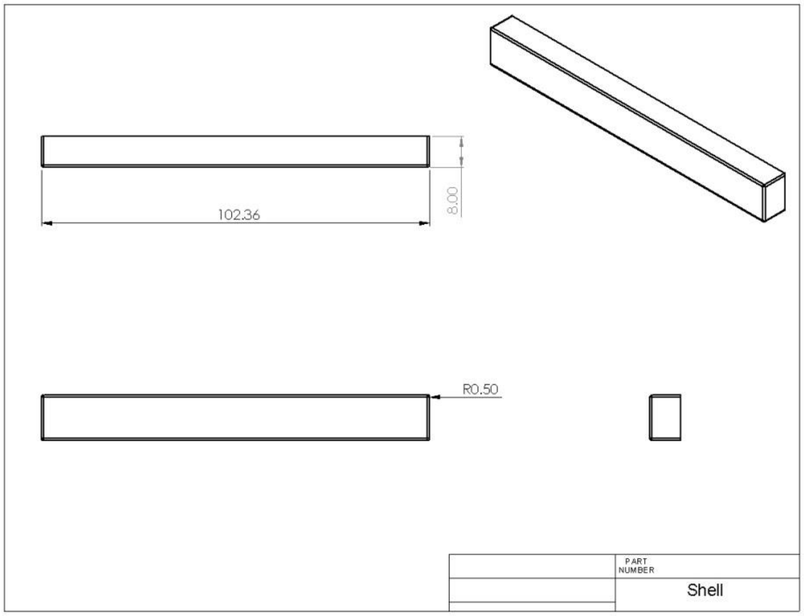


Figure 46: Case dimensions

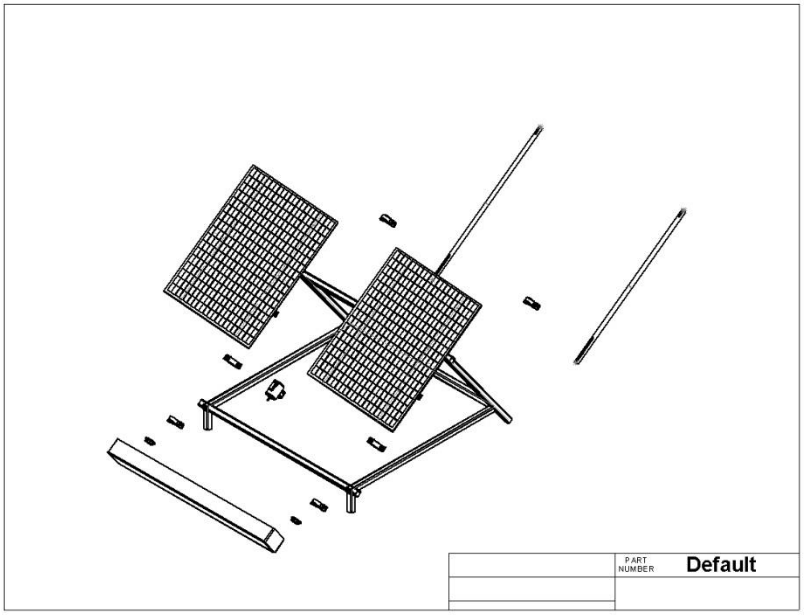


Figure 47: Exploded view of solar array system

