Design of an Intelligent Dual-axis Solar Tracking Device for Solar System Usage

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Abstract— **One of the major problems facing solar energy systems is the efficiency as the sun moves on the celestial sphere. The solar tracker is a device that tracks the position of the sun and set the solar energy conversion system focusing normal to the sunbeams. This paper presents a design focused on harnessing the maximum available solar radiation using dual-axis tracking mechanism. The tracking mechanism is designed to focus the solar conversion system perpendicular to the rays of the sun (sunbeams) at all time of the day relative to the position of the sun in the sky dome. The driving mechanism for the motion are two direct current linear actuators of 12V each, which one of the actuators tracks the east to west motion of the sun while the second linear actuator tracks the seasonal motion/daily altitude of the sun. The main task of the tracking mechanism is to focus solar energy conversion system perpendicular to the sun to maximize the absorbed solar radiation and minimize the energy consumption for tracking system. The movement of the sun on the celestial sphere was the bases of the tracking mechanisms angles design. The azimuth angle at sunrise and sunset for the year was calculated and the maximum value for both situations was used for the design of the east to west tracking of the sun at Universiti Kebangsaan Malaysia – 3 ºN, 101.8 ºE. For the north to south tracking process which is related to the altitude, the altitude angles was calculated for a period of one year and the maximum value was used to decide the design for the north-south tracking on the second axis of the tracker. Analytical study of clear sky solar radiation at the location for the tracking system and 15º fixed solar system was conducted, it was found that the performance of the solar system increased by over 20% assuming the tracker is 80% efficient.**

***Keywords:** Solar energy; dual-axis tracker; sun position; energy efficiency*

I. INTRODUCTION

The world demands for energy grow exponentially with the increasing population and the advancement in technology both in developed and developing countries. Conventional energy has been the major source of meeting the daily energy needs but conventional energy supplies, such as fossil fuel, nuclear energy, etc have environmental burdens that come with their usage. Similarly, there is a fact that the fossil fuels (gas, oil, coal) are limited and hand strong pollutants [1]. The increase in the emissions of carbon dioxide (CO_2), which is responsible for the global warming and for the greenhouse effect have devastating results on the environment. On the other hand, the use of nuclear energy for energy supply pose waste disposal problems coupled with the threat of radiation when there comes any failure as in the case of Japan nuclear power plant. Based on the environmental challenges associated with conventional energy supply, renewable energy should be the desired mediator between meeting the energy demand and mitigating the environmental impacts. Solar energy conversion is one of the most addressed topics in the field of renewable energy systems [2]. The beauty of solar energy is its free supply which is in abundant and environmental friendly. Solar radiation can be converted into useful energy, using various technologies in the form of thermal energy, direct or indirect electric energy conversion [3]. The solar thermal operation is the process where solar energy is absorbed by absorber plate/collector and converted to heat energy for the purpose of hot water generation for domestic or industrial uses, steam generation for food processing, power generation, space heating etc while the solar photovoltaic uses PV to convert solar energy directly to electricity [4]. The performance of photovoltaic systems and solar thermal conversion systems depend on the available solar radiation and the rate of absorbtivity of the surface. There are two ways of maximizing the rate of useful energy for solar converters which are optimization of the conversion of the absorber by harnessing the maximum available incident solar radiation to the collector and decreasing the losses by proper choice of the absorber materials. Material selection and manufacture is a challenging condition and thus harnessing maximum available solar radiation by proper orientation of the solar system is a more cost effective option. To increasing the incident radiation rate, the collector should be focused normal to the sunbeams and this can be achieved using mechanical tracking systems [1].

A solar tracking system is a device for orienting a solar panel or concentrating a solar reflector or lens normal to the sun rays. Maximizing power output from a solar system is desirable to increase efficiency, hence reduction in the cost of energy. In order to maximize power output from the solar panels, the panels must be aligned with the sun [5, 6] and thus, a means of tracking the sun is required. The use of sun tracking equipment is a far more cost effective solution than purchasing additional solar panels [7]. The required accuracy of a solar tracker depends on the application. Concentrators, especially in solar cell applications, require a high degree of accuracy to ensure that the concentrated sunlight is directed precisely to the powered device, which is at (or near) the focal point of the reflector or lens. Non-concentrating applications require less accuracy, and many work without any tracking at all. However, tracking can substantially improve both the amount of total power produced by a system and that produced during critical system demand periods. The use of trackers in non-concentrating applications is usually an engineering decision based on economics as when tracker price is compared to additional photovoltaic system, trackers can be inexpensive [8]. This makes them especially effective for photovoltaic systems using high-efficiency (and thus expensive) panels.

Solar trackers may be active or passive and may be single axis or dual axis. Single axis trackers use a polar mount for maximum solar efficiency. Single axis trackers will usually have a manual elevation (axis tilt) adjustment on a second axis which is adjusted on regular intervals throughout the year. Compared to a fixed type, a single axis tracker increases annual output by approximately 15 to 20 % [6, 9], and a dual axis tracker an additional 5 % to 10 % [10]. A dual-axis solar tracker is more efficient than a single axis tracker because it follows the sun both on the azimuth and elevation to track the sun position accurately, thus, follows the sun in multiple angles ensuring that the sunbeam angle is about 100% normal on the panel.

The paper present the design calculations based on the position of the sun at different time of the day used for decision making in the construction of a dual axis sun tracking device at Universiti Kebangsaan Malaysia. The design is to achieve efficient dual-axis tracking of the sun on the celestial sphere all year round and thus position solar panels/collectors perpendicular to sunbeam using actuators as the mechanical driving mechanism. Similarly, the calculation was used to generate design data for the design of open loop time based control system that can be used with the tracker system to position the collector perpendicular to the sun even on cloudy and rainy day.

