

Article

Design and Implementation of a Dual-Axis Solar Tracking System

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Abstract: A dual-axis solar tracking system with a novel and simple structure was designed and constructed, as documented in this paper. The photoelectric method was utilized to perform the tracking. The solar radiation values of the designed system and a fixed panel system were theoretically estimated and compared, showing that the proposed system is more efficient in collecting solar energy than a fixed solar panel with a 30° tilted fixed surface facing south. The experimental results verified the validity of the prediction as well as the efficiency of the proposed solar tracking system. In a comparison of the data obtained from the measurements, 24.6% more energy was seen to have been obtained in the dual-axis solar tracking system compared to the fixed system. This study possesses potential value in small- and medium-sized photovoltaic applications.

Keywords: solar tracking system; solar panel; dual-axis; solar angles; photoelectric tracking method

1. Introduction

Due to the already high and constantly increasing demand for energy worldwide, the exploitation of various conventional energy sources has been induced [1]. Considering the environmental issues that non-renewable energy sources cause—for instance, the emission of greenhouse gases—renewable sources of energy such as solar, wind, biomass and hydro have been adopted to limit and reduce this degradation [2]. Among these, solar energy holds significant promise [3], as it is one of the most abundant, clean, cost-free and inexhaustible resources of energy. To convert solar energy into electrical energy, Photovoltaic Voltage (PV) solar panels have been widely used as important components of solar tracking systems [4]. A PV solar panel comprises a large number of solar cells composed of silicon-like semiconductors. It works by transferring the energy of photons from sunlight that strikes the solar cells to silicon electrons, which then flow through electrodes and the external circuit and generate an electric current [5].

Fixed solar panels have been utilized over the past few decades since fixed tracking can easily accommodate harsh environmental conditions [6]. There are three typical structural installations for fixed solar panels: namely, fixed-angle, vertical and season-adjusted fixed-angle installations. Fixed-angle solar panels have been extensively applied in large solar power stations [7] and rooftop solar tracking systems [8], while vertical panels are available for vertical structures with limited space, such as the façades of high-rise buildings [9,10]. With season-adjusted fixed-angle systems, the solar panels' tilt angles in the horizontal direction can be modified for seasonal variations in order to maximize the collected amount of solar radiation [11,12]. Nevertheless, angle adjustment is not that convenient due to many site attributes, such as security measures for working on rooftops or other high buildings and the human cost of adjusting a large number of solar panels in solar power stations.

Compared to fixed solar panels, solar tracking systems [13] that can track the position of the sun based on both the season and the moment of each day have higher solar energy collection efficiency [14], thus possessing broader applications and higher research value.



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Based on the different degrees of freedom of structures, there are two different types of solar tracking systems: single-axis and dual-axis [15,16]. The former is designed to track the sun on a single axis according to the azimuth angle, while the latter is designed to track it via dual axes corresponding to the azimuth and solar altitude angles. In recent years, novel technologies and designs for both types have been developed to achieve high control accuracy and structural reliability for these systems' practical performance.

For the design of single-axis solar tracking systems, Poulek and Libra [17] have proposed a simple solar tracker based on a new auxiliary bifacial arrangement connected directly to a Direct Current (DC) motor; Mavromatakis and Franghiadakis [18] have presented an azimuthal tracker with the capability of moving the collector's plane in two directions via a special support structure so as to be efficient in smaller photovoltaic solar applications; Kim et al. [19] have designed a single-axis Compound Parabolic Concentrator (CPC) tracking solar collector and found it more stable and efficient than stationary CPC solar collectors through a numerical evaluation of its performance; Kiyak and Gol [20] have developed a single-axis solar tracking system based on both fuzzy logic and a Proportional Integral Derivative (PID) controller and found via experimental results that the efficiency of the fuzzy logic was much higher than that of the PID controller; and Li et al. [21] have proposed a new solar tracking approach based on kirigami by taking the advantage of paper-like Organic Photovoltaics (OPVs) made on flexible substrates, thus providing stretchability and robustness.

Even though it is easier and more economical to construct single-axis solar tracking systems, considering the higher possibility of the solar panels of dual-axis tracking systems facing the sun perpendicularly and thus resulting in higher energy collection efficiency, an increasing number of investigations of dual-axis tracking systems have been conducted recently. Abdallah and Nijmeh [22] designed and constructed an electromechanical dual-axis solar tracking system with an open-loop Programmable Logic Controller (PLC). Their experimental study showed that the measured solar energy collected on the system's moving surface was significantly larger than that on a fixed surface. Sungur [23] focused on the design of programmable logic control for a dual-axis solar tracking system and experimentally verified that 42.6% more energy could be obtained from the system than from PV panels at fixed positions. Based on the derivation and calculation of the mathematical formulation of a dual-axis solar tracking system using its mechanical components and photoresistances, Kentli and Yilmaz [24] proposed a system that could produce 30% more energy than a fixed one. Syafii et al. [25] have presented a sensorless dual-axis solar tracker based on a database of sun positions that uses sunrises and sunsets, created from exact calculations of solar azimuths, elevations/geographic locations, altitudes and time zones. According to theoretical studies of solar angles, which used time and geographic parameters, in Tunisia, Skouri et al. [26] constructed three accurate dual-axis solar tracking systems. Laseinde and Remere [27] have developed a maximum power point tracking algorithm for a dual-axis servo motor feedback tracking system using an Arduino board, showing the advantages of energy and space savings. Al-Rousan et al. [28] have proposed a dual-axis solar tracking system by integrating supervised logistic regression and a supervised multilayer perceptron in order to increase the accuracy of tracking prediction. It is not hard to observe that, compared to the structural design of dual-axis solar tracking systems, more attention has been paid to the design of their control systems [29].

