Development and Accuracy Assessment of a High-Precision Dual-Axis Pre-Commercial Solar Tracker for Concentrating Photovoltaic Modules

Marthoz Angulo-Calderón 1, Iván Salgado-Tránsito 2, Iván Trejo-Zúñiga 3, Carlos Paredes-Orta 2, Sajjad Kesthkar 4,5 and Arturo Díaz-Ponce 2,*

Abstract: In recent decades, advances in the development of solar tracking systems (STSs) have led to concentrating solar technologies to increase their energy conversion efficiency. These systems, however, still have areas of opportunity or improving their performance and reducing their manufacturing costs. This paper presents the design, construction and evaluation of a high-precision dual-axis solar tracking system with a technology readiness level of 7–8. The system is controlled by a low-cost Arduino board in a closed-loop control using a micro-electromechanical solar sensor. Real-time tracking experiments were performed under a clear sky as well as during partly and mostly cloudy days. Solar tracking accuracy was evaluated in an operational environment using test procedures adapted from the International Electrotechnical Commission (IEC) 62817 standard. The total mean instantaneous solar tracking error on a clear day measured with a calibrated digital solar sensor was 0.37° and 0.52° with a developed pinhole projection system. Similarly, the total mean reported solar tracking accuracy achieved was 0.390° on a sunny day and 0.536° on a partially cloudy day. An annual power generation analysis considering a conventional photovoltaic (PV) panel system and a typical concentrator photovoltaic (CPV) module as payloads was also presented. Simulations showed an increase in the generation of up to 37.5% for a flat panel with dual-axis tracking versus a fixed panel. In the case of the CPV system, first, a ray tracing study was implemented to determine the misalignment coefficient, then the annual power generation was estimated. The developed STS allowed the CPV modules to reach at least 90% of their nominal energy conversion efficiency.

Keywords: solar tracking system; solar tracker; concentrating solar power; on–off control; concentrating photovoltaics; Arduino

1. Introduction

A solar tracking system is a mechatronic device employed to automatically orient the payload towards the Sun’s rays. These devices are mainly used in CPV and concentrating solar power (CSP) systems since they need to collect the direct solar radiation throughout the day for their proper performance. Conventional PV systems utilize both direct and diffuse solar radiation; therefore, STSs are not recommended for this technology [1].

In the literature, several configurations of single- and dual-axis STSs have been proposed [2]. One of the most used configurations, because of their simplicity and high performance, is the vertical primary dual-axis tracker (VPDAT), which is based on a vertical pole-mounted tracker to transfer the load of the structure to the ground [1]. Another
common configuration is the horizontal primary dual-axis tracker (HPDAT) which has its primary axis horizontal to the ground, and the secondary axis is normal to the primary axis [1]. The main disadvantages of the VPDAT and HPDAT are their susceptibility to wind loads and the deformation or bending generated by the weight of the payloads. A comparison of some solar tracking techniques is detailed in [3]. In recent years, parallel manipulators have been suggested as trackers [4–10]. Some of the reported advantages are the lack of big gearboxes, greater robustness against disturbances and less deformation generated by gravity and wind loads on the structure. However, because of the complexity in implementation, these mechanisms are not the most used in utility-scale STSs. In [11], the variables that influence the electricity generation in PV system with dual-axis solar tracking are analyzed.

Because of technological advances in CSP and CPV systems, the requirements for STS are becoming more demanding, and they need to achieve better performance at a lower cost. The solar tracking accuracy is commonly affected by multiple factors, such as high backlash of the actuators, misalignment in the payloads installation, non-linearity or malfunction of the sun sensors, dynamic wind loads, dependency on constant maintenance, calculation errors in the positioning deviation of the sun position algorithms, payload structure deflection, lack of robustness to disturbances, among others [12]. Therefore, it is necessary to continue researching innovative solar trackers that eliminate or reduce the effects caused by the factors mentioned and are low-cost, autonomous, highly scalable and low maintenance, with long-lasting durability and manufacturing ease.

