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Design and Fabrication of Low Cost Dual Axis Solar Tracker Mechanical Structure

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Abstract

Global warming had been a serious issue these recent years, the use of alternative energy sources such as solar energy are being more important. To make it more feasible, the efficiency of solar modules must increase. Sun tracking system is one of the methods to increase efficiency. In this paper, design and fabrication of a low cost Dual Axis Solar Tracker (DAST) is proposed. The DAST and control system that control the movement of solar panel to ensure it is always perpendicular to the sun are discussed. The DAST system is a hardware and software system that automat-ically tracks the sun's location during the day. For optimum performance, make sure it's in the best possible position with the sun. When compared to a static solar panel, DAST has been found to provide 16 percent more power output. The low cost me-chanical structure has been fabricated and stress analysis had been performed. Rota-tion axis is control by stepper motor with pulley and belt, while the elevation is control by a linear actuator. It is proved that the low cost mechanical structure design can be used for automatic tracking system along with electronic design..

Keywords: Solar energy, tracking system, dual axis, mechanical structure.

1. Introduction

The energy crisis has reached extraordinary level due to increase in population and the significant increase in industrialization. The main energy sources comes from fossil fuels, since 1850’s 135 billion tons of oil is utilized for power station, houses and also automobile[1]. The renewable energy sources are the best possible solution is minimize the use of non-renewable energy resources such as coal, petroleum and etc. One of the eternal renewable energy resources available on earth is the solar radiation from the Sun. The energy in the form of heat and light and it is transmitted through the universe and only partially reached earth. Under optimal condition earth can receive only 1 kilowatt of power per meter square[2]. However the exact value depends on the intensity of the rays on location, season, day time and also weather conditions.

Solar panels use the sunlight as the input and convert it to electrical energy. However, the energy output of the static solar panel is low. In order to increase the efficiency of the solar panel, one and two axis solar tracker are introduced. One axis solar tracking simply means it will follow the sun throughout the day in one axis. The sunlight might not always face perpendicular to the solar cell, but its efficiency is higher than static solar panel. The dual axis solar tracker tracks the sun in two axis (Azimuth and Altitude) and the mechanical structure of the system will ensure that panel is always perpendicular to the sun to achieve high efficiency. There is few type of tracking method, for example the most basic method is by using light depending resistor (LDR) sensor. Another tracking method is by using solar radiation sensor also known as pyrometer. This method is less popular, a pyrometer is a type of acidometer that measure solar radiation flux density and solar irradiance and [5].

The other commonly used method is by using astronomical equation. This is done by calculating the sun position for the whole year then creates a solar path trajectory database by utilizing the information of Global Positioning System (GPS) sensor module. The whole control system is an open loop system [6].In this work, Sidek et.al [6] had used digital compass sensor and global positioning system (GPS) to determine the location of the sun. The algorithm designed with the principle of astronomical equation and integrated it with proportional integral derivative (PID) controller to enhance the accuracy of PV position. They carried out an experiment for static solar system and a dual axis tracking solar system. They concluded that dual axis solar tracking is a needed for efficient solar power generation systems. Alexandru et.al [7] had discussed the efficiency between one axis and dual axis solar tracking. In this paper, single tracking system calculates the position of the sun by few seasons whereas the dual axis tracking system is calculated for a year based on a calculation. The experiment is carried out with various type of weather; of course most of the results are assured in a sunny day.

Tarlochan et.al [8] described the development of prototype dual axis solar tracker and single tilt solar tracker. They detect the sun by using LDR sensor so that the sun will always give maximum sunlight to the panel to capture the ray at maximum. However 25º is selected to be the most suitable angle for the sensor design. Sensors are placed at the slanted surface of the sensor unit evenly. When sun 's position is at the centre of the solar panel each LDR will receive the same amount of light intensity, in this way it ensured the solar panel is always perpendicular to the sun. From the result, the efficiency from the tilted single axis and dual axis solar tracker are 30% and 40% respectively[8]. T. Kaur, S.Mahanjanet. al [9] used LDR sensor to track the sun position and it is also have dual axis movement. Results shows that dual axis efficiency is higher than static solar PV system by 13.44% in term of power generation[9].Falah Mustafa et. al [10] had integrated LDR sensor tracking method by means of a pyramid structure with circles around them. By observing at the shadow drop on the circle, it can easily detect the level of error of the tracking systems [10].