In the present study, a simple dual-axis solar tracking system has been designed and implemented. The outline of this paper is as follows: The designed structure and the operational principle of the system are presented in the next section. The collection efficiency of solar energy is discussed analytically in Section 3. Experimental results are provided to illustrate the efficiency of the solar energy collection system in Section 4. Finally, Section 5 contains a discussion and conclusions.

2. Structural Design and Operational Principles of the Solar Tracking System

The mechanical structure of the system, shown in Figure 1, includes solar panel components, gears, support members, power storage units, photodiodes and control modules. In this solar tracking device, a Microcontroller Unit (MCU) is the core controller that analyzes the signals transmitted from each component and controls the motor to rotate the solar panel to the appropriate angle. Photoresistors on the boundaries of the solar panel are used to adjust the device. The battery stores power transferred from solar energy and supplies it to the control modules and the dynamic devices.

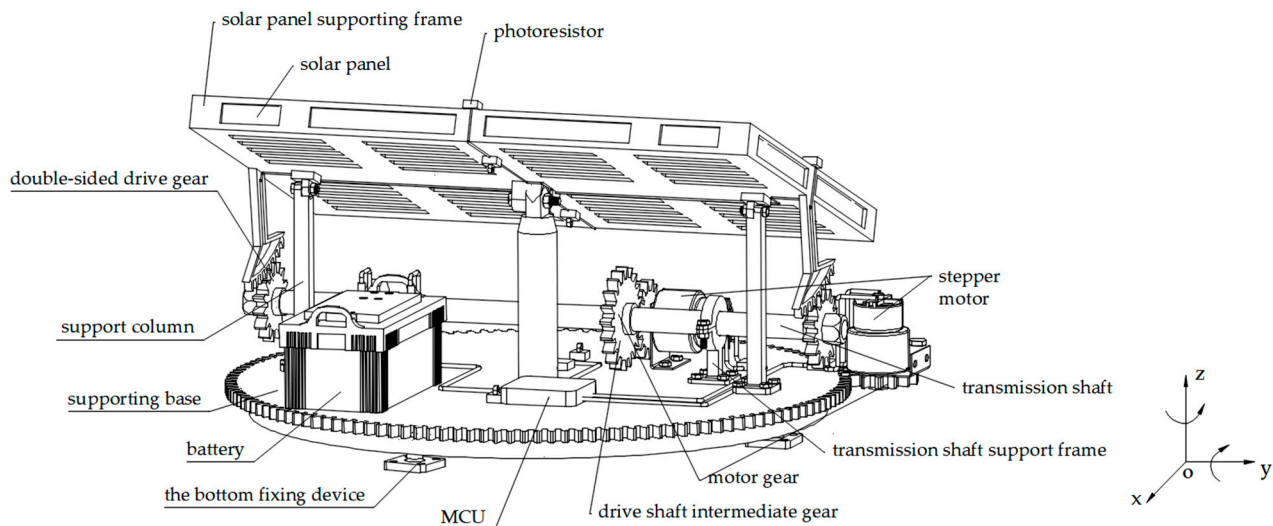


Figure 1. Structure diagram of the solar tracking device.

For dual-axis solar tracking performance, the structure in Figure 1 should have the ability to rotate in the east–west and south–north directions. The components that fulfill this rotation can be seen in Figure 2. For the rotation of the solar panel in the east–west direction, the supporting base is driven by a motor gear. A diagram of its bottom is depicted in Figure 2a, illustrating that the bottommost fixed device is placed on the ground and linked by a supporting base and pins. In the center of the supporting base, there is a base bearing. The stepping motor can lead to the rotation of the base via driving the motor gear, thus inducing the east–west rotation of the solar panel on the base, namely, the rotation in the plane xOy . For the south–north rotation of the solar panel, i.e., the rotation in the plane xOz , the stepping motor can trigger the rotation of the solar panel’s supporting frame by driving the rotations of the motor gear, the intermediate drive shaft gear, the transmission shaft and the double-sided drive gears (see Figure 2b). Accordingly, the rotations of the panel in both directions are independent of each other.