Regarding the control system, in the literature, there are several STS design methods that use control units, such as programmable logic controllers, microcontrollers, Arduino boards, single-board computers like Raspberry Pi, and even personal computers, but these approaches are typically developed as proof of concept or at the laboratory level, see [12]. In [13], an interesting design of a scaled-down prototype of a dual-axis STS with four-quadrant photosensor feedback was proposed, which was driven by an AC motor. The PV payload increased the energy generation up to 28.31% compared with a fixed PV system. The authors in [14] proposed a sensorless dual-axis sun tracker prototype that uses the PV output current and voltage as a solar sensor to estimate the Sun’s position. A closed-loop control updated the solar tracker orientation by the maximum power point tracking unit of the PV modules. In similar works, Refs. [15,16] designed and implemented dual-axis STS prototypes in closed-loop through light-dependent resistors (LDRs). The former used a Wheatstone bridge circuit. The latter directly compared the LDRs signals by an electronic circuit. Experimental results showed an energy generation of 48.2% and 35% higher than that produced by a fixed PV system, respectively, showing that this kind of result enriches and encourages the importance of the STSs for energy generation. In [17], an automated intelligent STS with cloud detection was proposed; under rainy or cloudy conditions, an adaptive control algorithm optimized the position of the solar tracker prototype to increase the energy generation of a PV system. Similarly, the authors in [18] developed a dual-axis STS prototype with an Arduino board that employed a stepper motor and a linear actuator for the azimuth and zenith axes, respectively, but the solar tracking accuracy was not characterized. In the same way, in [19] another dual-axis STS prototype was proposed; the authors built two mobile structures, one for the four-quadrant solar sensor and the other to move the PV payload. They employed an on–off control with hysteresis to achieve system stability during solar tracking. All the STSs mentioned above propose and report interesting results; however, they are prototypes that lack tests in real weather conditions. In addition, they have been built with a technology readiness level (TRL) 1-4, which does not mention the solar tracking precision achieved.

As for the STSs with a TRL 5–7, which consist of the prototype demonstration in a relevant environment and/or an operational environment, currently there are only a limited number of experimental or industrial designs and control systems. In [20], three pilots of dual-axis STSs for a parabolic dish concentrator with a closed-loop and open-loop control are presented. These systems were programmed in different control units:
a microcontroller, a personal computer and a programmable logic controller. After a comparative study, the authors recommended a system with a cost of €1300 and a solar tracking error (STE) of <0.2°. The authors in [21] proposed an open-loop solar tracker to move a Fresnel lens that concentrates the Sun’s rays on a Stirling engine’s heating head. The reported system reached a temperature of 900 °C, but the total STE was not measured. Similarly, the design and evaluation of a microcontroller-based smart solar tracker was proposed in [22]. This system employs LDRs to give feedback to a closed-loop control system with an on–off control. The tracker increased the energy production of a PV system, but the STE was not calculated. It is important to mention that none of the aforementioned works have performed the characterization of solar tracking by means of the IEC 62817 standard of design qualification of solar trackers, which defines test procedures for both key components and for the complete tracker system [1]. This standard allows for evaluating and comparing the performance of solar tracking systems using standardized methodologies. In this sense, some works on the implementation of these test procedures for single- and dual-axis STSs have been reported. For example, Ref. [23] performed an experimental evaluation of the mechanical testing of the IEC 62817 standard in a dual-axis solar tracker, and the authors identified several mechanical testing improvements in the standard. Furthermore, Ref. [24] implemented environmental testing of the IEC 62817 standard in a solar tracker driver to validate the tracker design under varying conditions. In addition, the usefulness of the environmental tests of the standard was confirmed. In the same way, the authors in [25] evaluated the general performance of a horizontal single-axis tracker through this IEC standard. They also identified improvements to consider for the next standard editions. Table 1 summarizes some of the reported work on STSs. In this table, the various differences between cost, tracking accuracy, TRL level and characterization methodologies can be seen; therefore, it is not feasible to compare these systems with the proposed STS, taking only one parameter as a reference.

| No. | Ref. | Tracking Type | STE | Charact. Methodology | Cost (USD) | Approx. TRL | Annual Energy Increase vs. a Fixed PV System |
|-----|------|---------------|-----|----------------------|------------|------------|---------------------------------------------|
| 1   | [26] | Dual          | NM  | NM                   | $92        | 3–4        | 44.89%                                      |
| 2   | [15] | Dual          | NM  | NM                   | NM         | 3–4        | 48.20%                                      |
| 3   | [16] | Dual          | Shadow bar with concentric circles | NM        | 4–5        | 35.00%                                      |
| 4   | [19] | Dual          | 0.11° | STE measured with the sensor that give feedback to the control system | NM        | 4–5        | 39.50%                                      |
| 5   | [14] | Dual          | 0.5° | STE measured with the sensor that give feedback to the control system | NM        | 3–4        | 43.60%                                      |
| 6   | [27] | Dual          | 0.2° | NM                   | $1484      | 7–8        | NM. STS for a parabolic concentrator system |
| 7   | [28] | Single       | NM  | NM                   | NM         | 4–5        | 29.90%                                      |
| 8   | [18] | Dual          | NM  | NM                   | $913       | 3–4        | 18.00%                                      |
| 9   | [20] | Dual          | 2°  | Shadow bar with concentric circles | NM        | 3–4        | 23.6% and 31.8%                            |
| 10  | [29] | Dual          | 0.15° | Shadow bar with concentric circles | NM        | 4–5        | 19.1% and 30.2%                            |
| 11  | [14] | Dual          | 0.43° | NM                   | $190       | 3–4        | 60.45%                                      |
| 12  | [30] | Dual          | 0.15° | STE measured with the sensor that give feedback to the control system | NM        | 3–4        | 44.44%                                      |
| 13  | [31] | Dual          | 2°  | STE measured with the sensor that give feedback to the control system | NM        | 3–4        | NM                                          |
| 14  | [32] | Single       | 2°  | Shadow bar with concentric circles | NM        | 7–8        | NM                                          |
| 15  | [33] | Dual          | NM  | NM                   | NM         | 4–5        | 44.44%                                      |
| 16  | [34,35] | Dual        | <0.1° | STE measured with the sensor that give feedback to the control system | NM        | 7–8        | NM                                          |
| 17  | [36] | Single       | NM  | NM                   | NM         | 3–4        | 36%                                         |