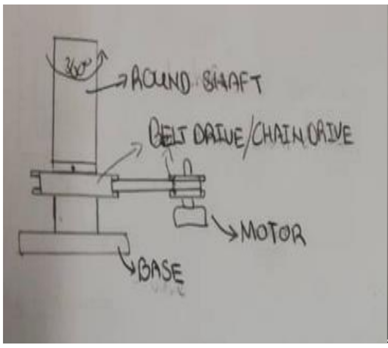
Ivan Jorge et.al [11] had designed the LDR sensor with four LDRs placed with equal spacing and separated by an extrusion cross section of 90º. The shade on the LDR sensor will trigger the microcontroller identify the error differences and will trigger the motor to move to the position where four sensor receive the light intensity [11]. Mustafah et. al [12] and Nallathambi et. al [13] had designed the Dual-Axis solar tracking system with Electromechanical Structure. The structure of dual axis solar tracker with the use of motor and chain for the North to South and East to West axis with counter weight placement [14].Wind speed is calculated from[15].

It is clear from the literature review that the dual axis solar tracker is proved to much more successful than the single axis and other models of solar tracker. In paper, the design of simple low cost dual axis solar tracker is discussed. The paper is organized as follows. The detailed methodology is explained in section 2. The results and discussions are covered in section3. The paper ends with section 4 conclusion and recommendation.

2. Material Selection and Product Design

2.1 Design Ideas

The first dual axis solar tracker design idea using belt drive or chain drive system to generate a 360-degree movement is shown in Figure-1. The shaft needs to be welded to the supporting frame on top of it. However, the belt drive system is driven by a stepper motor or dc motor. The second idea is shown in Figure-2. It is basically using linear actuator instead of motor to create an axis of movement. Therefore by using linear actuator instead of rotating 360 degree, is just pushing the panel to left and right (North and South) or up and down (East and West).The third design idea is shown in Figure-3. This is controlling the movement of east and west using v-belt drive or chain drive system. As shown in figure there will be a U-shape support being design and there is a shaft connected through the U-shape support. At the centre of the shaft there is sprocket or gear being installed and it is driven by stepper motor or dc motor.



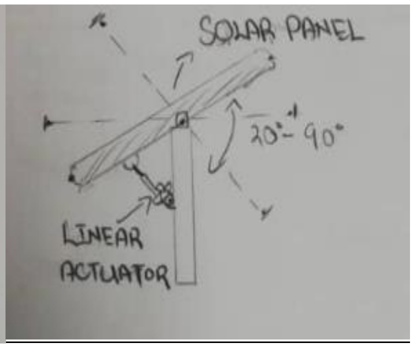


Figure-1: Design Idea 1 **Figure-2:** Design Idea 2

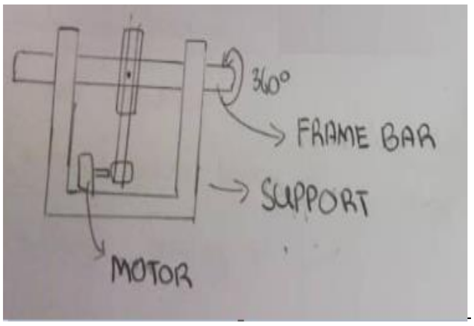


Figure-3: Design Idea 3

By comparing the required axis along with alternative design idea 1, 2, and 3 and selected the one that is more suitable for this work. Table-1 shows the comparison between North-South movements with alternative designs and Table-2 shows comparison between East-West movements with alternative designs. Rating is given from 1 to 5, very poor, poor, moderate, good and very good respectively.

