ICIC Express Letters
Part B: Applications
Volume **15**, Number **3**, March **2024**
 ISSN 2185-2766
pp. **217–226**

POLAR DUAL-AXIS SOLAR TRACKER WITH SUN MOTION ALGORITHM AT EQUATORIAL MOUNT FOR IMPROVING THE PERFORMANCE OF SUN-TRACKING METHOD

Syafaruddin[1,*], Putri Aisyah Kurnia[1], Yusran[1]
Gabriel Samuel Abadi Matongan[1], Arson Marianus[1] and Satriani Latief[2]

[1]Department of Electrical Engineering
Universitas Hasanuddin
Jl. Poros Malino Km. 6 Bontomarannu, Gowa, Sulawesi Selatan 92127, Indonesia
{ kurniapa23d; matongangsa17d; marianusa17d }@student.unhas.ac.id; yusran@unhas.ac.id
*Corresponding author: syafaruddin@unhas.ac.id

[2]Department of Architecture
Universitas Bosowa
Jalan Urip Sumoharjo Km. 4, Makassar 90231, Indonesia
satriani.latief@universitasbosowa.ac.id

Received June 2023; accepted August 2023

Abstract. *There has been substantial increase in solar energy capacity recently worldwide due to the significant installation cost reduction. In fact, the solar panel should be always perpendicular by the solar tracker movement to the sunlight direction in order to maximize the energy capture. This paper presents a model of dual-axis solar tracker with polar axis that uses sun motion algorithm at equatorial mount. The tracking system allows photovoltaic (PV) panel to follow the sun movement daily and annually with single actuator requirement. The dual-axis movement strategy will eliminate the individual daily motion of actuator that will impact the reduction of energy system consumption without disturbing the tracking mechanism. Real-time testing results show the proposed dual-axis solar tracker increases PV output with average value of 56.677% with low tracking energy consumption with average value of 7.502 Wh. The testing results also indicate low tracking errors of below 3 degree towards East and West directions and maximum value of 0.837 degree for daily and annual tracker movement, respectively.*
Keywords: Polar dual-axis solar tracker, Sun motion algorithm, Equatorial mount, Sun tracking performance

1. **Introduction.** Most of the existing solar panels still use a fixed (permanent) leg frame. As results, the solar panels are not being able to produce maximum electricity energy, because the panel position is just practically perpendicular to the sun direction for short time period. To overcome this problem, the solar tracker is designed to be an active mechanical system that allows solar panels to follow the movement of the sun [1]. In general, there are two types of solar trackers, namely single and dual-axis solar tracker systems. The single axis solar tracker has limited moving directions, such as single axis East and West or North and South directions and single axis vertical that causes low energy output production. In comparison, the dual-axis system can follow the sun's movement more dynamic and precisely, so they have advantages in terms of increasing energy output. A study in Amman-Jordan about the performance of different designs of solar tracker indicates the dual-axis solar tracker yields much energy output from solar paned of 43.87% higher compared with other types of single solar tracker designs [2].

DOI: 10.24507/icicelb.15.03.217

Sorts of study and design regarding the proposed solar tracker have been proposed in scientific community. In the past, the solar tracking system was designed by using sunlight sensor to drive the actuator movement. However, the performance of solar tracker decreases when the visibility of sunlight is reduced. In comparison, the sensorless solar tracking systems need extensive historical climate data based on geographic positioning, as well as complex mathematical and computational models to reach the optimal sun's position [3]. The design of low-cost and portable solar tracker has been proposed to increase the energy output from solar panel using modified ball-joint devices in which their components are easily found in the market for tracking movement [4]. This finding is claimed to lower the cost of solar tracker in the expanded large-scale systems and to maximize the energy capture from PV panels installation. Another approach to improving solar energy utilization is proposed by giving solution to some problems regarding the movement of solar tracker by optimizing the performance of tilt angles based on mathematical modelling [5]. These above efforts are mainly to achieve the best performance of solar tracker with the main objective of maximum energy capturing with minimum cost utilization [6].