Table 1. STS developments reported in the literature (NM: not mentioned).
This paper presents the development, control and evaluation of a dual-axis active STS with a mean tracking accuracy of $\pm 0.4^\circ$ and $\pm 0.55^\circ$ for sunny and partly cloudy days, respectively, using a low-cost control system based on Arduino. The STS was tested in an operational environment at the Laboratory for Innovation and Characterization of Solar Thermal and Photovoltaic Systems (LICS-TF) of the Optical Research Center A.C., in Aguascalientes, Mexico. The present work is organized as follows: Section 2 describes the materials and methods used in the design and construction of the STS and its control and monitoring panel. In Section 3, the manual and automatic operating modes as well as the control strategy are detailed. Experimental solar tracking testing results under real environmental conditions are presented in Section 4. In addition, this section presents the optical-energetic analysis, considering a conventional PV system and a typical concentration PV module as the payloads, as well as the cost analysis of the developed STS. Finally, a brief discussion and conclusions are presented in Sections 5 and 6, respectively.

2. Dual-Axis Solar Tracking System Design and Construction

After an analysis of the advantages and disadvantages of each configuration of the STSs, a decision was made to build a VPDAT based on a vertical pole-mounted tracker to transfer the load of the structure to the ground. To know the required STS movement limits, the annual Sun path in Aguascalientes, Mexico, was analyzed (latitude N 21°50'39" and longitude W 102°20'38"), as shown in Figure 1a [37]. Afterwards, we proceeded with the mechanical design of the STS, which comprises an actuator capable of moving in the azimuth and zenith axes. This system can rotate 324° on the azimuth axis, from 48° to 372° from the northern axis. In the zenith axis, the system can be moved from 10° to 92° from the surface plane; see Figure 1b.

Figure 1. STS movement planning: (a) Sun path at the Optical Research Center A.C., in Aguascalientes, Mexico and (b) rotational axes of the STS.

Figure 2a depicts the STS built. The steel pedestal is 2.3 m high and supports a commercial slew drive manufactured with a dual-axis motoreductor. This actuator moves a steel frame of 4 m$^2$, where the payload is placed. This system is anchored to the ground by a reinforced concrete isolated footing of 60 × 50 × 50 cm (height, weight and length). To easily assemble the payload, four aluminum profiles were placed on the steel frame. Since the solar tracker is designed for CSP and CPV applications, the desired solar tracking accuracy is $<0.3^\circ$, so a PDE3 H-Fang slew drive was selected. The slew drive has two main components: a precise dual-shaft close-turn drive with a 62:1 worm gear ratio, and two motoreductors of 24 V of direct current (VDC) and 2.8 A (one for each axis: azimuth and zenith), which has a transmission ratio of 236:1. Therefore, the total gear reductions of
the slewing drive on the azimuth and zenith axes are 14,632:1 (62 times 236). Because of the high level of reduction, if the motor is de-energized, it maintains its position. Each motoreductor has an absolute encoder with 8 pulses per revolution. The slew drive accuracy reported by the supplier is <0.08°; it has a small uncertainty due to the backlash. The rated output speed of the solar tracker is 0.12 revolutions per minute: it takes 4.16 min to rotate 180°. It is fast enough, however, to track the Sun’s apparent position during the day. In order to avoid overturning the slewing drive and to ensure a robust operation, the system has four limit switches, as seen in Figure 2b: clockwise (CWA) and counterclockwise (CCWA) sensors on the azimuth axis and upper (UZ) and lower (LZ) sensors on the zenith axis. The range of motion of the STS is defined by the limits’ switches. Video 1 (https://youtu.be/GU-461boFCA, accessed on 20 January 2010) depicts a time-lapse video of the full motion of the system.