II. SOLAR TRACKING DESIGN PRINCIPLES

From energy efficiency point of view, the performance of a solar system using tracking mechanism is considered efficient on the following condition: $\varepsilon = (E_T - E_F) - E_C >> 0$, where E_T is the electric energy produced by the energy conversion system with tracking, E_F is the energy produced by the same system when fixed, and E_C is the energy consumed by the mechanical driver for orienting the panels. The maximization of the efficiency parameter, ε through the optimal design of the tracking system is an important issue for consideration in solar tracker designs. To achieve optimal design, a standard solar tracking system should orient solar collector/PV cell normal to the sun, compensating for both changes in the altitude angle of the sun (throughout the day), latitudinal offset of the sun (during seasonal changes) and changes in azimuth angle [2].

Sun-tracking systems are usually classified into two categories: passive and active trackers. Passive solar trackers are based on thermal expansion of a matter (usually Freon) or on shape memory alloys. Active trackers can be categorized as microprocessor and electro-optical sensor based, PC controlled date and time based, auxiliary bifacial solar cell based and a combination of these three systems.

The study was for active tracking system based on date and time at the location using Azimuth/Elevation Tracking principles.

A. Azimuth/Elevation Tracking

The dual axis azimuth/elevation solar trackers combine two motions so they are able to follow precisely the sun trajectory along the whole year and position the solar panel normal to the sunbeam. The design of the azimuth/elevation tracking includes one axis rotating about the zenith axis (perpendicular axis) with a tracking angle, ρ_1, equivalent to the solar azimuth angle:

$$\rho_1 = \gamma \quad [1]$$

While the other axis is parallel to the surface of the earth and is rotating with a tracking angle, ρ_2, equal to the altitude angle:

$$\rho_2 = \alpha \quad [2]$$

In the azimuth/elevation tracking, the two driving mechanism (actuators) are obliged to work all day long near the zenith.

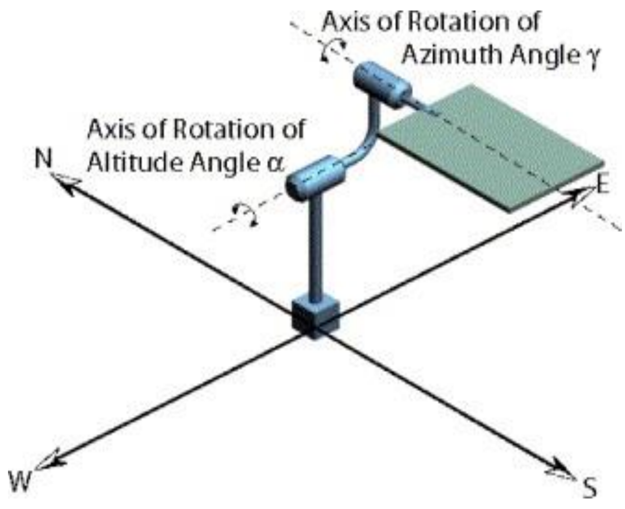

Figure 1. Two axis azimuth/elevation sun tracking system

III. SUN POWER, POSITION AND TRACKING

The Earth is an obligated sphere, meaning that it is a sphere that is flattened at the poles and bulges around the equator. For solar system design calculations it is sufficient to treat the Earth as a simple sphere with reference points on the Earth's surface known as longitude and latitude. The Earth rotates around its axis every 24 hours and orbits the Sun on approximately every 365.25 days. The Earth's orbit follows an elliptical path with the Sun at one of the foci such that the minimum distance between the Sun and the Earth is 146.10×10^9 m and the maximum distance is 152.10 × 10^9 m. The difference between the maximum and minimum distance is about 3.3 % with a mean distance of 149.5985×10^9 m. The axis of rotation is tilted at an angle of 23.45 ° with respect to the plane of the orbit around the Sun [11].

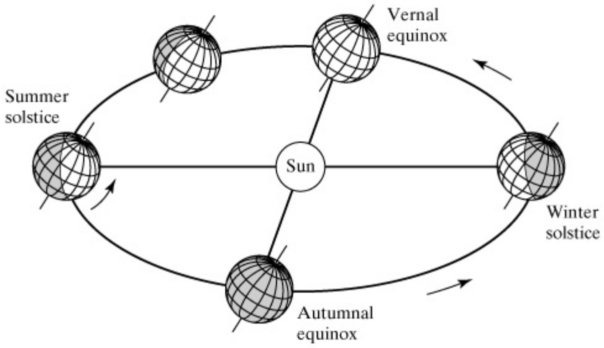

Figure 2. The orbit of the earth around the sun

Another way to view the motion of the Earth around the Sun is to consider the Earth as stationary and plot the apparent motion of the Sun throughout the course of one year, such a view is called the celestial sphere. Here the sun moves around the ecliptic and the Earth's equator is projected onto the celestial sphere as the celestial equator. The solar tracker design principles are based on the sun movement on the celestial sphere.

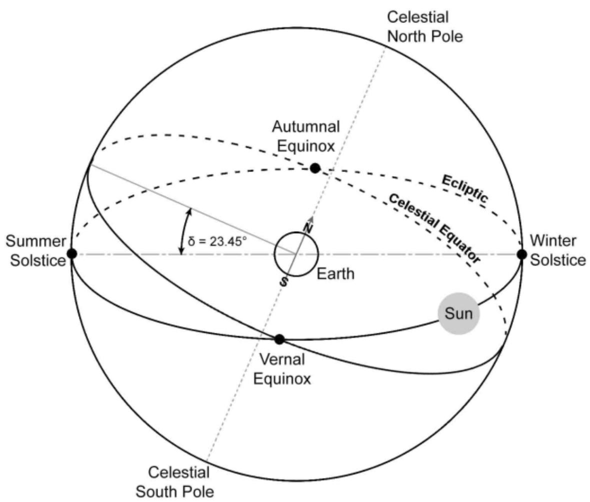

Figure 3. The motion of the sun on the celestial sphere

A. Sun Power

Almost all of the energy that drives the various systems (climate, ecosystems, hydrologic systems, etc.) originates from the sun. The sun is a blackbody and its surface called the photosphere, is at a temperature of about 5762 ± 50 K. Only a fraction of the total power emitted by the sun impinges on an object in space which is some distance from the sun (about 149.5985 x 10^6 km). The solar irradiance (H_0 in W/m^2) is the power density incident on an object due to illumination from the sun [11]. At the sun's surface, the power density is that of a blackbody at about 6000K (σT^4). Mathematically, Sun power density can be calculated as follows:

$$H_{sun} = \sigma T^4 \quad [3]$$

where H_{sun} is sun power density (W/m^2), σ is Stefan Boltzmann constant = 5.67 x 10^{-8} Wm^{-2}K^{-4}, T is Photosphere's Temperature = 5762 ± 50 K;

» $H_{sun} = (5.67 \text{ x } 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}) \text{ x } (5762 \text{ K}^4)$

$$H_{sun} = 62{,}499{,}433 \text{ Wm}^{-2}$$

The total power emitted by the sun is H_{sun} multiplied by the surface area of the sun A_{sun}.

$$A_{sun} = \text{Area of a sphere} = 4\pi r_{sun}^2 \quad [4]$$

where r_{sun} = radius of the sun (6.96 x 10^8 m)

$$A_{sun} = 4 \text{ x } \pi \text{ x } (6.96 \text{ x } 10^8)^2 = 6.087 \text{ x } 10^{18} \text{ m}^2$$

Total Power emitted by the sun = H_{sun} * A_{sun} [5]

= 62,499,433 x 6.087 x 10^{18} = 3.80434 x 10^{26} W

Only a fraction of this total power emitted by the sun impinges on an object in space which is some distance from the sun. The solar irradiance on an object some distance, D, from the sun is found by dividing the total power emitted from the sun by the surface area over which the sunlight falls.

$$H_o = \frac{r_{sun}^2}{D^2} H_{sun} \quad [6]$$

where H_o is available solar radiation on object in space; D is the distance from the sun to the earth (149.5985 x 10^9m)

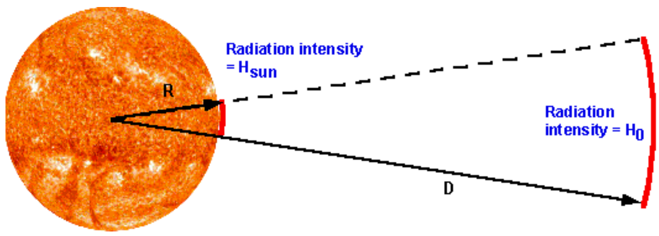

Figure 4. Radiation intensity, H_o, on object at distance, D

$$H_o = \frac{(6.96 \text{ x } 10^8)^2}{(149.5985 \text{ x } 10^9)^2} \text{ x } 62{,}499{,}433 = 1{,}353 \text{ Wm}^{-2}$$

This is the average solar constant but daily solar constants can be calculated on daily bases using same equation and the distance, D, between the sun and the earth at the day.

B. Solar Radiation Outside The Earth's Atmosphere

The solar irradiance at the Earth's atmosphere is about 1.353 kW/m^2. The actual power density varies slightly since the Earth-Sun distance changes as the Earth moves in its elliptical orbit round the sun. Equation [6, 7] describes the variation in the sun power density throughout the year based on the day at the earth's atmosphere [11].

$$\frac{H_o}{G_{sc}} = 1 + 0.033\cos\left(\frac{360(n)}{365}\right) \quad [7]$$

where H_o is the radiant power density outside the Earth's atmosphere (in W/m^2) on the specific day, n; G_{sc} is the value of the solar constant, 1.353 kW/m^2; and n is the day of the year, n = 1 for January 1st.

C. *Sun Position on the Celestial Sphere*

i.) Solar Time (t_s)

Solar times are measures of the apparent position of the Sun on the celestial sphere. They are not actually the physical time, but rather hour angles, that is, angles expressed in time units. Twelve noon local solar time (t_s) is defined as when the sun is highest in the sky. Thus, it is the time that the sun is at the observer's meridian. Local/standard time (t_l) usually varies from t_s because of the eccentricity of the Earth's orbit, and because of human adjustments such as time zones and daylight saving.

The Local Standard Time Meridian (L_{ST}) is a reference meridian used for a particular time zone and is similar to the Prime Meridian, which is used for Greenwich Mean Time. L_{ST} is calculated according to the equation:

$$L_{ST} = 15^{\circ} \times \Delta T_{GMT} \quad [8]$$

Where ΔT_{GMT} is the difference between the Local Time (t_l) and Greenwich Mean Time (GMT) in hours. In consideration of the earth eccentricity, the equation of time (E) which is an empirical equation that corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt was introduced [11].

$$E = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B) \quad [9]$$

where $B = \frac{360}{364}(n - 81)$; in degrees and n is the number of the days in the year.

The net Time Correction Factor (in minutes) accounts for the variation of the Local Solar Time (t_s) within a given time zone due to the longitude variations within the time zone and also incorporates the equation of time (E).

$$TC = 4(L_{ST} - L_{loc}) + E \quad [10]$$

The constant, 4 comes from the fact that the Earth rotates 1 ° every 4 minutes.