As shown in Figure 2, for the spur gears to perform the rotation, a 20° pressure angle was set, as it is the preference of most designers [30]. The solar panel was set to be a rectangular shape with a length of 840 mm, a width of 600 mm and a thickness of 20 mm. Considering the stability of the base of the solar panel, the pitch diameter of the base gear was set to nearly the diagonal length of the solar panel, namely, $d_{pb} = 996$ mm. Since the most common module for spur gears is 6 mm [30], we set the module for the gears of this device at $M = 6$ mm. The number of teeth on the base gear can be calculated as $N_1 = \frac{d_{pb}}{M} = 166$. For the motor gear meshed with the base gear, we used the dimension of the pitch diameter, $d_{pm} = 90$ mm; thus, the number of teeth is $N_2 = 15$. On this basis, in Figure 2b, the gear ratio is $m_{G1} = \frac{N_1}{N_2} = 11.07$, and the dimensions of the gears are used as follows: the pitch diameter of the driving shaft intermediate gear, $d_{ps} = 120$ mm, and the number of teeth, $N_3 = 20$; the pitch diameter of the double-sided drive gears being the same as that of the motor gear in Figure 2a, i.e., $d_{pm} = 90$ mm, and the number of teeth of each gear, $N_2 = 15$; and the pitch diameter of the transmission shaft on the solar panel

supporting frame, $d_{pt} = 462$ mm, and its number of teeth, $N_4 = 77$. From the gear ratio in Figure 2b, the following can be concluded:

$$m_{G2} = \frac{d_{ps}d_{pt}}{d_{pm}^2} = \frac{N_3N_4}{N_2^2} = 6.84. \quad (1)$$

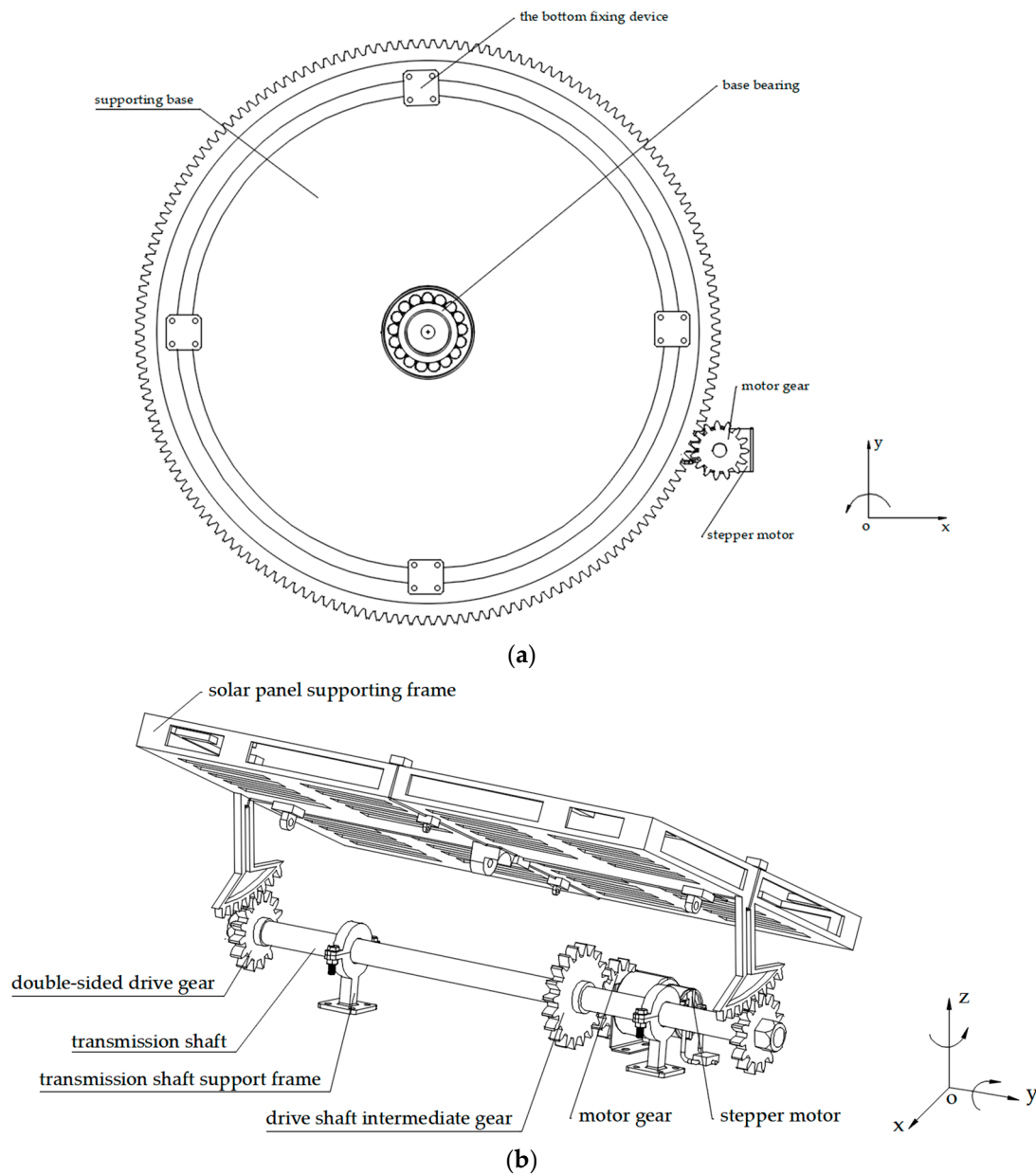


Figure 2. Components to perform rotation in two directions: (a) east–west and (b) north–south.