Table-1: Comparison between North-South Movements with Design Models

Criteria	**Weightage (%)**	**Design 1**	**Score**	**Design 2**	**Score**
Flexibility	10	Good	**5**	Good	**5**
Accuracy	20	Good	**5**	Good	**5**
Cost	30	High	**4**	High	**3**
Complexity	40	Moderate	**4**	High	**3**
Total	100	-	**18**	-	**16**

Table-2: Comparison between East-West Movements with Design Models

Criteria	**Weightage (%)**	**Design 3**	**Score**	**Design 2**	**Score**
Flexibility	10	Good	**5**	Good	**5**
Accuracy	20	Good	**5**	Good	**5**
Cost	30	High	**4**	High	**3**
Complexity	40	High	**2**	Moderate	**4**
Total	100	-	**16**	-	**17**

As seen in Table-1 and Table-2, the four criteria will amused us to select the best method for each axis of tracking. The criteria being concern are flexibility, accuracy, cost and complexity which they contain had the weightage of 10%, 20%, 30%, and 40%. Total up the weightage are 100%. Complexity is the main concern at this point, followed up by cost, accuracy and flexibility. For North-South axis movements, design 1 and design 2 scored the same score in term of flexibility and accuracy. However, design 2 scored lower than design 1 in both cost and complexity, resulting in a score of 18 for design and 16 for design 2. From this design 1 is definitely better and it is used for North-South axis. In addition for East-West axis movements, design also scored the same in term of flexibility and accuracy. But in term of complexity design 3 being more complicated than design 2. Therefore design 3 score is lower than design 2 resulting in 16 for design 3 and 17 for design 2. For East-West axis, design 2 will be the choice of selected design idea.

2.2 Product Design

Full assembly of the mechanical and dual axis solar tracker is shown in Figure-4.

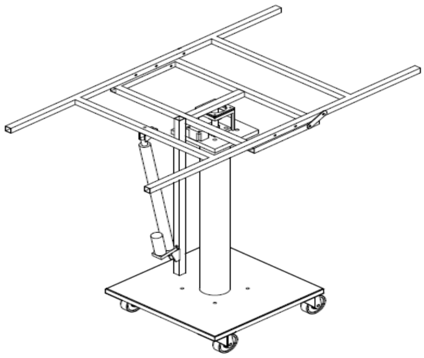


Figure-4: Complete Structure of the Dual Axis Solar Tracker

The first section is construction of the frame and the material to be used for the frame. The solar panel weight is 20kg and the dimension is 1250x808x35 mm. By using equation (1) Newton 2nd Law of Motion [14]the force produced by the solar panel is calculated.

$$F = ma = mg \qquad (1)$$

Where m is equal to the mass of the solar panel and g is the gravitational forces.

After the force calculation the stress is calculated and applied on the frame by using the stress equation (2) [14], whereas F is the force due to the solar panel and A is the area of the contact surfaces. In this case the panel will be placed horizontally across the frame due the availability of hole on the solar panel, which the area is 65 x 80 mm.

$$\sigma = \frac{F}{A} \qquad (2)$$

As a result, the stress applied on the frame is 377 N/m^2, therefore the material of the frame should have the availability to handle the stress more than this amount of stress. However, the frame is separate to two different parts, the aluminum frame will be responsible for holding the panel and allowing it to be elevate (East-West) while the other frame will be responsible for the rotating axis (North-South). Table-3 shows the comparison of different material.

Table 3: Comparison of Aluminum and Steel

Criteria	**Weightage (%)**	**Aluminium 6061**	**Score**	**Steel**	**Score**
Availability	10	Local	**5**	Local	**5**
Density (kg/m^3)	40	2.7	**5**	7.85	**3**
Price/kg	10	8.68	**3**	4.65	**4**
Ultimate Stress (MPA)	40	310	**5**	590	**5**
Total	100	-	**18**	-	**17**

As the frame that is responsible for the elevation (East-West), the main concern is that it must be able to handle the stress and the weight of the frame. It must be as light as much as possible to reduce the amount of torque produced to the rotating shaft. From the Table-3 aluminum had scored the 18 points out of 20 while steel scored 17 out of 20. Therefore aluminum would definitely be the material for the frame. However for the frame that responsible for the rotating axis will use steel as the material because there would be a shaft needed to be welded at the center of it. The CAD drawing of panel holding frame and rotating frame is shown in Figure-5 and Figure-6.