More detailed research outcomes for dual-axis solar tracker have been proposed in different perspectives. The cheap design of solar tracker for PV systems is designed for educational kit purpose in institutional level which is able to respond dynamically in real-time environment [7]. To solve the problems of non-responsive of solar tracker under low intensity of sunlight, the solar tracker is designed with global positioning system receivers and real-time clock for satellite compass and inclinometer for automatic positioning and tracking to the sun orientation of North-South [8]. Nevertheless, the dual-axis solar tracker has also sort of drawbacks. The dual-axis system requires more investment costs with low efficiency conversion, especially for some locations of the latitudes near the equator. In this case, the use of the single axis system is more recommended regarding the increase in efficiency of 25%-40% [9]. The use of two actuators in a dual-axis system also requires more power consumption. A study in Santa Marta Colombia found that the dual-axis system spends energy consumption of 6.1-6.5 Wh/panels which cause small increase in the output energy of about 9.87% [10].

Based on the above-mentioned problems regarding the solar tracker model and design, there are still open opportunities and challenges to reach the optimal performance of movement to rotate the solar panel towards the sunlight intensity. The prototype dual-axis solar tracker has been designed in our previous research based on Arduino Uno microcontroller performance based on breadth search algorithm of maximum output power of solar panel [11]. The development of dual-axis solar tracker is improved for the better tracking performance in the implementation level which is presented in this article. In this case, the DS3231 timer module is used as input for the Arduino Mega microcontroller and then converted by the sun movement algorithm into the sun's equatorial coordinates in real time. Then, the MPU6050 angle sensor will provide feedback in the form of a solar panel tilt angle for desired tracking process once the tilt angle is obtained. The current proposed solar tracker development is by adding latitude axis or polar axis for the basis axis movement [12]. The addition of axis aims to change the movement of the solar tracker which was originally based on the horizon into equatorial coordinates. Based on the capability movement scenarios, our proposed dual-axis solar tracker design can be utilized not only for solar panel, but also for solar thermal systems such as parabolic through collector systems and solar parabolic concentrator [13,14].

The article is organized as follows where the importance design of solar tracker is consecutively explained with recent literature review as shown in Section 1. Then, the theoritical approach of equatorial mount systems with declination and Hour Angle as the basis method of the proposed solar tracker movement is presented in Section 2. Then, more detailed implementation algorithm regarding the Hour Angle and declination is descibed in Section 3. Sections 4 and 5 present the solar tracker design about the mechanical and electrical control design systems including the discussion of measurement results of Hour Angle, declination and tracking accuracy. Finally, Section 6 provides the conclusion and summary results of our proposed solar tracker performances.

2. **Equatorial Mount Systems.** Equatorial system implements celestial equator as base/mount to define the celestial bodies position. In Figure 1, the equator plane connects the points of East (E) and West (W). The celestial equator position is different at each location, depending on the latitude levels. Therefore, the equatorial system can precisely determine the celestial bodies trajectory because the latitude of the observer (ϕ) is taken into account. Thus, the equatorial coordinates of a celestial body will be the same for each observer even though they are in different location.

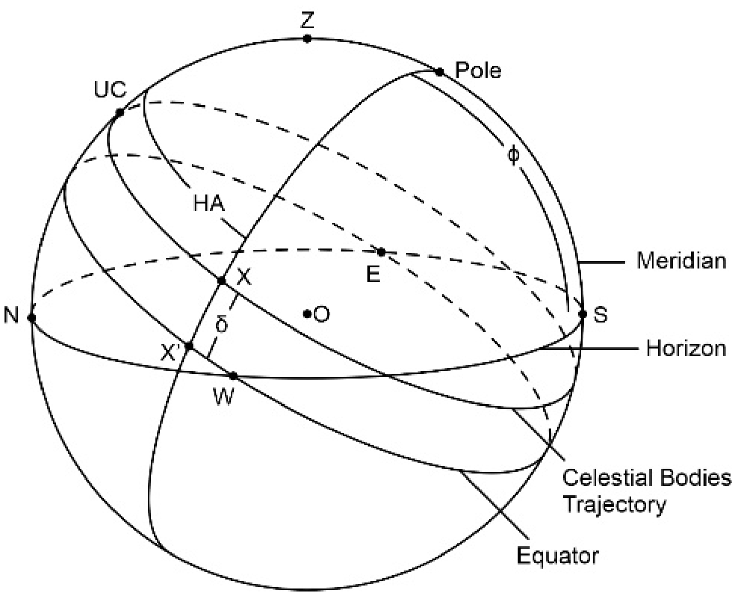

FIGURE 1. Celestial bodies (X) position on equatorial mount system

There are two coordinates of axes in equatorial system, namely declination and Hour Angle [15,16], which are explained as follows.