The Local Solar Time (t_s) can be found by using the previous two corrections to adjust the local time (t_l).

$$t_s = t_l + \frac{TC}{60} \quad [11]$$

ii.) Hour Angle (ω), Declination Angle (δ) and Elevation Angle (α)

The Hour Angle converts the local solar time (t_s) into the number of degrees which the sun moves across the sky. By definition, the Hour Angle, ω, is 0 ° at solar noon. Since the Earth rotates 15° per hour, each hour away from solar noon corresponds to an angular motion of the sun in the sky of 15°. In the morning the hour angle is negative, and after the solar noon, the hour angle is positive.

$$\omega = 15^{o}(t_s - 12) \quad [12]$$

The declination angle, denoted by δ, varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun as the Earth is tilted 23.45° on its axis and the declination angle varies plus or minus this amount. The declination angle can be calculated by the equation [11]:

$$\delta = 23.45^{o}\sin\left[\frac{360}{365}(284 + n)\right] \quad [13]$$

where n is the day of the year with n = 1 on January 1st.

The declination is zero at the equinoxes (March 22 and September 22), positive during the northern hemisphere summer and negative during the northern hemisphere winter. The declination reaches a maximum of 23.45 ° on June 22 (summer solstice in the northern hemisphere) and a minimum of -23.45 ° on December 22 (winter solstice in the northern hemisphere).

The elevation angle (α) is the angular height of the sun in the sky measured from the horizontal. The elevation is 0 ° at sunrise and about 90° when the sun is directly overhead. The zenith angle is similar to the elevation angle but it is measured from the vertical rather than from the horizontal, thus making the zenith angle = 90° - α (elevation). The elevation angle varies throughout the day. It also depends on the latitude of a particular location and the day of the year. An important parameter in the design of dual axis solar tracking systems is the maximum elevation angle, that is, the maximum height of the sun in the sky at a particular time of year. This maximum elevation angle occurs at solar noon and depends on the latitude and declination angle. The elevation and zenith angles can be found using the following formulas:

$$\text{Elevation}, \alpha = \sin^{-1}[\sin\delta\sin\text{Ø} + \cos\delta\cos\text{Ø}\cos\omega] \quad [14]$$

$$\text{Zenith}, \theta_z = 90° - \alpha \quad [15]$$

iii.) Solar Azimuth, Sunrise Angle (ω_{sr}) and Sunset Angle (ω_{ss})

To determine the maximum east to west tracking angle of a solar tracker, the sunrise angle and sunset time and angles for the year should be calculated for the location and the maximum angles should be consider with precision for the design of the east to west tracking (azimuth angle tracking). To calculate the sunrise and sunset time the equation for elevation is set to zero:

$$\text{Sunrise} = 12 - \frac{1}{15}\cos^{-1}\left(\frac{-\sin\text{Ø}\sin\delta}{\cos\text{Ø}\cos\delta}\right) + \frac{TC}{60} \quad [16]$$

$$\text{Sunset} = 12 + \frac{1}{15}\cos^{-1}\left(\frac{\sin\text{Ø}\sin\delta}{\cos\text{Ø}\cos\delta}\right) + \frac{TC}{60} \quad [17]$$

where Ø is latitude of the location.

The azimuth angle is the compass direction on the system surface to the sun. The azimuth angle varies throughout the day. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thus making the azimuth angles 90 ° at sunrise and 270 ° at sunset when we take the north to be $0^o/360^o$ using the compass method. In general however, the azimuth angle varies with the latitude and time of year and the full equation to calculate the sun's position on the azimuth throughout the day is given below:

$$\text{Azimuth} = \cos^{-1}\left(\frac{\sin\delta\cos\text{Ø} - \cos\delta\sin\text{Ø}\cos\omega}{\cos\alpha}\right) \quad [18]$$

The azimuth angle and the elevation angle at sunrise solar time, solar noon and sunset solar time are the two key angles which are used to orient solar conversion systems. However, to calculate the sun's position throughout the day, both the elevation angle and the azimuth angle must be calculated throughout the day.

IV. SOLAR TRACKER CONSTRUCTION

A. *Material selection*

The material selection is very important in relationship with the design of a solar tracker. In this design, the weight of the material and the strength are also considered as there are forces that must be analyzed in relation to the tracking system design. For the solar panel seat, the best choice made is aluminium based on the following reasons [12, 13]: Lightweight, good strength/high strength-to-weight ratio, corrosion resistance, cost effectiveness and recyclability.

For the tracker hinge, spindles and the frame design; the material choice that fit very well to this purpose is stainless steel grade 304; based on the following unique properties [13]: Corrosion Resistance, Heat Resistance Excellent weldability, and machinability.

B. *Mechanical Design*

The efficiency of every machine depends on the accurate analysis of the forces on the different linkages and selection of the most suitable material for the fabrication of such linkages. The sun tracking system is not an exception. In this design, the system is designed to accommodate three solar panels of 8kg weight each. The dimensions of each panel are as follow: Length – 1195 mm, width – 548 mm and base height – 30 mm. The wattage of the panel is 360 W.

Figure 5. Panel seat design

Weight analysis of the panel seat: the total length of material used for the forming of the panel seat is equals the perimeter of the panel seat;

Perimeter of the panel seat = 2 x (1200 mm +1650 mm) = 5700 mm

Mass of the panel seat = Perimeter x weight per unit length
= 5700 mm x 0.24 g/mm = 1368 g = 1.37 kg

Total mass of solar panel and panel seat
= 24 kg +1.37 kg = 25.37 kg

Force Analysis on the moment pin support (Azimuth rotation/tracking point); the force is analyzed as a distributed load as shown below.