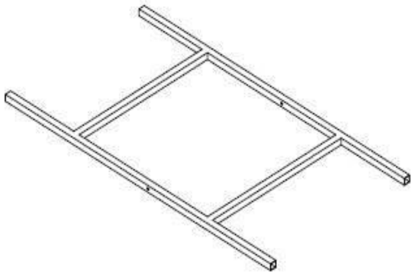


Figure-5: CAD Drawing for Solar Panel Holding Frame

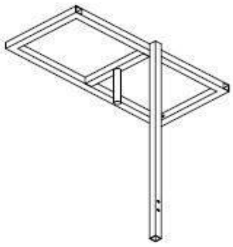


Figure-6: CAD Drawing for Rotating Frame

Furthermore, to calculate the required diameter of the shaft to be used for the rotational movement, Euler buckling theory is applied. Where P is total force from the frames, N is safety factor (N=2), E is Young Modulus of the material, and l is equal to L_e which is 0.65L for fixed-fixed end[14]. By substituting all the value in, the required diameter is 4.65mm. As result, a shaft diameter with the length of 200mm and diameter greater of 4mm is required.

$$\frac{Pcr}{A} = \frac{C*\pi*E}{(l/k^2)} \quad (3)$$

$$Pcr = N*P \quad (4)$$

$$A = \frac{\pi*d^2}{4} \quad (5)$$

$$k = \sqrt{\frac{I}{A}} \quad (6)$$

$$I = \frac{\pi d^4}{64} \quad (7)$$

$$d = \left(\frac{64*Pcr*l^2}{\pi*c*E}\right)^{\frac{1}{4}} \quad (8)$$

Since this structure will be placed outdoor, it must be able to withstand the element of nature's such sun (heat), rain (water) and wind (air). The most critical part is wind force acting to the structures. Base on records the great wind occurs in Melaka area is 13.6 miles/hour [15]. Assuming the wind flow is acting perpendicularly upon the maximum area of the solar panels, the wind load is calculated using the generic formula [15]as follows:

$$F = A*P*Cd \quad (9)$$

$$P = (0.00256)*v^2 \quad (10)$$

A = Projected Area

P = Wind Pressure

Cd =Drag Coefficient

A is the area of the solar panel and Cd for flat plate is 2. Substituting the values in equation, the force by the wind at maximum is 96.72N which means the supporting base (bottom structure) must have a static force more than that. Next is the bottom part of the solar tracker, the priority criterion to be concern is stability, the bottom structure must be strong enough to sustain the weight from the top part and also to withstand wind force. It must also be simple to assemble, such as joining the individual parts together. The material relation for the bottom structure is shown in Table-4.

Table-3: Material Comparison for Bottom Structure

Criteria	**Weightage (%)**	**Aluminium**	**Score**	**Steel**	**Score**
Flexibility to design	30	Could not be welded	**2**	Can be welded	**5**
Density (kg/m^3)	30	2.7	**2**	7.85	**5**
Price/kg	20	8.68	**2**	4.65	**4**
Ultimate Stress (MPA)	20	310	**3**	590	**4**
Total	100	-	**9**	-	**18**

Table-4 shows the material comparison of the bottom structure of the solar tracker. In this case, the weight can help to improve stability of the structure. The heavier the weight the greater the force to withstand the wind force, so in term of density steel scored much more higher than aluminum. Besides a solid aluminum is much more expensive than steel, this is another factor that steel scored higher than aluminum. In the end steel scored 18 and aluminum only scored 9 at this point, so steel is used for bottom structure. The CAD drawing for the bottom part of the tracker is shown in Figure-7.