- Declination (δ) is the angular distance from the equatorial plane along the meridian to the celestial bodies. In Figure 1, declination is the angle between X′ on the equatorial plane to point X on the trajectory of celestial bodies. Declination will be positive if the celestial body is at north of the equator and will be negative if it is at south of the equator.
- Hour Angle (HA) is measured from the culmination (UC) to the West towards the celestial body. The upper culmination is the point where the altitude of the celestial body is maximum. In Figure 1, the HA is the angle between UC as the culmination point to X where the celestial body is located. HA has a positive value indicating that the celestial body has passed the upper culmination point and vice versa.

The trajectory of the sun's motion can be determined accurately with equatorial mount system. Because of the earth rotation, sun apparent moves from East to West, known as sun apparent daily motion [17]. Sun daily motion causes a change to sun Hour Angle coordinate ($HA_{\odot}$) as in (1):

$$HA_{\odot(rad)} = \frac{2\pi(12 - t_{zone})}{24} - (\lambda - \lambda_{zone}) - TEQ \quad (1)$$

where t_{zone} is the local time, $(\lambda - \lambda_{zone})$ is longitude correction component where λ is the longitude of location and λ_{zone} is longitude of meridian defining local time zone, and TEQ

is the time correction. TEQ correction has maximum value of $3^{\mathrm{m}}41^{\mathrm{s}}$ and minimum value of $-6^{\mathrm{m}}30^{\mathrm{s}}$, and the value is negligible if it is small enough.

Besides the Earth rotating around its axis, it also revolves the sun with the trajectory as shown in Figure 2. Due to the tilt of the earth's rotational plane is 23.45°, the sun appears to shift North-South of the sky during the earth's revolution period, known as sun apparent annual motion. Sun annual motion causes a change to sun declination coordinate ($\delta_{\odot}$) which is equal to (2):

$$\delta_{\odot} = 23.45^{\circ} \sin\left(\frac{360(284+n)}{365}\right) \tag{2}$$

where n is the day numbering in a year (i.e., January 1 being $n = 1$).

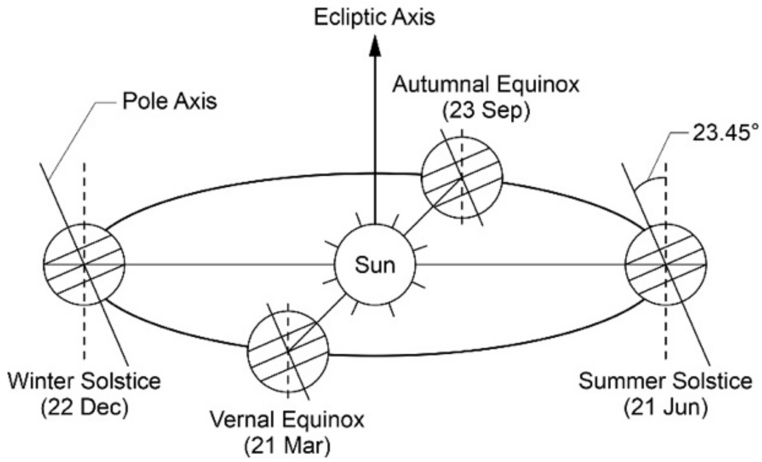

FIGURE 2. Earth revolutionary motion during a year

The approach of equatorial mount systems is taken in this research because it is simpler than the sun's motion with horizontal system. In addition, the sun coordinates will be different at each location when using horizon system. One of the most important points as in (2), the sun declination coordinate values tend to be constant and only the hour angle coordinates constantly change in a day. In contrast to the horizon coordinates, the sun azimuth and altitude both change all the time.

3. **Proposed Tracking Algorithm.** In general, there are two basic solar tracker systems, single and dual-axis systems. In case of dual-axis system (Figure 3), there are two types depending on mount type for relative position of the revolute axes, polar and azimuthal [12]. The mount of polar dual-axis system in Figure 3(a) is tilted equal to latitude value, so the axes will revolute parallel with polar axis and tracking motion will be the same as equatorial system which is discussed previously. Meanwhile, different approach with azimuthal dual-axis system that is commonly used is shown in Figure 3(b).