We then applied the photoelectric method [31] of solar tracking. This method depends on the outputs of the photoresistors on the edges of the solar panel, as shown in Figure 1. Here, we note the signals of the photoresistors on the upper, lower, right and left edges with the coefficients m_1 , m_2 , m_3 and m_4 , respectively. The route of the photoelectric tracking method of the designed structure is displayed in Figure 3. m_1 and m_2 were converted into digital signals with an Analog/Digital (A/D) conversion circuit and transferred to the MCU, which then induced the rotation of the stepping motor so as to lead to the rotation of the solar panel's supporting frame, as shown in Figure 2b. This process is for the panel adjustment of the rotation in the south–west direction, which would not stop until the values of m_1 and m_2 were equal. Considering that this solar tracking system is sensitive

to practical weather disturbances such as clouds and shadows, we set the equality of m_1 and m_2 to mean that m_1 was within the range of 97.5% to 102.5% of m_2 . A tolerance range of $\pm 2.5\%$ was adequate for this application. For the adjustment of the rotation in the east–west direction, the process was similar; the deterministic parameters were m_3 and m_4 . The solar tracking was completed when the adjustment in the two directions was finished.

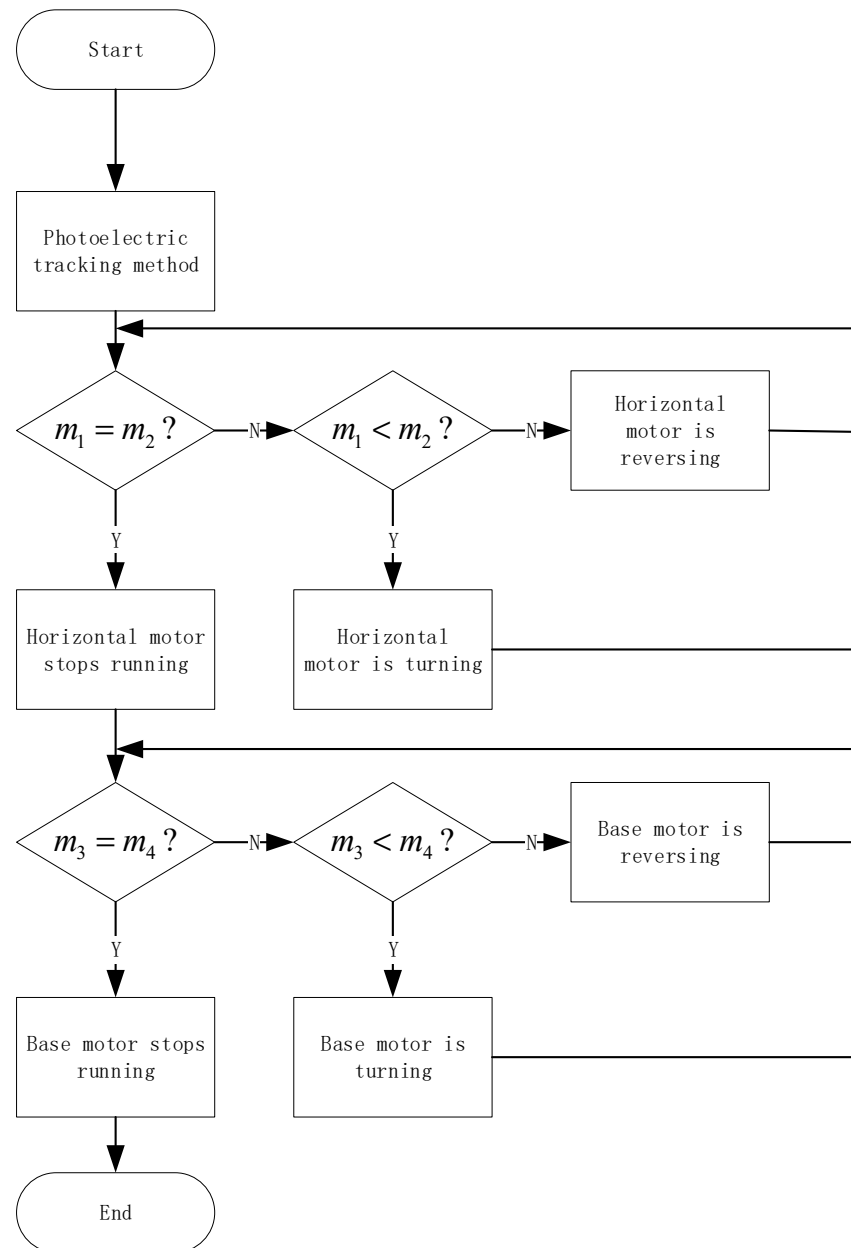


Figure 3. Control algorithm of the solar tracking system.