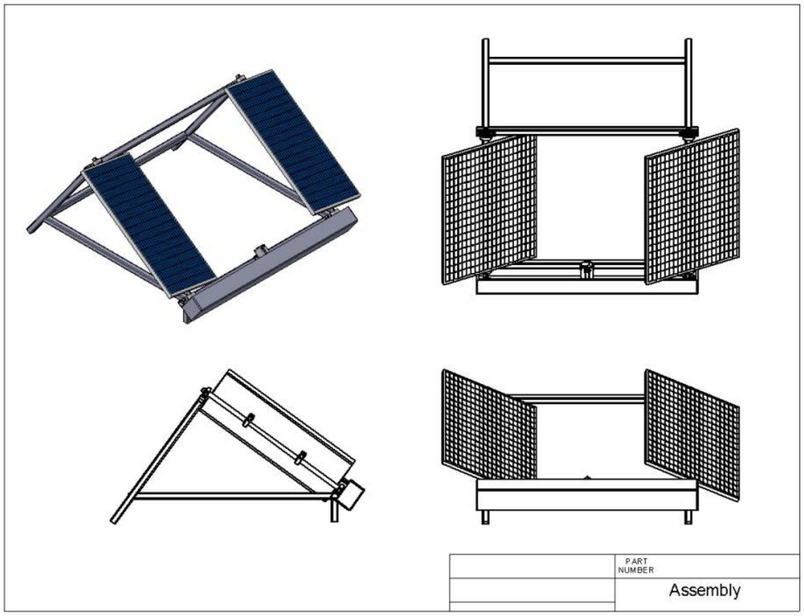


Figure 48: Isometric view of solar array system

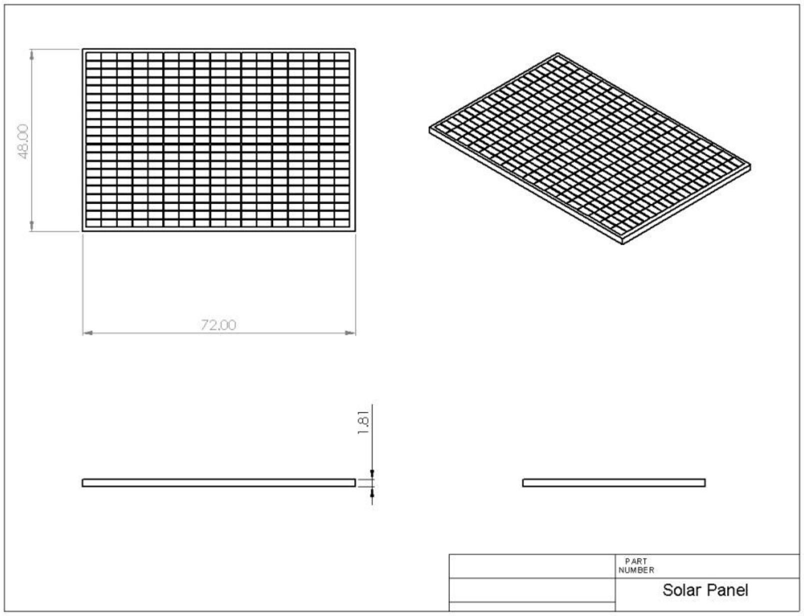
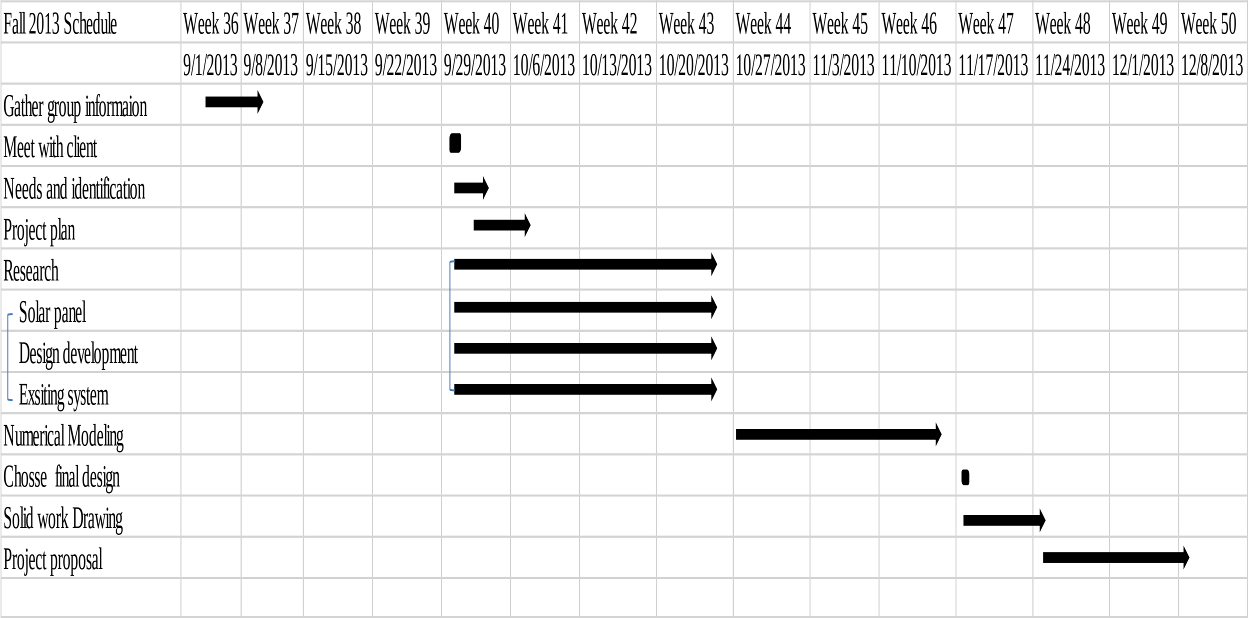