Figure 2. Developed STS: (a) lateral view of the STS and (b) frontal view of the STS.

For measuring the Sun’s apparent position, the proposed solar tracker employs an analog solar sensor based on a micro-electromechanical system (ASS-MEMS) model ISS-A60, as seen in Figure 2b. This sensor has a low power consumption, an accuracy of 0.06°, an IP65 protection, as well as a wide field of view (FOV) of ±60°, among other advantages [38]. The operating principle of the sensor is based on a four-quadrant array of photodetectors that generate voltages ($V_{PH1}$, $V_{PH2}$, $V_{PH3}$ and $V_{PH4}$) depending on the angle of incidence of the Sun’s rays through a window, as shown in Figure 3. The incidence angles of the Sun’s rays with respect to the ASS-MEMS are obtained on $\alpha$ and $\beta$ by the set of Equations from (1) to (4) and from (5) to (8), respectively, where the C value is a geometric correction of the solar sensor model, $C = 1.889$. The $\alpha$ variable is the angle of the incident sunlight with respect to the plane generated by the perpendicular axis and the azimuth axis, while $\beta$ is the angle of the sun rays and the plane generated by the perpendicular axis and the zenith axis. This sensor is mounted in the center of the solar tracking plane, at the point of minimum deflection of the system:

\[
X_1 = V_{PH3} + V_{PH4},
\]

\[
X_2 = V_{PH1} + V_{PH2},
\]

\[
F_x = \frac{X_2 - X_1}{X_2 + X_1},
\]

\[
\alpha = \arctan(C \times F_x),
\]

\[
Y_1 = V_{PH1} + V_{PH4},
\]

\[
Y_2 = V_{PH2} + V_{PH3},
\]
\[ F_y = \frac{Y_2 - Y_1}{Y_2 + Y_1}, \quad (7) \]
\[ \beta = \arctan(C \times F_y). \quad (8) \]

Figure 3. Angle references of the ASS-MEMS model ISS-A60.

The developed system has a real-time control and monitoring system performed inexpensively and with easily accessible elements, as shown in Figure 4a. The main devices of the panel are as follows: an Arduino Mega 2560 as the central control unit, two BTS7960 H-bridges to drive the actuators by pulse width modulation (PWM) signals, two thermal-magnetic switches, a four-channel 5 V relay module, a DIN rail screw clamp terminal block, and two power supplies of 5 and 24 VDC. In addition, as seen in Figure 4b, the control panel has a teach pendant human–machine interface (HMI) used for monitoring and/or selecting the operation modes of the system. The HMI was performed on the Nextion touch screen NX8048T070, which sends/reads information of the Arduino embedded system. The costs of the solar tracker and its control and monitoring panel are described in Section 4.4.

Figure 4. Control and monitoring panel of the STS: (a) control panel elements and (b) control panel exterior and HMI.

3. Operating Modes of the Proposed Solar Tracking System

The developed STS can be operated in two modes: manual and automatic. In both cases, however, the system must have been in its home position (HP) at least once to reset the absolute encoders’ values; this process is detailed in Section 3.1. After the HP process is finished, the user can select the operating mode of the system. In manual mode, as is
analyzed in Section 3.2, the STS can be operated by indicating the direction of movement or through a desired angular position established via the HMI. In the automatic mode, the STS is automatically positioned perpendicularly to the Sun’s rays by a solar sensor; see Section 3.3.

3.1. Home Position

As mentioned above, when starting, the STS must be placed in its HP to make an initial angular reference. As shown in Video 2 (https://youtu.be/-v6BQh6VUPw, accessed on 20 January 2010), this process is activated when the HP button is pressed on the HMI, then the STS moves counterclockwise in the azimuth axis and downward in the zenith axis until the CCWA and LZ sensors are activated. At that moment, the azimuth and zenith encoders’ values are set at 15,608 and 3252, which correspond to a deviation of 48° from the geographic north and 10° from the surface normal, accordingly. The limit switch indicators and the encoders’ values can be observed in the HMI screen. This process can take several minutes depending on the position of the solar tracker when the system was started. It must be pointed out that this STS is a testing bench, and the stow position is the HP. Nonetheless, this position could vary for a specific payload. It is important to mention that in the home position process, the STE measured by the ASS-MEMS could be wrong because the Sun’s apparent position could be outside the FOV of the sensor.