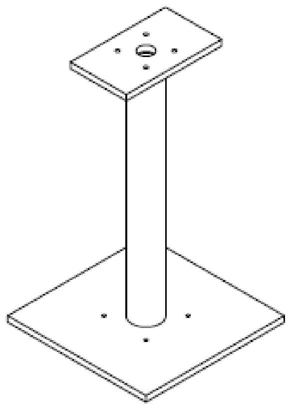


Figure-7: CAD drawing for Bottom Structure

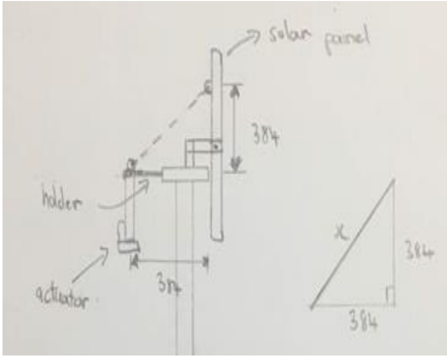


Figure-8: Calculation for Linear Actuator Strok

Furthermore, after selecting material for the structure the next thing to be concern is the force required to rotate and also to elevate the frames. Firstly, linear actuator is being used for East-West Axis as the result from previous idea generation part. In order to calculate the force required to elevates or push the frame in East-West axis, using equation (1) that the force require to push the frame is calculated. Furthermore, the require length to move the frame from 0 degree to 90 degree is need to be calculated. Using Pythagorean Theorem [14] get the require length of stroke by setting the horizontal and vertical length. Figure-8 shows the setting position the linear actuator. Using equation (3) the required length from 0 to 90 degree is calculated as 543mm. In addition, linkage simulator is also being use to simulate the result of the linear actuator movement as shown in Figure-9. Therefore a linear actuator with pushing force greater than 200N and stroke length around 543mm will be selected

$A^2 + B^2 = C^2$ (11)

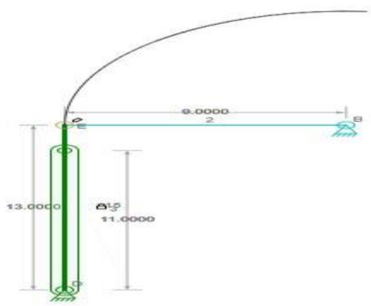


Figure-9: Linkage Simulator for Linear Actuator

Before calculating the torque, the very first step to start with is by eliminating the friction as much as possible. In this project the best way to do it is by using bearing. A thrust bearing will be placed at the bottom of the shaft while on top of the thrust bearing there would be a square flange bearing installed on in to reduce the weight and friction. On the other hand, a turn table will be introduced for additional support. This support structure will help to increase the contact surface (improve stability) and dividing the force acting on it. For the torque required to rotate the frame, the following equation (12) and (13) are used [14].

$T = F\ x\ r$ (12)

$F = m * g * c * f$ (13)

Where

T= Torque

r = Radius of gear/sprocket

m = Mass

g = Gravitational force

c = friction of bearing

f = surface friction

The friction for the bearing coefficient (c) is 0.001 for cylindrical bearing and for the surface friction coefficient (f) is 0.42 for steel to steel surfaces. As result the required torque to rotate is 7.911 x 10^{-3} Nm. Table-5 shows the comparison between stepper motor and DC motor.

Table-4: Comparison between Stepper and DC Motor

Criteria	Weightage (%)	Stepper Motor	Score	DC Motor	Score
Accuracy	30	High	**5**	Moderate	**4**
Torque	40	1.8 Nm	**5**	1.8 Nm	**5**
Price	20	Moderate	**3**	Moderate	**3**
Application	10	Good	**4**	Moderate	**2**
Total	100	-	**17**	-	**14**

From Table-5 stepper motor scored higher than DC motor in the criterion of application. DC motor is more suitable for continuing rotating purposes while in this solar tracker it does not need to continuously rotate and stepper motor gives better accuracy than DC motor. Beside stepper motor can remain in position for unlimited period of time. So stepper motor will be to rotate the frame. To rotate the frame there are two type of driving method which is either chain drive or V-belt drive. Table-6 shows the comparison between chain drive and V-belt drive.