The PID control algorithm [31] was utilized to carry out the control of the intermittent position adjustments made by the motors. The control logic was simple, with a fast reaction time to meet the requirements of the device. The process included several steps. First, the tracking error, $m_1 - m_2$ or $m_3 - m_4$ and the output of the control term in direct proportion to this error were calculated. Next, the proportional effect provided a quick initial response by enabling the tracking device to rapidly move toward the target position. Then, based on the error signal, the integral control term constantly adjusted the position of the device, thus eliminating steady-state errors. When the target position was nearly reached, the error would decrease, and the differential control term would respond to the change in the error.

If the change were too rapid, the differential effect would generate a reverse control output to slow down the rate of the change, thus suppressing the overshoot and oscillation of the system. Since each adjustment was independent, there was no cumulative error over time in the system.

In the structure of the proposed solar tracking system, a few gears driven by step motors could make the solar panel rotate in two directions to perform the tracking. Additionally, the solar supporting frame and columns, designed to distribute vertical pressure, could avoid the bulking instability of the components. The structure is simple, with not many components, and it is easy to follow the working principle of the control of this system. Hence, the designed dual-axis solar tracking system can be easily installed and assembled, which may also reduce the maintenance and possibility of failure of the system.

3. Energy Harvesting Efficiency Analysis

On the basis of the photoelectric tracking method, we analytically evaluated and compared the total radiation of the solar panels of the designed and fixed systems in the same location and with the same weather. To this end, formulas to determine the relevant parameters, such as time, declination angle, day length, hour angle and ratio of hourly radiation, were expressed at first.

We adopted the time parameter reported in Ref. [32]. The Equation of Time (EoT) for each day of the year is expressed as:

$$EoT(N) = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B), \quad (2)$$

where

$$B = \frac{360(N - 81)}{364}, \quad (3)$$

and N is the day number. For instance, on 1 January, $N = 1$.

The corresponding declination angle in degrees is expressed as the following formula:

$$\delta = 23.45 \sin\left(\frac{360(284 + N)}{365}\right), \quad (4)$$

based upon this, the hour angle at sunset and the length of the day in hours can be expressed as follows:

$$h_{ss} = \arccos(-\tan(L) \tan(\delta)), \quad D_l = -\frac{2}{15} \tan(L) \tan(\delta), \quad (5)$$

respectively. Here, the parameter L represents the local latitude. Since the time intervals between noon and sunrise/sunset are equal, the following number, n , was introduced to note the time interval in hours:

$$n = \left\lfloor \frac{D_l}{2} \right\rfloor, \quad (6)$$

within each time interval, namely, the number of the exact ranges from 1 to n , the angle for each hour can be expressed as:

$$h_i^{\pm} = 15^\circ (LST + EoT(N) \pm 4(SL - LL) - 12) \quad i = 1 \dots n, \quad (7)$$

where LST means Local Standard Time, SL means Standard Longitude and LL means Local Longitude. The plus and minus signs in Equation (7) correspond to cases of afternoon hours and morning hours, respectively. The solar incidence angle, θ_i , in each hour, depending on the location of the solar panel, is expressed as:

$$\theta_i = \arccos(\sin(L \pm \beta_0) \sin(\delta) + \cos(L \pm \beta_0) \cos(\delta) \cos(h_i)) \quad i = 1 \dots n, \quad (8)$$

where β_0 is the tilt angle of the fixed solar surface from the horizontal plane, and the plus and minus signs apply to the locations of the solar panel in the northern and southern hemispheres, respectively.

Thus, the ratio of hourly to daily total radiation can be written as:

$$r_i^{\pm} = \frac{15\pi(a + b \cos(h_i^{\pm}))(\cos(h_i^{\pm}) - \cos(h_{ss}))}{360 \sin(h_{ss}) - 2\pi h_{ss} \cos(h_{ss})} \quad i = 1 \dots n, \quad (9)$$

where

$$a = 0.409 + 0.5016 \sin(h_{ss} - 60^{\circ}), \quad b = 0.6609 - 0.4767 \sin(h_{ss} - 60^{\circ}), \quad (10)$$

on this basis, the energy collected by the stationary solar tracking system for the whole day can be obtained as follows:

$$W_{fixed} = HS\eta \sum_{i=1}^n r_i^{\pm} \cos(\theta_i). \quad (11)$$

In the above equation, the parameters H , S and η represent the daily solar irradiation per unit area, the solar panel area and the energy conversion efficiency of the solar panel, respectively. Here, it is worth mentioning that the case for $\cos \theta_i < 0$ does not mean the dissipation of solar energy via the solar panel; instead, it indicates that the sun is behind the solar panel and, thus, no solar energy can be harvested. Therefore, when $\cos \theta_i < 0$, we set $\cos \theta_i = 0$ in Equation (11). In most of the daylight hours, for the fixed panel, $\theta_i \neq 0$, namely, $\cos \theta_i < 1$.