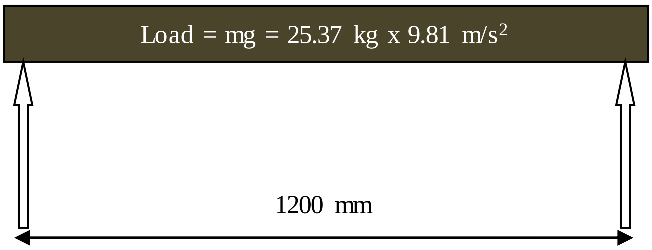

Figure 6. Load analyses of the panel seat and solar panels as Distributed load

The above distributed load is resolved in the form of concentrated load as follows:

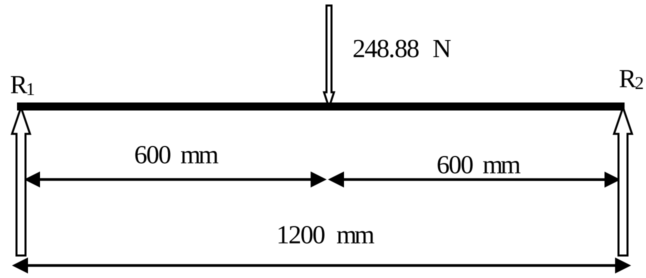

Figure 7. Concentrated load analyses of the panel seat and solar panels

Force resolution for a rigid body [13, 14] for equilibrium: Summation of force: $\sum F = 0$; Moment about a point: $\sum M = 0$; Appling the above equations to resolve the force/load in the above diagram,

$\sum F = 0 = R_1 + R_2 - 248.88\text{ N} = 0$

Taking moment about support-2 (R_2),

$\sum M = 0 = (R_1 \text{ x } 1200\text{ mm}) - (248.88\text{ N x } 600\text{ mm}) = 0$

$R_1 = \frac{248.88\text{ N x }600\text{ mm}}{1200\text{ mm}} = 124.44\text{ N}$

Therefore R_2 = 248.88 N – 124.44 N = 124.44 N

Design and force Analysis of Pin 1 and Pin 2: for each of pin1 (figure 8) should have strength of 1.5*R_1; where 1.5 is the safety factor against external force that may arise as a result of wind and unforeseen disasters. The strength of the pin is calculated as follows:

$F_{(pin1)}$ = 1.5 x 124.44 = 186.66 N = 187 N

The force that can act on pin2 (figure 8) equals half the total load (weight of the panel and the panel seat) added to the weight of the actuator. Where the actuator has a mass of 6 kg which can be analyzed as a force (F = mg – where m = mass and g = gravitational force = 9.81 m/s^2); the force impact of the actuator is 6 kg x 9.81 m/s^2 = 58.86 N.

The total force acting on pin 2 = R_1 + force from actuator = 124.44 + 58.86 = 183.3 N but for the case of this design, there are external forces that may arise due to wind and unforeseen attacks; pin 2 is designed to accommodate force = 1.5 x 183.3 = 275 N

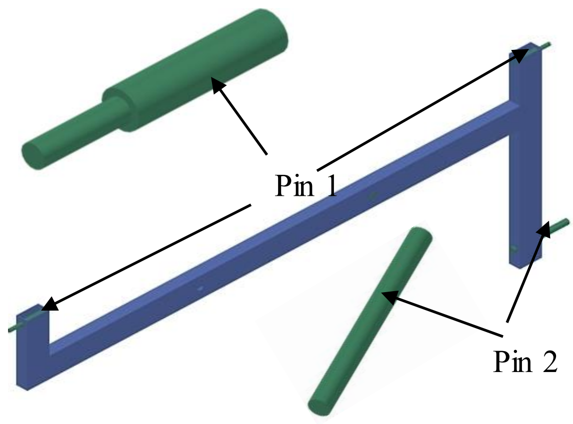

Figure 8. Diagram of the supporting pins

Sizing of Actuator 1: The load at the actuator is (R_1 +R_2); but for safety $F_{actuator1}$= 1.5(R_1 +R_2) = 1.5 x 248.88 N = 373.32 N. But in the selection, 400 N - actuator is a very good option for this design.

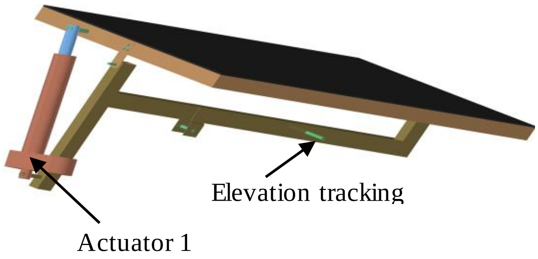

Figure 9. Illustration of Actuator 1

Analysis of the Force on the Hinge Mechanism and Actuator 2
The hinge mechanism is designed with a rectangular stainless steel tube – gauge 304, the tube dimensions are 25.4 mm x 50.8 mm and thickness of 1.2 mm. Below is the diagram of the hinge mechanism.

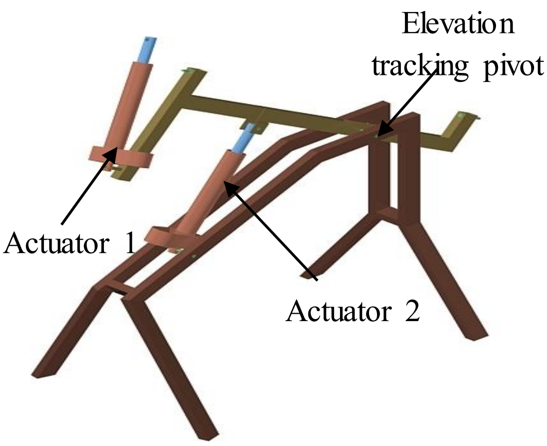

Figure 10. Actuators and the hinge mechanism

Mass of each link to the system = 152.4 mm x 1.41 g/mm = 214.88 g = 0.215 kg
1098.4 mm x 1.41 g/mm = 1548.75 g = 1.549 kg
458 mm x 1.41 g/mm = 645.78 g = 0.646 kg