Figure 49: Solar panel dimensions

Appendix B

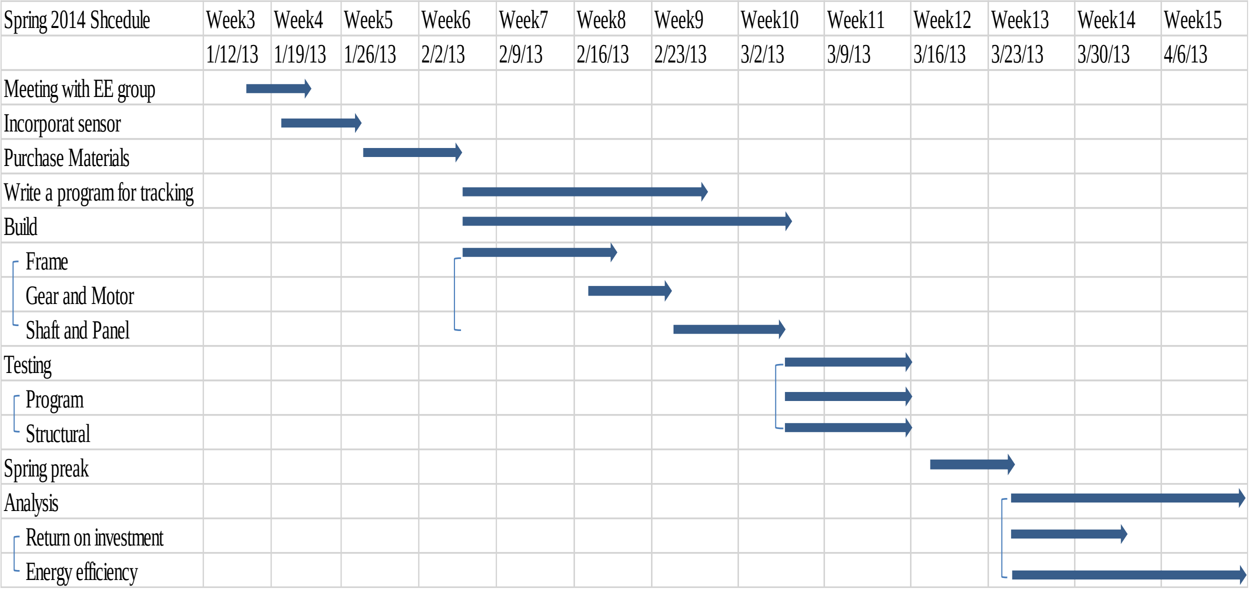
Fall Semster Schedule



The black arrows stand for completed activities

The team has closely followed the original timeline created in the beginning of the semster. The one change since our last update was which day our final propusal was due which was the 9th of December instead of the 2nd .

Spring Semster Schedule



The blue arrows stand for uncompleted activities

This gnatt chart is of the building,testing and analysis the solar tracking system for the 2014 Spring Semster. We will meet with the EE capstone group and finalize the sensor design within the first week. The building of the tracker and writing of the tracking program will be done simintanouely, and the group has slotted 19 days to complete the tasks. The testing of the tracking system while be over a week. During that time making only small adjustments to the program to track the sun. The group is taking a off for spring break and when we get back from break the group will to start the analysis on the return on investment and the increase of energy efficiency of the system. The plan is to end the building and testing by mid of April giving a nice cushion for the unknown tasks.