3.2. Manual Operation Mode

3.2.1. Manual Operation by Direction of Movement

In this operation mode, the STS can be moved by indicating the desired direction of rotation. To start this process, the user needs to press the buttons that indicate the axis and the desired direction of rotation of the actuators; see Video 3 (https://youtu.be/ELemq0b2oCs, accessed on 20 January 2010). The solar tracker can be moved in the azimuth and zenith axes simultaneously. This mode can be used for mounting payloads, as well as maintaining and repairing the STS. It is important to mention that in all operation modes, when a limit switch sensor is activated, the movement of the solar tracker stops in the corresponding direction.

3.2.2. Manual Operation by Desired Angle

This manual tracking mode can be used mainly for the assembly of the payloads of the STS since it can orient the STS to an angular position established in the HMI screen. Figure 5 shows the closed-loop on–off position control of this operation mode, which is the simplest, easiest and most inexpensive control method. First, the control error $e$ is calculated by Equation (9), where $r$ is the desired angular position or reference, and $TP_G$ is the actual angular position of the solar tracker. At the same time, $TP_G$ is calculated by $TP_G = TP_E \times k$, where $TP_E$ is the position tracker measured by the encoders’ values, and $k$ is the inverse of the total gear reductions of the slewing drive: $k = 1/14632$. It is important to mention that for dual-axis solar tracking, it is required to duplicate the control diagram of Figure 5 and Equation (9), corresponding to the azimuth and zenith axis:

$$ e = r - TP_G = r - (TP_E \times k) = r - \frac{TP_E}{14,632}. \quad (9) $$

Thus, the calculated error $e$ is used to determine the control signal ($u$) through a closed-loop on–off control. In this control system, the $u$ value switches abruptly according to three possible conditions as seen in Figure 6, where $L_T$ and $U_T$ are, respectively, the lower and upper threshold of the allowed tracking hysteresis, which is commonly the same but with opposite signs. This threshold prevents excessive changes in the control signal because of the noise in the solar sensor. In the presented STS, the hysteresis has a value of $±0.3°$; however, the user can change it in the HMI. As observed in Figure 6, if the $e$ value is greater than $U_T$, $u$ is positive, and, by means of the H-bridges, the motor turns clockwise on the azimuth axis and/or up in the zenith axis. On the contrary, if the $e$
value is lower than the $L_T$, $u$ is negative and the motor turns counterclockwise in the azimuth axis and/or downward in the zenith axis to reduce the $e$. In the ideal case, when the $e$ value is between the $U_T$ and $L_T$, $u$ is 0, and the actuators do not move. Video 4 (https://youtu.be/fz_K2xjqwJ8, accessed on 20 January 2010) shows the manual operation mode by desired angle. In this mode, the STS remains in its HP until the desired angle or reference value $r$ is entered via the HMI screen. The system then begins its journey until it reaches the desired position: until the $U_T > e > L_T$. The HMI displays the current $e$ value. Note that the feedback produced by the encoders generates a closed-loop control. There is no solar tracking, however, since the STS tracks an established angular reference.

![Figure 5. Schematic control diagram of the manual operation mode.](image)

### 3.3. Automatic Operation Mode

Automatic operation mode allows the STS to automatically stay perpendicular to the Sun’s rays during the day. Figure 7 shows the schematic control diagram of this mode, which employs an Arduino Mega as a control unit. Similar to the case of manual mode, this control system also employs a closed-loop on–off control; however, the control feedback is performed with the ASS-MEMS detailed in Section 2. Because of the feedback and the wide FOV of the solar sensor, the Sun can be easily located at sunrise; however, if the STS is started in the afternoon, the system may require a manual pre-location. In this operation mode, the ideal position of the STS is when the $\alpha$ and $\beta$ angles are 0. Therefore, the control error $e$ is calculated by Equation (10), where the reference $r$ is equal to $0^\circ$, and $f(\alpha, \beta)$ is the Sun’s position measured by the solar sensor; see Figure 3. Once $e$ is calculated, the on–off control determines the behavior of the solar tracker’s slewing drive, considering the three possible states of the controller shown in Figure 6: with a clockwise turn, with a counterclockwise turn or with a motor off. The direction of rotation may vary according to the configuration of each STS:

$$e = r - f(\alpha, \beta) = -f(\alpha, \beta).$$ (10)
In order to evaluate the solar tracking accuracy, the IEC 62817 standard considers two types of STEs: the instantaneous pointing error (ISTE) and reported solar tracking accuracy (RSTA) [1]. Both types, however, represent the angular difference between the beam solar radiation and the place the solar tracker is pointing to. It is worth noting that STE is the sum of all errors generated in the actuators, in the gearbox, in the control algorithm, in the controller, in the solar tracker installation, among others [1]. In order to directly measure the ISTE and the RSTA, two devices were used, and they are described below.