The proposed tracking method using polar axis solar tracker could be able to perform sun tracking perfectly with lower power consumption. Tracking movement will be based on sun motion algorithm at equatorial mount with characterized simplicity, lower power consumption and effective and reliable mechanical tracking system. The proposed system will convert time variable from RTC DS3231 to roll movement (represented by HA algorithm) and pitch axes (represented by declination algorithm) that is defined using MPU 6050.

3.1. **Hour Angle (HA) motion algorithm.** HA motion represents the daily motion of the sun, shown by Equation (1). Considering the research location (λ) at $119°30'12''$ E that differ less than 0.5° from longitude of meridian (λ_{zone}) for GMT+8 time zone of

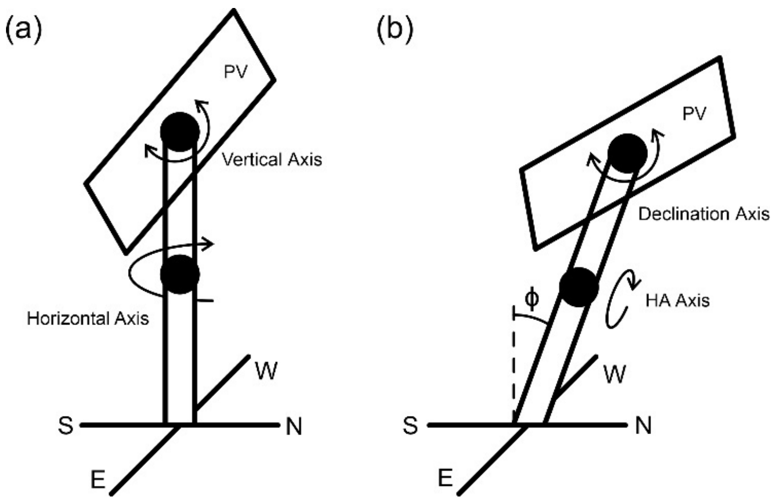

Figure 3. Types of dual-axis solar tracker: (a) Polar and (b) azimuthal

120° and by ignoring the *TEQ* correction, the HA motion algorithm could be simplified by

$$HA_{\odot(rad)} = \frac{2\pi(12 - t_{zone})}{24} \tag{3}$$

where $(12 - t_{zone})$ can be written as time interval from 12 p.m. (t_{12pm}), and $2\pi/24$ can be written as $1^\circ/4^{\mathrm{m}}$.

Considering system reliability by keeping the frame sturdy from the wind and not overloading the motor, the HA tracking is restricted from -45° to 45° or from 09:00 a.m. to 2:56 p.m. The system is also designed to move HA-axis in 1° for every 4 minutes. Therefore, the roll degree (θ_{roll}) value that represents HA for the proposed tracking method could be determined with this following step.

- For 6:00 p.m. $\leq T <$ 09:00 a.m.

$$\theta_{roll} = -45^\circ \tag{4}$$

  At this interval, the roll degree is kept at 45° towards East until tracking mechanism at 09:00.
- For 09:00 a.m. $\leq T <$ 2:56 p.m. (tracking step)

$$\theta_{roll} = 1^\circ + \lfloor HA_\odot \rfloor \tag{5}$$

  At this interval, the roll angle will be adjusted following the sun. Rounding down ($\lfloor HA_\odot \rfloor$) value is expected so that the roll angle value will increase after 4 minutes. The increasing of 1° is intended to make the tracker leads 1° more than the sun motion. For example, at 09:00 a.m., the HA value according to Equation (3) is equal to -45°, the θ_{roll} in Equation (4) is equal to -44°, the tracker leads 1° more than the sun motion.
- For 2:56 p.m. $\leq T <$ 6:00 p.m.

$$\theta_{roll} = 45^\circ \tag{6}$$

  At this interval, the roll degree keeps at 45° towards West until the end of day (6:00 p.m.) and the roll angle will be returned to the East position.