Force Analysis on the moment pin 3 support (Altitude/elevation tracking point); the force is analyzed as a concentrated load as shown below.
Force acting at the left side (0.215 kg) = 0.215 kg x 9.81 m/s^2 = 2.11 N
Force acting on the centre of the link equals the weight of the panels plus the weight of the centre connection = (25.37 kg + 1.549 kg) x 9.81 m/s^2 = 264.1 N
At the end where the first actuator is connected, the total weight equals the weight of the actuator plus the weight of the material for the connection; mathematically, weight = (6 kg + 0.646 kg) x 9.81 m/s^2 = 6.20 N

Force resolution for a rigid body:
$\sum F = 0 = R_3 + R_4 = 2.11\text{ N} + 264.1\text{ N} + 6.2\text{ N} = 272.41\text{ N}$
Taking moment about support 4,
$\sum M = 0$
$(R_3 \text{ x } 400) - (2.11 \text{ x } 800) - (264.1\text{ N x } 200) + (6.2\text{ N x } 400) = 0$
$R_3 = \frac{52{,}028\text{ Nmm}}{400\text{ mm}} = 130.07\text{ N}$
Therefore R_4 = 272.41 N – 130.07 N = 142.34 N

The hinge support pin should have strength of 1.5R_3; this is because it is the major point to withstand the wind forces and unforeseen disasters. The strength of the pin is calculated as follows:
$F_{(pin\text{-}hinge)}$ = 1.5 x 130.07 = 195.105 N = 195 N
Similarly, the load strength of the actuator that should be rotating the panel along the azimuth (east to west) is 1.5(R_3 +R_4) = 1.5 x 272.44 N = 408.7 N. But in the selection, 450 N actuator is a very good option for this design.

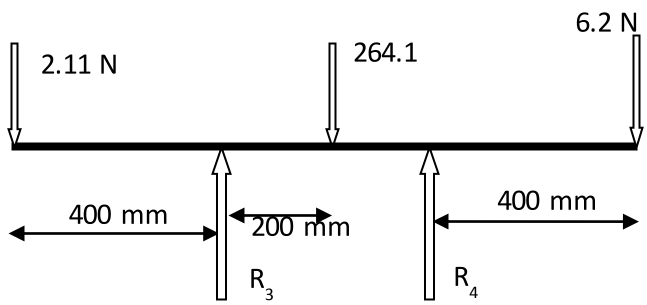

Figure 11. Free body diagram of the forces acting at R_3 and R_4

Frame Design: The frame is designed in such a way that it will give maximum support to the whole system and also reduce material usage. The four legged frame stand has the following features as can be shown in the figure below;

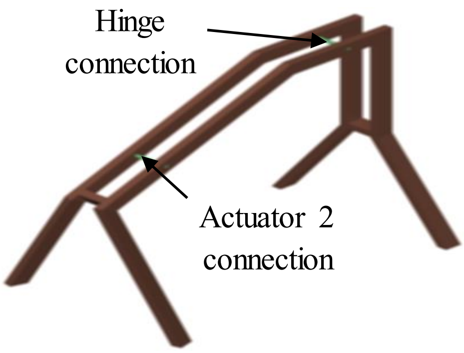

Figure 12. Tracker frame structure

The tracker frame is designed to stand vertical at an angle of 90° at one end and to be sloped at angle of 45° from the second side; this is to withstand the forces that may arise from the weight of the panels or wind. The straight vertical side is to allow for the tracking angles of the second actuator that tracks the elevation angles. It designed such that angle from 0° to 90° degrees can be tracked for the elevation.

Figure 13. Illustration of the frame structure design

At the top of the tracker frame, the two frame which are joined with a support is separated by a distance to allow for the hinge that tracks the elevation angle and also to allow the tracking from east to west which this tracker can track the azimuth angle up to 90° from the horizontal.

Figure 14. Illustration of azimuth and elevation tracking directions

TABLE I. SUNRISE AND SUNSET AZIMUTH AND ZENITH ANGLES FOR MEAN DAYS OF EACH MONTH

Month	**Sunrise and sunset Azimuth and zenith angles for mean days of each month**				
	day, n	***Sunrise Azimuth*** $\omega_{(max)}$	***Sunrise Zenith;*** $\alpha_{(max)}$	***Sunset Azimuth*** $\omega_{(max)}$	***Sunset Zenith;*** $\alpha_{(max)}$
Jan	17	110.95	90	249.05	90
Feb	47	102.97	90	257.03	90
March	75	92.42	90	267.58	90
April	105	80.57	90	279.43	90
May	135	71.18	90	288.82	90
June	162	66.88	90	293.12	90
July	198	68.78	90	291.21	90
Aug	228	76.52	90	283.47	90
Sept	258	87.78	90	272.22	90
Oct	288	99.61	90	260.38	90
Nov	318	108.94	90	251.05	90
Dec	344	113.08	90	246.91	90

From the table above, it can be seen that from October to March, the sunrise azimuth angle is higher than 90° and this is the time the sun is heading to the south. In this case the sunrise azimuth equals (180 – γ). The tracking angle is designed to track the sun up to 90° at sunrise and sunset. It can be illustrated below; the total angle of rotation for this design is 180° for the actuator 1, tracking east to west. In order to determine the tracking speed of the actuator, it is important to remember that the angular speed of the earth about the sun is 1° per 4 minutes. This can be calculated as follows:

Angular velocity, φ = θ (radian)/t (seconds) [19]

$$\varphi = \frac{1 \text{ x } \pi}{180} \text{ x } \frac{1}{4 \text{ x } 60} = 7.27221 \text{ x } 10^{-5} \text{ rad/s}$$

where linear velocity, v = φ*r;

r is the radius/stroke of the actuator.