For differences in the solar tracking system with the same solar panel and under the same weather conditions, since the solar tracker keeps the solar panel perpendicular to the solar radiation during daylight hours, $\cos(\theta_i) = 1$. As the sum of the ratio, $r_i^{\pm}$, for a whole day, $\sum_{i=1}^n r_i^{\pm} = 1$. The collected energy of the solar tracking system for the same day would be:

$$W_{tracked} = HS\eta, \quad (12)$$

obviously, $W_{tracked} > W_{fixed}$.

Taking the location at the 30.8466° latitude and 121.5164° longitude in Shanghai, China, as an example, the exact period we considered was five days long, from 27 March 2023, to 31 March 2023. Assuming sunny weather, we calculated the approximate collected energy of the solar panels of the fixed solar panel and the proposed solar tracking system. The values of some related parameters are provided in Table 1.

Table 1. Parameter table of values for calculation.

Symbol	Meaning	Value
LST	Local Standard Time	China Standard Time
N	Annual Solar Altitude Days	From 86 to 90
SL	Standard Longitude	120° East Longitude
LL	Local Longitude	121.5164° East Longitude
L	Latitude	30.8466° North Latitude
β_0	Tilt Angle of the Fixed Surface from Horizontal	30°

In substituting the values of the parameters in the above table in Equations (11) and (12) and noting the average collected energy of the five days as:

$$\tilde{W}_{fixed} = \frac{1}{5} \sum_{N=86}^{90} W_{fixed}^N, \quad \tilde{W}_{tracked} = \frac{1}{5} \sum_{N=86}^{90} W_{tracked}^N, \quad (13)$$

we obtained

$$\frac{\tilde{W}_{tracked} - \tilde{W}_{fixed}}{\tilde{W}_{fixed}} \approx 26.7\%, \quad (14)$$

implying that ideally, the energy collected via the designed solar tracking system would be much higher than that of the fixed solar panel on a daily basis.

Whether the designed solar tracking system can be more efficient in energy harvesting than the fixed system depends on not only the extra energy collected but also the energy consumption required to control and drive the solar panel rotation in each system. Expressing $\tilde{W}_{tracked}$ as the average power of the solar panel, P_{sp} , and the length of the day, D_l , and substituting their form into Equation (14) yielded:

$$\tilde{W}_{tracked} = D_l P_{sp}, \quad (15)$$

and

$$W_{extra} = \tilde{W}_{tracked} - \tilde{W}_{fixed} = 0.2111 D_l P_{sp}. \quad (16)$$

Next, we applied two stepping motors to the designed system. Every half hour, the selected motors could work for 30 s, hence operating up to 4n times per day. Their working period for each time is $t_m = \frac{1}{120}$. Considering that the stepping motor operates at full power and the total power consumption of the sensors and other control modules is negligible relative to the energy consumption of the motor [33], the energy consumption of the stepping motor can be written as:

$$W_{consume} = 8nt_m P_m = \frac{[D_l]}{30} P_m \quad (17)$$

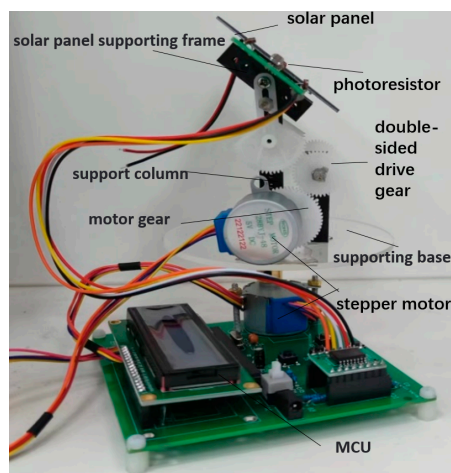
since the designed structure is lightweight with typical materials [34], the power of the motor to drive the rotation, P_m , can be less than P_{sp} . Comparing the extra collected energy, W_{extra} , and the consumed energy of the device, $W_{consume}$, yields:

$$\frac{W_{extra}}{W_{consume}} = \frac{6.333 P_{sp}}{P_m} \gg 1. \quad (18)$$

It follows that the increase in collected energy when the proposed solar tracking device is used to replace the fixed one can be far greater than the energy consumed in driving the designed device, demonstrating the energy-harvesting efficiency of the designed system.