3.2. **Declination motion algorithm.** Declination motion represents the annual apparent motion of the sun, shown by Equation (2). The system is designed to move declination axis as close as possible to the sun declination value at that day. Therefore, the pitch degree (θ_{pitch}) value that represents declination for the proposed tracking method is equal to

$$\theta_{pitch} \approx \delta_\odot \tag{7}$$

Pitch angle will be rounding result of sun declination value from Equation (2). Rounding (≈) is intended so that the pitch angle will be close as possible with the sun declination value.

4. Solar Tracker System.

4.1. Mechanical structure. The mechanical component as shown in Figure 4 based on the polar dual-axis solar tracker where the tilted position by $-5°13'58''$ or $-5.2327°$ according to research location latitude. Frame is driven by Venus Plus 18″ Linear Actuator. The threaded system at linear actuators helps to provide greater torque with less motor efforts. In addition, the angular tilt of the frame can be also maintained because the length of the linear actuator does not change even when the motor is off.

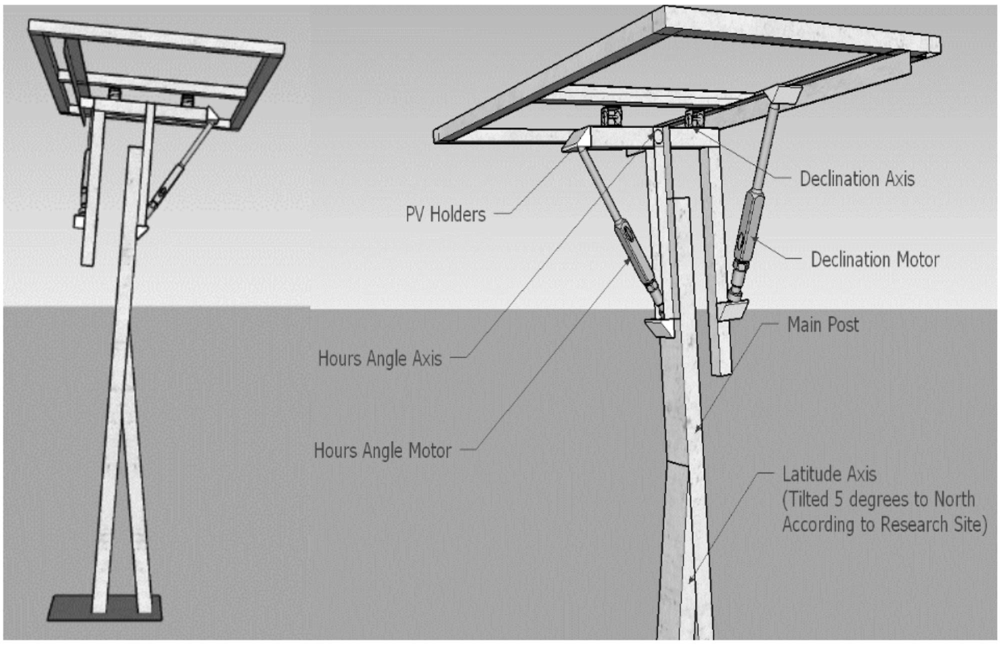

FIGURE 4. Mechanical structure of polar dual-axis solar tracker

4.2. Electrical and control components. The proposed tracking system is designed to be self-powered equipped with battery and charge controller as shown in wiring diagram in Figure 5. The measurement will use 3.4 Ω/200-Watt power resistor as load. The other components are described as follows:

- Buck Converter LM2596 to regulate 5 V voltage;
- Microcontroller Arduino Pro Mini to perform logical function;
- Motor Driver L298N to drive the actuator;
- MPU6050 to define tracker system inclination angel;
- RTC DS3231 to provide local time input;
- Current Sensor ACS712 to measure current;
- Voltage Sensor 25 V to measure voltage;
- SD Card Module to save data.