In this design, the actuator stroke employed is 620mm.

$$v = 7.27221 \text{ x } 10^{-5} \text{ rad/sec x } 620 \text{ mm} = 0.0451 \text{ mm/sec}$$

On the other hand actuator 2 can be analyzed based on the tracking principle stated above. It tracks the elevation of the sun with the highest value at solar noon (Appendix B). The table below which is derived from calculation based on the formulas in chapter III is used to generate altitude angle for the mean days of each month of the year as follows.

From the above data it can be understood that the elevation angle at solar noon is very close to 90° and equals 0° at sunrise and sunset time. To analyze the system velocity, it is important to know that for an approximate of 6 hours the actuator 2 tracks the solar elevation from 0° at sunrise to 90° at solar noon and start a retracting backwards motion of another 6 hours from 90° to 0° at sunset. With this information the tracking speed of the actuator can be derived.

Angular velocity, φ = θ (radian)/t (seconds) 20

$$\varphi = \frac{90 \text{ x } \pi}{180} \text{ x } \frac{1}{6 \text{ x } 60 \text{ x } 60} = 7.27221 \text{ x } 10^{-5} \text{ rad/sec}$$

, linear velocity, v = φ x r; where r is the radius/stroke of the actuator.

In this design, the actuator stroke employed is 1020 mm.

$$v = 7.27221 \text{ x } 10^{-5} \text{ rad/sec x } 1020 \text{ mm} = 0.0741 \text{ mm/sec}$$

C. Linear Actuator Selection

A linear actuator is a device that applies force in a linear manner, as opposed to rotationally like an electric motor. There are various methods of achieving this linear motion. Some actually convert rotational motion into linear motion. The movement of the sun in celestial sphere is an angular motion and to accurately position a system normal to the incident radiation of the sun, the linear actuator has the best features. The solar tracking system must be exposed to the sun and will be faced with some environmental/weather challenges (rain, corrosion, snow, wind etc) and the linear actuator that is employed in this design has the potentials of withstanding all the challenges. As the sun moves, the tracking system need to maintain stability and consistency in motion and linear motion is the best suit for it.

Advantages of Linear Actuator

The choice for linear actuator has reasons behind it based on the features/benefits of the linear actuator (ID8A – 1500N). The following are the features of the ID8A [15]:

- It can work at an ambient temperature of -26ºC to +65 ºC.
- It is well sealed (O – ring) to prevent water from entering into the gear and electric motor.
- The ID8A -1500 with Acme screw can achieve full-load speeds up to 25 mm/s and force up to 1500 N in both push and pull modes.
- Their rugged construction features powder coated aluminium housing, steel protection tube, stainless extension tube, and powder metal gears;
- A clutch provides overload protection for safety; and actuators are lubricated at the factory for their service life.
- ID8A -1500 actuators offer duty cycles up to 25 % (speed adjustment).
- Can easily be controlled with photo sensors.

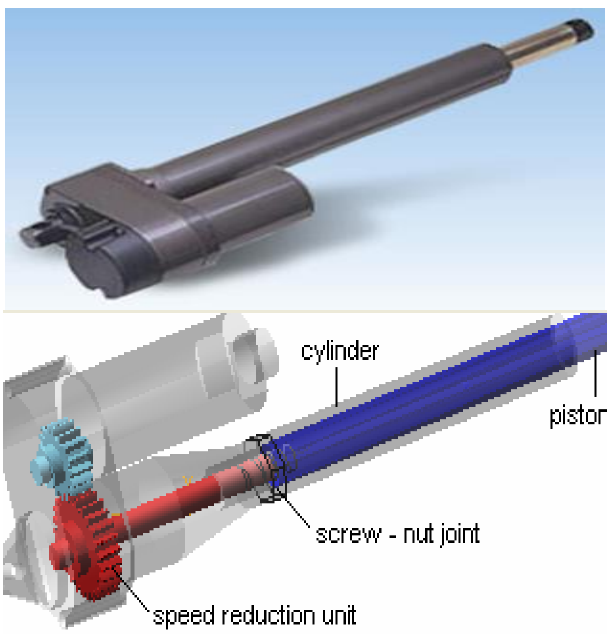

Figure 15. JAEGER brand "ID8A Series" linear actuators

V. RESULT ANALYSIS

The performance of the solar tracking device was studies analytically assuming that the tracker is 80% efficient and was compared with analytically calculated fixes solar system tilted at 15º due south in the case of UKM. The study result for the monthly performance is shown in table 2. The mean day of the months are plotted (figures 16-19) for March, June, September and December. The comparison shows that about 20% more energy can be generated on from morning to night.