1. An ISS-D5 digital solar sensor. This digital solar sensor, based on a microelectromechanical system (DSS-MEMS), measures the tracking error in two orthogonal axes at a FOV of ±5° with an accuracy of <0.005° and a position error of <0.1°. Furthermore, it does not require constant calibration [39]. This sensor is manufactured by Solar MEMS Technologies®.

2. A pinhole projection system (PPS). This device is suggested in point 7.3.2 of the IEC 62817 standard. In addition, it has two flat plate systems with a pinhole to project the Sun’s rays to measure the deviation error between the PPS surface normal and incident solar rays. One plate was marked with concentric circles of different millimeter diameters, and the other has a sun vector pinhole that allows for projecting the Sun’s rays, as seen in Figure 8a,b. This device can measure pointing errors in the azimuth and zenith axes.

4. Experimental Results

This section presents the experimental results obtained during solar tracking in automatic mode. The manual mode was only used to maintain the system or the assembly of payloads. Solar tracking experiments were performed under clear sky, partly and
mostly cloudy conditions to analyze the performance of the STS. An energy analysis was then performed to estimate the increase in energy conversion efficiency in a conventional PV system. In addition, an optical-energetic analysis of a concentration PV system was presented, which was performed by the open source Monte Carlo ray tracing program, Tonatiuh. Finally, a cost analysis was conducted to determine the economic viability of the proposed system.

4.1. Automatic Solar Tracking Results

The solar tracking accuracy in the automatic mode was evaluated by measuring the ISTE and the RSTA with the sensor detailed in Section 3.3. The analysis of the tracking results is shown in the next subsections.

4.1.1. Instantaneous Solar Tracking Error

ISTE represents the actual angular difference between, where the tracker is pointing and where the Sun is at that moment [1]. The azimuth ($\alpha$) and zenith ($\beta$) ISTE can be directly observed by the digital sensor ISSX software, or they can be calculated with the PPS by Equations (11) and (12), respectively; where $h = 300 \text{ mm}$ is the separation between the two parallel plates, $x$ and $y$ are the projections on the Cartesian plane of the distance between the centroid of the projection of the Sun’s rays and the center of the concentric circles of the PPS, as seen in Figure 8. It is important to mention that due to its construction, the PPS can only measure small angles since its FOV is about $\pm 15^\circ$. As the standard suggests, the total ISTE ($\theta$) is obtained by Equation (13). Note that the total ISTE is always positive:

\[
\alpha = \arctan\left(\frac{x}{h}\right),
\]

\[
\beta = \arctan\left(\frac{y}{h}\right),
\]

\[
\theta = \arctan\left(\frac{v}{h}\right) = \arctan\sqrt{\frac{x^2 + y^2}{h}}.
\]

Solar tracking under clear sky conditions (8 October 2021) was performed, and the ISTE were measured by the DSS-MEMS and the PPS, which only monitor the tracking accuracy and do not influence the system control. These sensors were installed in the center of the tracking plane at the point of minimum deflection; see Figure 9. Direct normal irradiance (DNI) values were measured by the DSS-MEMS. Table 2 shows the experimental results obtained in 2-h intervals. The total mean absolute ISTE obtained with the DSS-MEMS and the PPS were 0.37° and 0.52°, respectively. It is worth mentioning that because of the high-precision solar tracking, the measurements of the ISTE obtained by means of the PPS are complex since the projection of the Sun’s rays is wide enough and falls between several measuring circles on the receiving plate; see Figure 8b. ISTE were not measured under cloudy conditions because the diffuse environmental radiation would considerably alter the measurements.

Figure 9. Solar sensors and devices for the solar tracking characterization of the designed STS.
Table 2. Azimuth, zenith and total ISTEs throughout a clear day. Date: 8 October 2021.

| Time   | DNI (W/m²) | Wind Speed | ISTEs (°) | DSS-MEMS | ISTEs (°) | PPS |
|--------|------------|------------|-----------|-----------|-----------|-----|
|        | α         | β          | θ         | α         | β         | θ   |
| 10:00  | 838       | Low        | 0.15      | 0.42      | 0.45      | −0.19 | 0.29 | 0.35 |
| 12:00  | 918       | Low        | −0.33     | 0.17      | 0.37      | −0.35 | 0.38 | 0.52 |
| 14:00  | 930       | Low        | −0.40     | −0.20     | 0.45      | 0.38  | −0.38 | 0.77 |
| 16:00  | 915       | Low        | −0.30     | 0.01      | 0.30      | −0.19 | 0.29 | 0.36 |
| 18:00  | 766       | Low        | −0.27     | 0.07      | 0.28      | −0.38 | 0.45 | 0.59 |
|        | Mean absolute ISTEs |           | 0.29      | 0.17      | 0.37      | 0.30  | 0.36 | 0.52 |

4.1.2. Reported Solar Tracking Accuracy

RSTA is the statistical processing of a set of ISTEs measured by a standardized method. In this work, RSTA was calculated using the following considerations established in the IEC 62817 standard [1]:

- The pointing error data set was measured in different weather conditions.
- The tracker pointing error was recorded in 1-second instantaneous increments.
- The data were filtered to remove possible data taken during low irradiance conditions.
- The wind speed was measured with a digital anemometer, and the data were classified into a high and low wind speed bin based on a 4 m/s threshold.
- Date, time and DNI parameters were recorded at all times.