5. Results and Discussion. The research is conducted at the Electrical Building rooftop of Faculty of Engineering, Universitas Hasanuddin, South Sulawesi, Indonesia with the coordinate position of $-5°13'58''$ South and $119°30'12''$ East. The data performance of solar tracker was recorded for 28 days from 06:00 a.m. to 6:00 p.m. with various types of weather conditions. Overview of measurement result is recapitulated in Table 1. Based

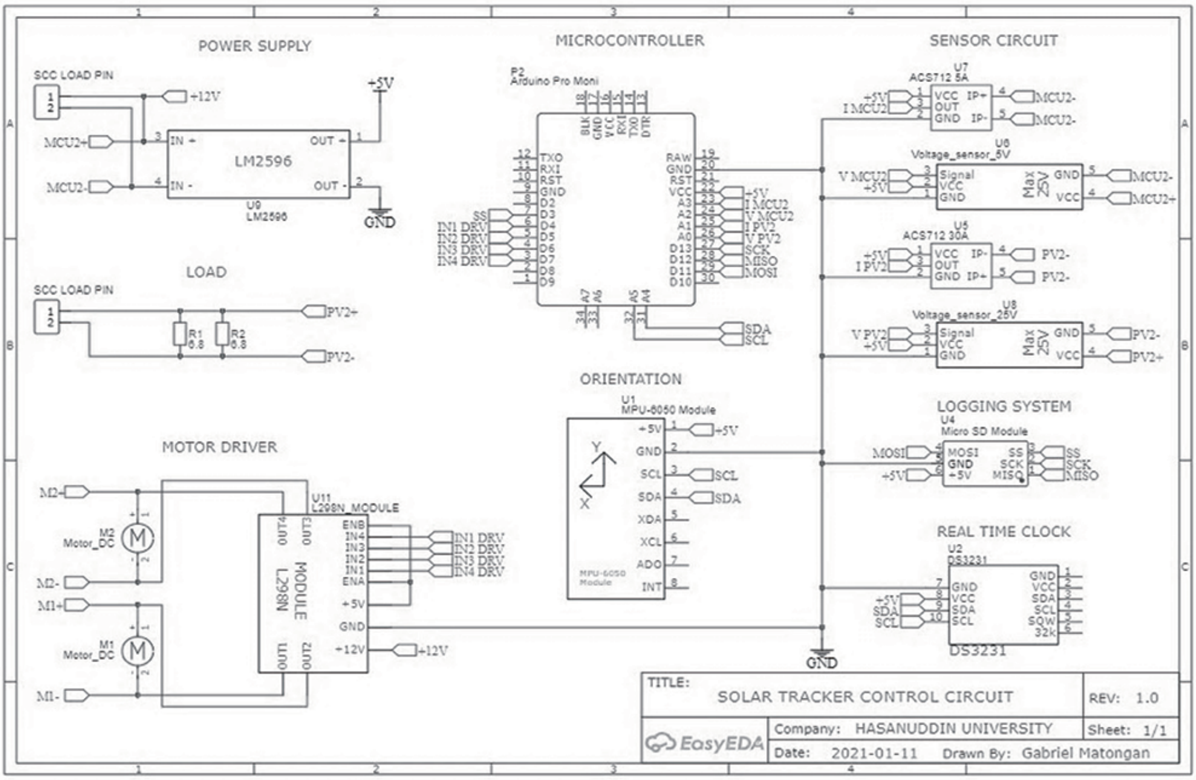

FIGURE 5. Wiring diagram of electrical and control components

on data in this table the energy output of solar panel and energy consumption of solar tracker is explained as follows.

5.1. **Photovoltaic energy output.** The proposed tracking system increases photovoltaic energy output with the average of 56.677% with the highest value 84.455% on 2 August 2021 and the lowest value 30.444% on 17 August 2021. The maximum energy output using and without tracking system was obtained on the same day on 15 August of 856.341 Wh and 516.999 Wh, respectively. Meanwhile, the minimum energy output with and without tracking system was also obtained on the same day on 17 August 2021 of value of 271.176 Wh and 202.139 Wh, respectively. The results indicate that the proposed solar tracking system may support the solar panel to produce more energy output than without solar tracker.

5.2. **Energy consumption.** The proposed tracking system tends to have almost the same value of energy consumption for daily operation with the average of 7.502 Wh. The maximum value is 7.514 Wh which is obtained on 22 August 2021 and the minimum value of 7.487 Wh is obtained on 10 August 2021. The energy consumption value is quite the same because of the similarity of daily tracking mechanism. The activation of declination motor does not provide significant additional power because the declination motor is only active at a very short time interval (1-2 seconds). Thus, the difference in obtained energy consumption value could be from the random factors that affect the current fluctuation when motor is activated. In fact, the overall energy consumption in our proposed solar tracker is guaranteed very low; therefore, it is very prominent to be used in different utilization of solar energy.