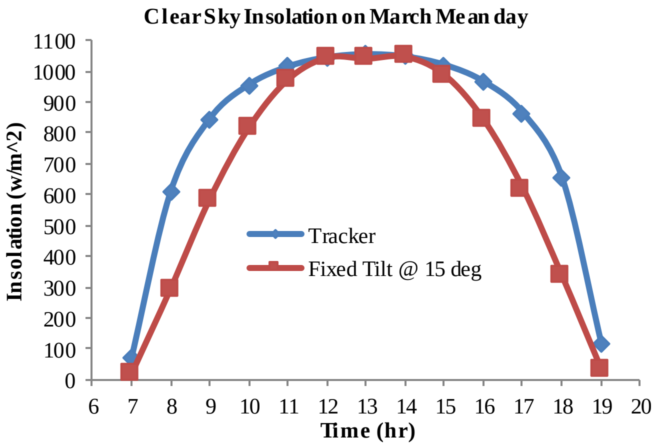

Figure 16. Clear Sky Insolation on March Mean day

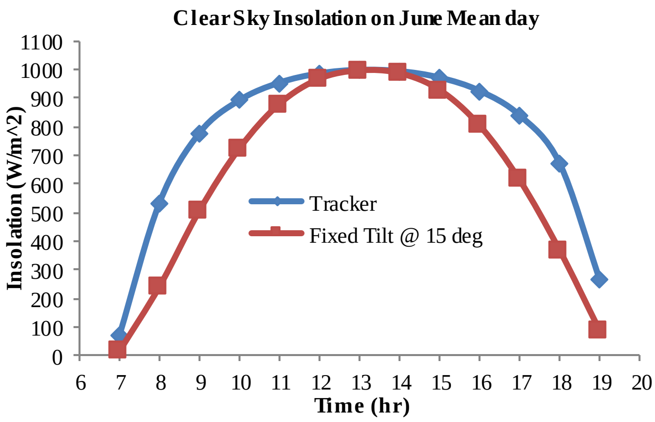

Figure 17. Clear Sky Insolation on June Mean day

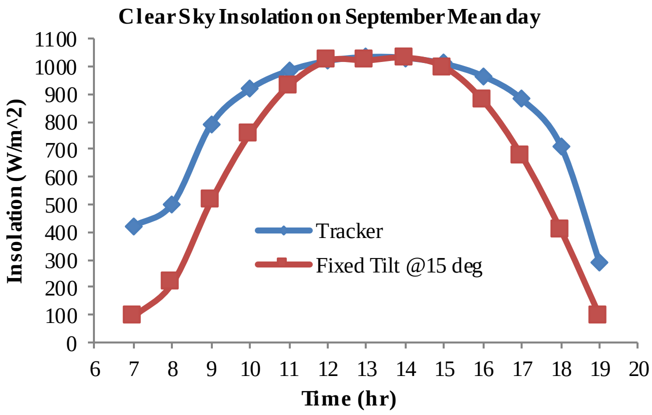

Figure 18. Clear Sky Insolation on September Mean day

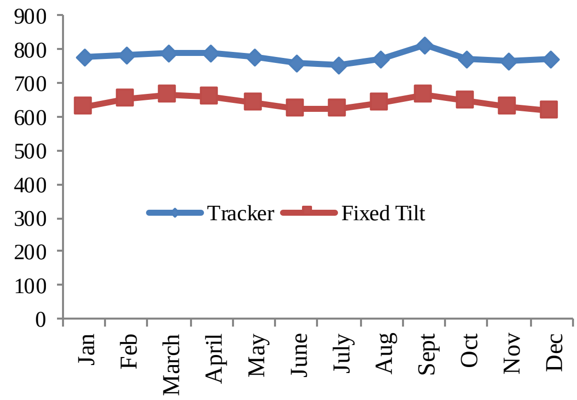

Figure 20. Graphical representation of monthly solar insolation available to fixed tilt solar system and sun-tracked solar system

Table 2 analyzed the annual monthly radiations for 15º fixed tilted solar system and sun-tracked solar system. It was found that the average annual increase of solar insolation using a solar tracker is 21.1 %. The graphical representation of the annual increment is in figure 20.

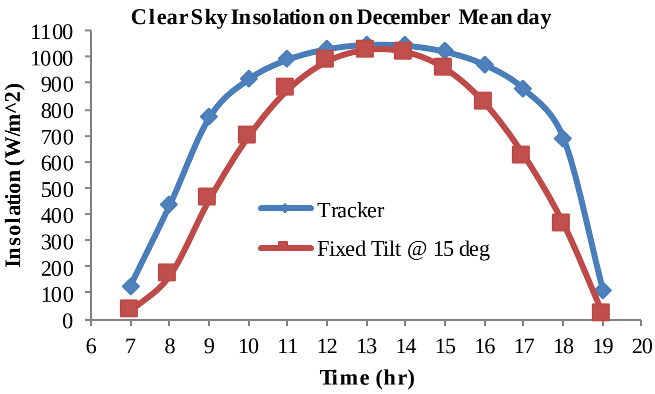

Figure 19. Clear Sky Insolation on December Mean day

TABLE II. ANALYSIS OF ANNUAL SOLAR INSOLATION ON TRACKING AND FIXED TILT @ 15°

Month	**Tracking and Fixed Tilt Annual Insolation**			
	Tracker; I_{Gtrack}	***Tilt Angle***	***Fixed; I_{GTilt}***	***Avg. Ins. (%)***
Jan	776.87	15	631.32	23.10%
Feb	785.09	15	653.64	20.11%
March	788.36	15	663.49	18.82%
April	788.45	15	658.38	19.76%
May	776.66	15	639.77	21.40%
June	759.56	15	623.19	21.88%
July	757.20	15	626.25	20.91%
Aug	769.86	15	644.35	19.48%
Sept	813.57	15	663.36	22.64%
Oct	770.54	15	647.31	19.04%
Nov	764.39	15	628.94	21.54%
Dec	772.87	15	620.50	24.56%
Annual Insolation	9323.48		7700.55	
Annual Avg. Ins.	776.95		641.71	21.10%
Percentage Increase / Efficiency				**21.10%**

VI. CONCLUSION

This work has developed a design method for a dual axis solar tracking system. The drawing for this design is done in AutoCAD. It present detail solar angles, time and sun position calculation in simplified manner such that it can be used at any location on the earth for development of time dependent open loop control circuit for sun tracking system. The linear actuator has very good features and benefits which makes them very attractive in tracking system design. The system is designed to be very simple and can be utilized anywhere on the globe. In the comparison between a fixed position solar collector (PV) and a tracked solar collector (PV), it was found that the system operating at 80% efficiency, on the average annual solar insolation available to PV system on a tracker was 21.1% higher than that of a 15º fixed tilted solar collector considering the location of study (UKM). By using the designed solar tracking system the space requirement for a solar park can be reduced by 21.1 %, and keeps the same output. After examining the information obtained in the calculations, the result analysis section, it can be inferred that the dual-axis sun tracking system is a feasible method of maximizing the energy received from solar radiation.

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