4. Experimentation and Results

In this section, experimental measurements are documented to verify the validity of our analysis as well as the efficiency increase for solar energy with the designed solar tracking system. A continuous test was carried out for 5 days, from 27 March to 31 March, at the Shanghai Institute of Technology, Shanghai, China. The location of this test was in Southeast China, at the latitude and longitude illustrated in Table 1. The outdoor temperature ranged from 9 °C to 20 °C. Pictures of the prototype of the designed solar tracker and the stationary solar panel are provided in Figure 4. Here, the dimensions of the prototype depicted in Figure 4a were one-tenth of the dimensions of the numerical model shown in Figure 1. The two solar panels, made of polysilicon, had the same-sized rectangular shape, with a length of 84 mm, a width of 60 mm and a thickness of 2 mm. Their maximum open-loop voltage was 6.3 V. The supporting base of the structure was made of polymethylmethacrylate (PMMA) plastics, and the double-sided drive gears, the motor gear, the support columns and the support frame of the solar panel were all made of polyoxymethylene (POM) plastics. We selected a 28BYJ-48 stepping motor with a working voltage range of 5 V–12 V and a step angle of $\frac{1}{64}^\circ$, as well as an STC89C 52 MCU with a working voltage of 3.3 V and photoresistors with a light resistance range of 2 kΩ–5 kΩ and a dark resistance of 200 kΩ. The fixed-surface solar panel, tilted at 30° toward the south with the same-sized solar panel, is presented in Figure 4b.



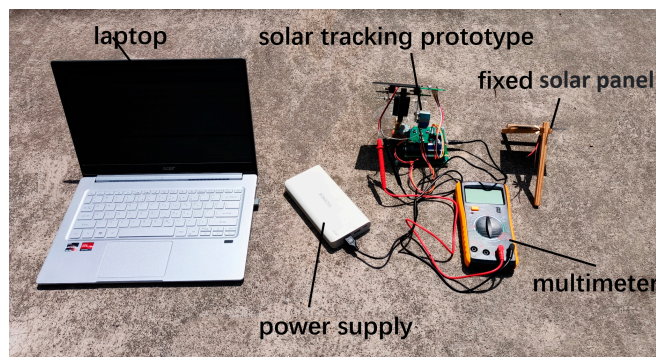
(a)



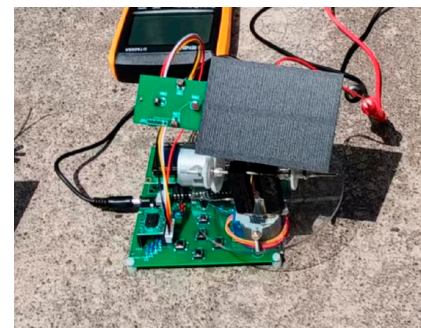
(b)

Figure 4. Installation of two solar panels: (a) tracking prototype and (b) fixed panel.

Both solar panels were installed facing the south and tested in outdoor field work. The experimental apparatus is illustrated in Figure 5. The multimeter was mounted between the dual-axis tracking device and the fixed solar collector, connecting to the data logger, which was in turn connected to a computer. Multimeter readings were recorded every hour. The collected and stored data were processed utilizing Microsoft Excel, and the measured solar radiation values were averaged to obtain the average hourly solar radiation power in Watts. The mobile power supply provided energy for the mechanical system during the solar tracking process.



(a)



(b)

Figure 5. Experimental apparatus: (a) the experimental setup and (b) the solar tracking system in operation.

Based on Equation (6), we calculated that from 27 March to 31 March 2023, the day lengths in hours were 12.16, 12.19, 12.22, 12.26 and 12.29, respectively. The average number of daylight hours was 12.22. For the convenience of measurement and calculation, we set the daytime for each day in the experimental period at 12 h: namely, from 6 a.m. to 6 p.m. Hence, we collected the average solar radiation power values of the two panels for each hour, measured from 6 a.m. to 6 p.m., as shown in Figure 6. The energy power of the solar tracking device was observed to be higher than that of the fixed panel during the daytime. Additionally, the solar radiation power of the two panels both increased from 6 a.m. to noon, i.e., 12 p.m., but decreased from 12 p.m. to 6 p.m.

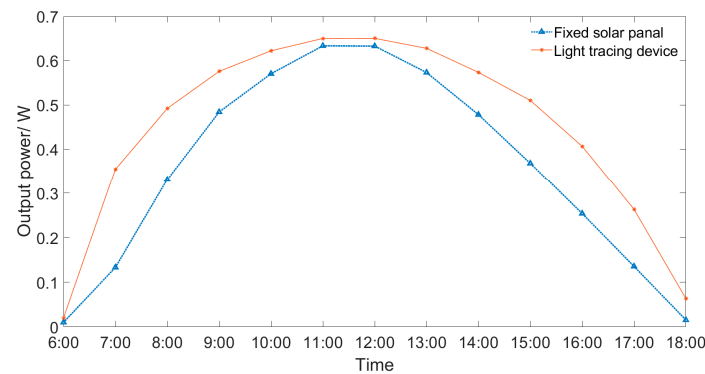


Figure 6. Output power comparison of the two solar panels.