5.3. **Mechanical system motion.** The accuracy of solar tracker movement can be measured by mechanical tracking motion. This part is defined using MPU 6050 in two axes motion, which are roll and pitch angles motion. The roll angle represents the hour angel, while the pitch angle at 12:00 represents the angle of declination. The roll angle value

TABLE 1. Overview of measurement results

Date	E_{ST} (Wh)	E_C (Wh)	E_T (Wh)	E_{FX} (Wh)	Energy regulation (%)
29/07/21	632.501	7.508	624.993	404.270	54.598
30/07/21	641.803	7.502	634.301	407.998	55.467
31/07/21	722.592	7.504	715.088	424.314	68.528
01/08/21	354.896	7.511	347.385	255.952	35.723
02/08/21	618.824	7.493	611.331	331.426	84.455
03/08/21	671.266	7.503	663.764	432.763	53.378
04/08/21	664.277	7.496	656.780	441.890	48.630
05/08/21	739.616	7.492	732.124	407.216	79.788
06/08/21	611.459	7.493	603.966	371.792	62.447
07/08/21	761.420	7.490	753.929	470.089	60.380
08/08/21	833.054	7.496	825.558	470.815	75.347
09/08/21	750.352	7.504	742.848	472.994	57.052
10/08/21	761.588	7.487	754.101	486.576	54.981
11/08/21	770.602	7.493	763.109	490.232	55.663
12/08/21	618.343	7.513	610.830	379.373	61.011
13/08/21	661.508	7.497	654.011	422.989	54.617
14/08/21	703.207	7.500	695.707	415.357	67.496
15/08/21	856.341	7.505	848.836	516.999	64.185
16/08/21	788.533	7.512	781.021	506.194	54.293
17/08/21	271.176	7.499	263.677	202.139	30.444
18/08/21	672.054	7.510	664.544	453.801	46.439
19/08/21	629.290	7.500	621.790	431.589	44.070
20/08/21	741.844	7.509	734.335	492.463	49.115
21/08/21	469.331	7.501	461.830	295.990	56.029
22/08/21	779.708	7.514	772.193	510.575	51.240
23/08/21	786.499	7.500	778.999	487.669	59.739
24/08/21	732.081	7.511	724.570	489.117	48.138
25/08/21	493.090	7.502	485.588	315.903	53.714
Max	**856.341**	**7.514**	**848.836**	**516.999**	**84.455**
Min	**271.176**	**7.487**	**263.677**	**202.139**	**30.444**
Avg	**669.188**	**7.502**	**661.686**	**421.017**	**56.677**

Remarks:

E_{ST} = Energy output production by the proposed tracking system

E_C = Energy consumption of solar tracker

E_T = Net value of energy output ($E_{ST} - E_C$)

E_{FX} = Energy output without solar tracking system

% = Percentange of energy output regulation [$(E_T - E_{FX})/E_{FX} \times 100\%$]

tends to be the same for each day because HA tracking mechanism is always the same for each day. In comparison, the pitch angle seems to be shifted slowly for every few days. The measurement result shows that the pitch angle value at 12:00 on 29 July 2021 is 19° and it is slowly shifted until reaching the 11° on 25 August 2021. This mechanism is caused by sun apparent annual motion that changes the sun declination value.

In terms of tracking system error validation, the accuracy of the tracking system is determined by the compared measurement between actual test movement and the sun movement algorithm. This validation is conducted on daily and annual movements of solar tacker. For daily movement, the roll angle from MPU6050 is compared with the sun Hour Angle (HA) value in Equation (3). In this case, the HA validation shows the error value is always below 3 degrees toward East and West for 28 days of data recording. For annual movement, the pitch angle at 12:00 (represent tracking system declination) from MPU6050 will be compared with the sun declination value from Equation (2). The validation results show the maximum error deviation is 0.837°, which was obtained on 11 August 2021.