The RSTA was measured by the DSS-MEMS; the PPS could not be used because it is a visual device that cannot store data. Solar tracking experiments were performed on 8, 9 and 20 October 2021, under clear sky and partially and mostly cloudy conditions, respectively. In all cases, the STS started at 8:30 from its initial position, where the Sun can be detected because of the wide range of the ASS-MEMS. Solar tracking ended at sunset.

Figure 10 depicts the typical solar tracking results under clear sky conditions. As seen in Figure 10a, when the STS starts (08:30), the Sun’s rays hit with an angle greater than the FOV of the DSS-MEMS (±5°), so the sensor cannot measure the angle of incidence. When the solar tracker is oriented towards the Sun’s rays (STE < 5°), the DSS-MEMS starts to measure the accuracy of the STS. Figure 10b shows the DNI during the experimentation. It can be observed that the solar irradiance exceeded 900 W/m², and there was no cloudiness during the day. Note that when DNI decreases at sunset (18:30), ISTEs increase because of the typical non-linear response of the photosensors under changes of radiation and temperatures levels [12]. During the solar tracking stage, the absolute mean azimuth and zenith axes errors and total error were 0.310°, 0.237° and 0.390°, respectively; see Table 3. Solar tracking was performed during other clear sky days, and an average variation of 7% was observed.

Table 3. Absolute mean RSTA in different weather conditions.

| Weather Conditions         | Absolute Mean RSTA Azimuth Axis | Absolute Mean RSTA Zenith Axis | Mean Total RSTA |
|---------------------------|---------------------------------|-------------------------------|-----------------|
| Sunny days                | 0.310°                          | 0.237°                        | 0.390°          |
| Partially cloudy days     | 0.466°                          | 0.297°                        | 0.536°          |
Figure 10. Solar tracking on 8 October 2021: (a) azimuth and zenith axes STEs and (b) DNI.

Figure 11 represents the RSTA during a partly cloudy day. In Figure 11a, it is observed that when there is a period of partially cloudy sky, without the DNI decreasing below 300 W/m² (from 8:30 to 10:30, as seen in Figure 11b), the STS remains in a solar location stage and continually tries to locate the Sun’s apparent position. Therefore, the tracking accuracy is low. Starting at 10:30, there is then a mostly clear sky stage, in which the tracking precision improves and the control algorithm compensates the disturbances caused by the diffuse radiation generated by the clouds. The RSTA for the azimuth and zenith axes was 0.466° and 0.297°, respectively; therefore, the total tracking precision was 0.536°, 37.5% higher than that achieved on a clear sky day; see Table 3. Similarly, Figure 12a shows the response of the STS to a period of the day that is mostly cloudy, from 16:00 to 18:00; see Figure 12b. At that time, the DNI drops below 300 W/m², and the DSS-MEMS cannot measure the angle of incidence of the Sun’s rays, so the precision of solar tracking cannot be plotted. In this situation, the STS control system does not update the position of the solar tracker in order to avoid unnecessary over consumption of electrical energy and the instability of the system. Once the DNI exceeds 300 W, the STS finds the Sun’s position again. The developed STS demonstrated robustness and stability in the face of partially and mostly cloudy days.
4.2. Energy Study in a Conventional PV System with Solar Tracking

In order to compare the energy generated by a fixed PV system versus one mounted on the proposed STS, two polycrystalline Perlight PLM-270-60 solar modules were considered; their electrical parameters at standard test conditions were as follows: module area of 1.627 m², nominal maximum power point of 270 Wp DC, open circuit voltage (Voc) of 38.23 V, short circuit current (Isc) of 9.13 A, maximum power voltage of 31.22 V and maximum power current of 8.65 A. The temperature coefficient of maximum power point is $-0.41 \%/°C$, while the temperature coefficients of Voc and Isc are $-0.11 \text{V/}°\text{C}$ and $0.004 \text{A/}°\text{C}$, respectively.