Appendix C

```
%This program calculates the angle required to minimize the anlge of
%incidence of beam radition and thus maximize the incident beam radition
%recived by our solar panels

%known information

Lat=35;             %Known latitude of Flagstaff Arizona
```

```
for i = input(' Desired day of the year 1-365: ');  %day of the year you wish
to recieve angles for
    if i>365
        display (' Please choose a number between 1-365 ')
    end
end

for n=i;                            %This for loop tells you what month the day
is you choose
    if n>=1 && n<=31;
        display January
    elseif n>31 && n<59;
        display February
    elseif n>59 && n<90;
        display March
    elseif n>90 && n<120;
        display April
    elseif n>120 && n<151;
        display May
    elseif n>151 && n<181;
        display June
    elseif n>181 && n<212;
        display July
    elseif n>212 && n<243;
        display August
    elseif n>243 && n<273;
        display September
    elseif n>273 && n<304;
        display October
    elseif n>304 && n<334;
        display November
    elseif n>334 && n<=365;
        display December
    end
end

B=(n-1)*(360/365);          %variable used in calculations
```

```
%the declination angle equation
Decl=23.45*sind((360*((284+n)/365)));

%Solar hour angle in incremens of 5 degrees
w=(-90:5:90);

%theta is the angle of incidence
Theta=acosd((1-((cosd(Decl).^2)*sind(w).^2)));

%Solar zenith angle incidence of beam radition on a horizontal surface
ThetaZ=acosd((cosd(Lat)*cosd(Decl)*cosd(w))+(sind(Lat)*sind(Decl)));

%solar azimuth angle Ys used to calculate the slope of the panel
Ys(1)=sign(w(1,1))*((acosd(((cosd(ThetaZ(1,1))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,1))*cosd(Lat)))));
Ys(2)=sign(w(1,2))*((acosd(((cosd(ThetaZ(1,2))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,2))*cosd(Lat)))));
Ys(3)=sign(w(1,3))*((acosd(((cosd(ThetaZ(1,3))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,3))*cosd(Lat)))));
Ys(4)=sign(w(1,4))*((acosd(((cosd(ThetaZ(1,4))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,4))*cosd(Lat)))));
Ys(5)=sign(w(1,5))*((acosd(((cosd(ThetaZ(1,5))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,5))*cosd(Lat)))));
Ys(6)=sign(w(1,6))*((acosd(((cosd(ThetaZ(1,6))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,6))*cosd(Lat)))));
Ys(7)=sign(w(1,7))*((acosd(((cosd(ThetaZ(1,7))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,7))*cosd(Lat)))));
Ys(8)=sign(w(1,8))*((acosd(((cosd(ThetaZ(1,8))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,8))*cosd(Lat)))));
Ys(9)=sign(w(1,9))*((acosd(((cosd(ThetaZ(1,9))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,9))*cosd(Lat)))));
Ys(10)=sign(w(1,10))*((acosd(((cosd(ThetaZ(1,10))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,10))*cosd(Lat)))));
Ys(11)=sign(w(1,11))*((acosd(((cosd(ThetaZ(1,11))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,11))*cosd(Lat)))));
Ys(12)=sign(w(1,12))*((acosd(((cosd(ThetaZ(1,12))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,12))*cosd(Lat)))));
```

```
Ys(13)=sign(w(1,13))*((acosd(((cosd(ThetaZ(1,13))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,13))*cosd(Lat)))));
Ys(14)=sign(w(1,14))*((acosd(((cosd(ThetaZ(1,14))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,14))*cosd(Lat)))));
Ys(15)=sign(w(1,15))*((acosd(((cosd(ThetaZ(1,15))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,15))*cosd(Lat)))));