6. **Conclusions.** The performance of the proposed solar tracker system shows significant energy output increases with average value of 56.677% compared to fixed mount system of solar panel. The percentage maximum value is achieved of 84.455% on 2 August 2021 and the minimum value is 30.444% on 17 August 2021. The proposed tracking method also can perform tracking mechanism with the loss tracking energy consumption with average value of 7.502 Wh with the maximum value of 7.514 Wh on 22 August 2021 and the minimum value of 7.487 Wh on 10 August 2021. For tracking accuracy, the daily tracking (HA tracking) shows high tracking accuracy with error value below 3° toward East and West for 28-day data recording. For annual tracking (declination tracking), the solar tracker could perform high accuracy tracking with maximum error value of 0.837°. The overall results indicate that the proposed solar tracker design is feasible to any solar energy utilization that needs the motion with perpendicular direction towards the sun.

REFERENCES

[1] A. El Hammoumi, S. Chtita, S. Motahhir and A. El Ghzizal, Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels, *Energy Reports*, vol.8, pp.11992-12010, 2022.

[2] S. Abdallah, The effect of using sun tracking systems on the voltage-current characteristics and power generation of flat plate photovoltaics, *Energy Conversion and Management*, vol.45, nos.11-12, pp.1671-1679, 2004.

[3] A. Pirayawaraporn et al., Innovative sensorless dual-axis solar tracking system using particle filter, *Applied Energy*, vol.338, 2023.

[4] R. Ramful and N. Sowaruth, Low-cost solar tracker to maximize the capture of solar energy in tropical countries, *Energy Reports*, vol.8, no.15, pp.295-302, 2022.

[5] S. S. Mohammad, S. J. Iqbal and R. A. Lone, Improved utilization of solar energy using estimated optimal tilt factor and trackers, *Energy Reports*, vol.8, no.14, pp.175-183, 2022.

[6] A. Soetedjo, I. B. Sulistiawati and Y. I. Nakhoda, Integration of solar tracker and maximum power point tracking for improving Photovoltaic (PV) system efficiency, *International Journal of Innovative Computing, Information and Control*, vol.16, no.2, pp.429-443, 2020.

[7] A. N. Vargas et al., Low-cost dual-axis solar tracker with photovoltaic energy processing for education, *Sustainable Energy Technologies and Assessments*, vol.53, 2022.

[8] C.-H. Wu, H.-C. Wang and H.-Y. Chang, Dual-axis solar tracker with satellite compass and inclinometer for automatic positioning and tracking, *Energy for Sustainable Development*, vol.66, pp.308-318, 2022.

[9] H. M. Fahad, A. Islam, M. Islam, M. F. Hasan, W. F. Brishty and M. M. Rahman, Comparative analysis of dual and single axis solar tracking system considering cloud cover, *Int. Conf. on Energy and Power Engineering (ICEPE): Power for Progress*, pp.1-5, 2019.

[10] C. R. Algarín, A. O. Castro and J. C. Naranjo, Dual-axis solar tracker for using in photovoltaic systems, *International Journal of Renewable Energy Research*, vol.7, no.1, pp.137-145, 2017.

[11] Syafaruddin, Gassing, F. A. Samman, N. Umniyah and F. Febriyana, Arduino Uno AVR ATmega328 microcontroller based dual axis solar tracker design, *ICIC Express Letters, Part B: Applications*, vol.13, no.4, pp.337-345, 2022.

[12] C. Alexandru and C. Pozna, Simulation of a dual-axis solar tracker for improving the performance of a photovoltaic panel, *Processdings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol.224, no.6, pp.797-811, 2010.

[13] T. Q. Saldivar-Aguilera, L. M. Valentín-Coronado and J. A. Dena-Aguilar, Novel closed-loop dual control algorithm for solar trackers of parabolic trough collector systems, *Solar Energy*, vol.259, pp.381-390, 2023.

[14] A. H. Asfaw, Manual tracking for solar parabolic concentrator – For the case of solar injera baking, Ethiopia, *Heliyon*, vol.9, no.1, pp.1-17, 2023.

[15] H. Karttunen, P. Kröger, H. Oja, M. Poutanen and K. J. Donner, *Fundamental Astronomy*, Springer Berlin Heidelberg, 2016.
[16] A. E. Roy and D. Clarke, *Astronomy: Principles and Practice*, 4th Edition (PBK), Taylor & Francis, 2003.
[17] B. Sørensen, Engineering information, in *Renewable Energy*, Elsevier Science, 2004.