Table-5: Comparison between Chain and Belt

Criteria	Weightage (%)	Chain	Score	Belt	Score
Durability	30	Moderate	**4**	High	**5**
Weight	30	Heavy	**3**	Light	**5**
Price	10	Moderate	**5**	High	**3**
Maintenance	30	Lubricant	**3**	No Lubricant	**5**

From Table-6, belt had scored 18 and chain had scored 15, obviously belt drive system will be the selected method of driving the shaft. As previously mentioned that it need to reduce the weight to reduce the required torque to rotate the frame, belt drive system had perfectly fulfil this requirement, it is light in weight and high durability. Besides it does not require any maintenance because it does not need to be lubricated. Although belt drive system is expensive in cost but cost just take over 10% out of 100% the major concern is on the weight durability and maintenance. Therefore, belt drive system had been chosen for the driving method.

2.3 Mechanical structure design steps

The very first step to start is to make the top frame that used to hold solar panel. By using saw blade the six meter aluminum bar is cut into the desire length of two 1250mm and 3x760mm. The distance is measured which the 760mm bar is join to form the structure shown in Figure-10. By using hand drill, create those hole with the same size of the hole that available on the corner bracket (3mm). After preparing the hole, join those frames together by using rivet and rivet gun. Furthermore, measure 4 holes on the panel and which need to be mounted on the frame, and also pre-prepare the require holes for it. At this point the top frame is already done fabricated.

Figure-10: Top Frame

Figure-101: Top frame installation

The next structure need to do is rotating frame, steel will be used to fabricate this part because at the centre of the frame a steel shaft is need to be weld on it. Using drop saw to cut the steel bar in to these dimension, two of 660mm, 3 of 250mm and weld it. The welding method used is gas metal arc welding, weld the shaft to the centre of the frame. Beside that also welded the linear actuator holder at the centre side of the frame.

With the fabrication of the rotating frame and supporting frame, the top part of the design had been completed. Next is the bottom part. The 250mm square plate to perform face milling using the milling machine. This is to ensure the four sides is flat and is an accurate square shape. A 30mm diameter hole is drilled and depth of 10mm for the flange bearing to be place inside. Furthermore, from the centre of the four holes (12mm) for the flange bearing and drill it using bench drill machine. Then manual tapping tool is used to create the threat for the four holes. The size of the threads are M12 with1.75 pitch diameter. After measuring the dimension of the holes using hammer and marker to make a mark at the centre of the hole, this is to ensure that it cut right at the centre of the hole otherwise the flange bearing will not fit in with the screw. Then adjust the steel plate to be align with the drill bit, using a clamp to hold the position of the plate. By starting the machine and moving the drill bit down slowly by put some oil on it to reduce wear and tear. The 4 holes for motor installation is pre-prepared. The square supporting stand with the installation of turntable on it is fabricated as shown in Figure-11. This structure has the purpose of separating the force on top of it. Instead of letting it handle by the shaft, this structure also helps to reduce the stress acting on it. In addition this also increases the contact surface of the rotating frame which results in adding more stability of the top part. First cut the steel bar to four of 135mm and four of 45mm then weld it together accordingly. The next step is fixed the turntable on the top of the structure with rivet.

At this point the fabrication process is done and continues to assembly process. Every part prepared is being welded up together and the mechanical design could be completed. Frist to assembly is the angle bar, welded it together to form a square base of 500mm x 500mm and install the 4 trolley wheel on it. Next is to put the square steel plate in, it should fit tightly on it, then welled the tube at the centre of the square plate. Before doing it, flatness of the plate should be measured using water level balance, similar method should be used for the tube. After that, the thirst bearing is placed at the centre of the hole and install the flange bearing of the 250mm x 250mm square plate and welded it in the tube, it also need to ensure that it is flat on it. In addition, weld the supporting structure at the centre of square 250mm x 250mm plate. Lastly install the top part of the frame on it. Then the mechanical structure is completed as shown in Figure-12.The stress analysis of mechanical structure is performed in the next section.