Via multiplication by the time interval, Δt , the experimental solar radiation values $P_{tracked}^i$ and P_{fixed}^i can be used to express the collected energy, $W_{tracked}$ and W_{fixed} , respectively, as follows:

$$W_{tracked} = \sum_{i=0}^{2n} \frac{P_{tracked}^i + P_{tracked}^{i+1}}{2} \Delta t, \quad W_{fixed} = \sum_{i=0}^{2n} \frac{P_{fixed}^i + P_{fixed}^{i+1}}{2} \Delta t, \quad (19)$$

here the time interval, Δt , is one hour, i.e., 3600 s, and $P_{tracked}^i$ and P_{fixed}^i represent the experimental values of the designed solar tracking system and the fixed solar panel, respectively, at the i -th hour after 6 a.m. For instance, $P_{tracked}^0$ and P_{fixed}^0 are the data for 6 a.m. Since the daytime is, at most, $2n$ hours, $P_{tracked}^{2n+1}$ and P_{fixed}^{2n+1} are both zero. According to the data in Figure 6, we could calculate that $W_{tracked} = 20768.4$ J, $W_{fixed} = 16664.4$ J, and

$$\frac{W_{tracked} - W_{fixed}}{W_{fixed}} \approx 24.6\%. \quad (20)$$

Comparing the experimental values above with the ideal value predicted in Equation (14), i.e., 26.7%, we could see the agreement of the experimental and theoretical results, which indicates that the proposed device is accurate enough to collect most of the solar energy of an ideal tracker. Considering that the energy consumed by its mechanical system during the tracking of the sun has such a negligible value that it can be omitted, the solar tracking system that we designed and constructed is more efficient in collecting solar energy than the fixed panel.

Compared to the fixed panel, the rough estimations of the extra cost for materials and labor and the extra collected energy of the prototype are CNY 3.98 and 0.4161 kilowatt-hours per year, respectively. Considering the local electricity price, it will take us nearly 14 years to recover the cost. The extra collected energy of the full-scale solar tracker is nearly 100 times that of the prototype, while the extra cost did not increase that much since some components chosen for the prototype, such as the MCU, photoresistors, crystal oscillator, switch, D/A converter, connectors and circuit board, are still available. Additionally, in the case of an industrial product, the price of the materials will be much lower than the estimation above. Taking more materials and motors with higher power into account, it is expected that the extra cost of the full-scale device with the same-sized fixed panel will be 10 times that of the prototype. Therefore, the period for paying back the extra cost of the full-scale device will be significantly reduced to 1.4 years, implying that after that time, the full-sized solar tracker can be more economical in collecting energy than the full-scale fixed panel.

5. Discussion and Conclusions

In this study, a novel dual-axis solar tracking system was designed and constructed to enhance solar radiation yield. The proposed structure is simple, as it consists of a small

number of components, among which a few gears driven by step motors will make the solar panel rotate in two directions for solar tracking. The working principles of the structure and the control algorithm are easy to follow. The photoelectric method was utilized for solar tracking. An extensive analysis of the total daily energy collection of the system was performed. According to the results of these measurements, the prototype solar tracker functioned as expected, specifically for small-sized solar panels. In Shanghai, China, where the experiment was conducted, 24.6% more energy was obtained from the solar panel that tracked the sun on two axes when compared with that of the 30° tilted fixed-surface panel.

The proposed dual-axis solar tracking system is characterized by a fairly simple and economical electromechanical setup and ease of installation and operation. Since the base is designed to rotate in the horizontal direction, thus determining the movement of the solar panel in 1 degree of freedom, its dimensions should be a bit bigger than those of the panel to ensure the dynamical stability of the device. With the fabrication cost and the consumed energy of the base taken into account, the designed solar tracking system is not applicable for large-sized photovoltaic applications. Instead, it should be suitable for small- and medium-sized applications, such as individual rooftop solar tracking systems.

Due to the benefits that would be obtained via the utilization of the designed solar tracking system, certainly fewer PV panels will be applied to it in proportion to the merits obtained using fixed panels. Hence, the designed system will be more economical regarding the number of PV panels used, which will decrease the investment costs. The use of this type of system in Southern China, with significant value specifically in terms of sun exposure time, has emerged as an important potential regarding energy savings and efficient use.

Our future research will focus on the fabrication of a full-scale model of the device and its field tests. After obtaining a sufficient amount of field experience, we will calculate the extra cost and the payback period of the developed system more precisely. As is known, a strong wind—for instance, a Beaufort 10 wind—can endanger the safety of machinery [35]. For this design, we did not consider the effect of the wind load, as the wind was not that strong in the area where these experiments were conducted. Still, for the overall consideration of the proposed system, it will be necessary for us to apply an air velocity transducer to the device to detect the wind speed, investigate the effect of the wind load on the drive mechanism and the energy efficiency and add the corresponding wind speed judgment to the control logic so as to minimize the damage to the device from strong winds. On this basis, the optimization of the device geometry, epitaxial structure and control algorithm will also be included in our future research.

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