Ys(16)=sign(w(1,16))*((acosd(((cosd(ThetaZ(1,16))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,16))*cosd(Lat)))));
Ys(17)=sign(w(1,17))*((acosd(((cosd(ThetaZ(1,17))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,17))*cosd(Lat)))));
Ys(18)=sign(w(1,18))*((acosd(((cosd(ThetaZ(1,18))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,18))*cosd(Lat)))));
Ys(19)=sign(w(1,19))*((acosd(((cosd(ThetaZ)*sind(Lat))-
sind(Decl))/(sind(ThetaZ)*cosd(Lat)))));
Ys(20)=sign(w(1,20))*((acosd(((cosd(ThetaZ(1,20))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,20))*cosd(Lat)))));
Ys(21)=sign(w(1,21))*((acosd(((cosd(ThetaZ(1,21))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,21))*cosd(Lat)))));
Ys(22)=sign(w(1,22))*((acosd(((cosd(ThetaZ(1,22))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,22))*cosd(Lat)))));
Ys(23)=sign(w(1,23))*((acosd(((cosd(ThetaZ(1,23))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,23))*cosd(Lat)))));
Ys(24)=sign(w(1,24))*((acosd(((cosd(ThetaZ(1,24))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,24))*cosd(Lat)))));
Ys(25)=sign(w(1,25))*((acosd(((cosd(ThetaZ(1,25))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,25))*cosd(Lat)))));
Ys(26)=sign(w(1,26))*((acosd(((cosd(ThetaZ(1,26))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,26))*cosd(Lat)))));
Ys(27)=sign(w(1,27))*((acosd(((cosd(ThetaZ(1,27))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,27))*cosd(Lat)))));
Ys(28)=sign(w(1,28))*((acosd(((cosd(ThetaZ(1,28))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,28))*cosd(Lat)))));
Ys(29)=sign(w(1,29))*((acosd(((cosd(ThetaZ(1,29))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,29))*cosd(Lat)))));
Ys(30)=sign(w(1,30))*((acosd(((cosd(ThetaZ(1,30))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,30))*cosd(Lat)))));
Ys(31)=sign(w(1,31))*((acosd(((cosd(ThetaZ(1,31))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,31))*cosd(Lat)))));
```

```
Ys(32)=sign(w(1,32))*((acosd(((cosd(ThetaZ(1,32))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,32))*cosd(Lat)))));
Ys(33)=sign(w(1,33))*((acosd(((cosd(ThetaZ(1,33))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,33))*cosd(Lat)))));
Ys(34)=sign(w(1,34))*((acosd(((cosd(ThetaZ(1,34))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,34))*cosd(Lat)))));
Ys(35)=sign(w(1,35))*((acosd(((cosd(ThetaZ(1,35))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,35))*cosd(Lat)))));
Ys(36)=sign(w(1,36))*((acosd(((cosd(ThetaZ(1,36))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,36))*cosd(Lat)))));
Ys(37)=sign(w(1,37))*((acosd(((cosd(ThetaZ(1,37))*sind(Lat))-
sind(Decl))/(sind(ThetaZ(1,37))*cosd(Lat)))));



%slope angle of the solar panel since we are not doing North South axis
%tracking
slope=36;

%The number of daylight hours for the day specfied are
Daylight=((2/15)*acosd(-tand(Lat)*tand(Decl)));

Ysneg=Ys(1:1:19);

Yspos=fliplr(Ys(19:1:37));

figure;
plot(Ys,w,Ys,-w)
axis([-110,110,-110,0])
title('Azimuth angle Ys Profile')
xlabel('Azimuth angle Ys')
ylabel('Sun Hour angle')

Thetaneg=(Theta(1:19)*-1);

Thetapos=(Theta(19:37));

figure;
```

```
plot(Thetapos,0:5:90,Thetaneg,-90:5:0)
title('Angle of Incidence vs Solar hour angle')
xlabel('Solar hour angle')
ylabel('Theta')

figure;
plot(w,ThetaZ)
title('Zenith Angle vs Solar hour angle')
xlabel('Solar hour angle')
ylabel('ThetaZ')

%Ratio of beam radition on a tilted surface to that on a horizontal surface
Rb=cosd(Theta)/cosd(ThetaZ);
```