3. Results and Discussion

3.1 Stress Analysis

Stress Analysis had been done using Autodesk Inventor. Three stress analysis had been done which are top part, bottom part and the complete structure. Figure-12 shows the result of analysis of top part structure while Figure -13 shows the result of analysis for bottom part structure and last Figure -14 shows the result of complete structure.

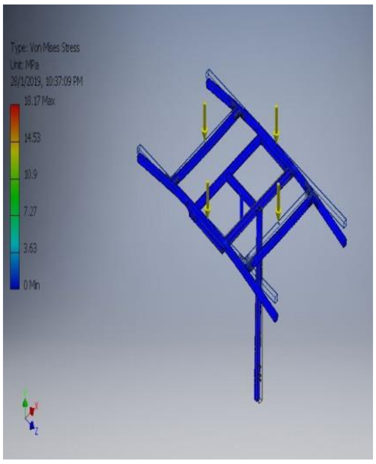


Figure-12: Stress Analysis for Top Part

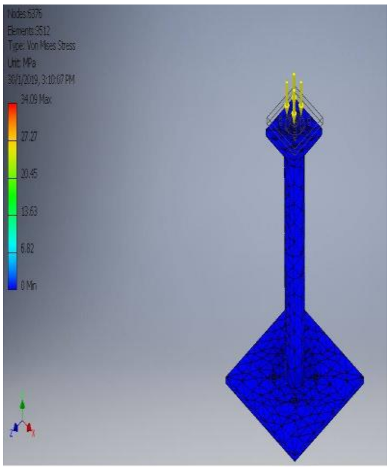


Figure-13: Stress Analysis for Bottom Part

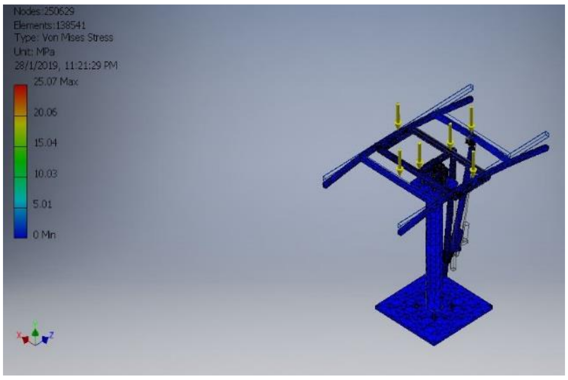


Figure-14: Stress Analysis for Completed Structure

Figure-12 shows the result of stress analysis for the top part of the structure. It's simply shows that the design can fit the load of the PV module because as shown in the whole structure are in blue which means that it had no problem with the load applied on it. However from the result, it shows that when the maximum stresses reaches 3.63 MPA the frame will start to bend. By using equation (2), the allowable load could be estimated accordingly. Where stress and area is known then the load could be calculated.

However Figure-13 shows the result analysis of the bottom structure. It shows that it could withstand the applied load from the top part. While Figure 14 shows the result of complete structure and it also shows that the structure is within the safety range. Although the bottom part is very strong but the most critical part is still depend on the top part of the structures. In short the maximum allowable stress should not exceed lesser than 3.63 MPA.

4. Conclusion

Dual axis solar tracker had been successfully customized at low cost. Autodesk inventor had been used to design the structure and performed the stress analysis. Other than that, Linkage was used to simulate the vertical movement of the tracker. Dual axis solar tracker is efficient and it is portable, it can be brought to any place for power generation if there is sun available.

The design of the dual axis solar tracker can be further improved by firstly changing the base design, it can consider as the base in this project is over designed. Instead of using solid steel plate which is very heavy, it could be done by using hollow steel bar which is also could be used to support the top frame and also counter the wind force at optimum condition. Besides that, the allowable movement angle of the linear actuator could be increase. Instead of welded the supporting bar directly toward the rotating frame, it could be design in such a way that there is an axis of ration on it. This help to increase the elevation angle towards 90º, this is possible only where the structure should be strong enough to support the load when it is at maximum angle..

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