The detailed PV model of the System Advisor Model (SAM) was used to estimate the electrical output of a PV system. Module and inverter specifications were input into data along with the array information, such as the number of modules and inverters. SAM software performs power production estimations dynamically using typical meteorological year (TMY) information with a time step resolution of 1 h. In this way, it simulates the dynamic operating conditions of the PV system such as irradiance, ambient temperature, wind speed, etc., and determines their effect on energy production [40]. During the comparison, the fixed modules were oriented to the south with an inclination of 22°, which is the optimal orientation for PV systems in Aguascalientes, Mexico (latitude N 21°50′39″ and longitude W 102°20′38″). For the PV system with tracking, the losses caused by tracking error were set at 2°. Figure 13 shows four representative scenarios for different months where the electric power generation is compared between a fixed PV system and a PV system with the developed dual-axis STS. Sunny days were selected for better comparison. As expected, on all days, the energy production with the tracking system was greater because the PV system receives radiation directly throughout the day. In the same way, Figure 14 summarizes the net DC electrical energy generated before the inverter throughout a year in Aguascalientes, Mexico. The developed STS allowed enhancing efficiency up to 37.5% compared to a fixed PV system.

4.3. Optical-Energetic Analysis of a Concentrating PV System with the Developed Solar Tracker

Despite the gain in energy production of a PV panel by using STSs, these systems are not usually used because of their high cost [41]. In contrast, in CPV and CSP systems, the STSs are mandatory because of the implementation of optics elements that redirect the Sun’s rays towards a specific target, which establish a significant angular dependence of the systems [42]. CPV technology has a higher performance than conventional photovoltaics since it can reach conversion efficiencies of over 47% [43]. Its construction and implementation, however, is more sophisticated. Energy generated by a CPV module is mainly affected
by changes in irradiance levels, temperature, spectrum and, above all, by the misalignment of the module towards the Sun’s rays, as with any kind of PV device [44].

![Graphs showing DC power gross and net generated electricity for different months and tracking accuracies.](image)

**Figure 13.** Net PV electricity generation per day: (a) 21 March 2022, (b) 24 June 2022, (c) 20 September 2022 and (d) 21 December 2022.

![Bar chart comparing DC energy generated by fixed-tilt and dual-axis tracking systems.](image)

**Figure 14.** DC energy generated: fixed-tilt PV system versus PV system with solar tracking.

It is well known that the solar tracking accuracy tolerance depends on the acceptance angle of the CPV module, which commonly is tenths of a degree. Small STEs could generate...
a significant decrease in optical efficiency, and thus, a less useful energy production in these systems [45]. In this work, Tonatiuh software was used to analyze the performance in a CPV module with the developed STS, which is an open source ray tracer tool for the optical simulation of solar concentrating systems [46]. Figure 15 depicts the schematic of a CPV module based on a point-focus Fresnel lens that was employed in the simulation. This lens reorients the Sun’s rays towards a secondary optics element that uniformly distributes the radiation in the CPV cell. In Figure 15a, the CPV module is perpendicular to the Sun’s rays: \( \text{STE} = 0^\circ \). In Figure 15b, the module has a misalignment \( \text{STE} \neq 0^\circ \); thus, the Sun’s rays can fall outside the cell because of tracking error.

![Figure 15. Schematic diagram of a typical CPV module: (a) under ideal alignment and (b) under misalignment.](image)

The script model followed in this simulation considers a CPV module with a \( 280 \times 280 \text{ mm} \) polymethylmethacrylate (PMMA) point focus commercial Fresnel lens and a 220 mm focal length. As a receiver, a flat surface of \( 10 \times 10 \text{ mm} \) is considered, simulating a multi-junction (MJ) solar cell. Four scenarios with different misalignment levels between the incident rays and the Fresnel lens were simulated in Tonatiuh software [47] to estimate the radiative flux distribution in the MJ cell, as shown in Figure 16. Considering an ideal situation in the first case, where the \( \text{STE} = 0^\circ \), the normalized radiative power (NRP) is equal to 1, and the irradiance distribution is higher at the center of the MJ cell than at the edge, as Figure 16a illustrates. In the second case (\( \text{STE} = 0.3^\circ \)), the STS presents a slight deviation; hence, the incident flux distribution moves towards an edge of the receiver, resulting in a 2% loss in the normal radiative power; see Figure 17. This behavior prevails as the \( \text{STE} \) increases, as shown in Figure 16c,d, with an \( \text{STE} \) of 0.5° and 1°, respectively. For these cases, the normal radiative power decays 7% and 33%, respectively. Figure 17 summarizes the relationship among normal radiative power and the \( \text{STE} \). Note that the NRP decreases as the CPV module misalignment error increases. In addition, observe that the NRP decreases drastically when the absolute \( \text{STE} \) exceeds 0.6°, which corresponds to an NRP = 0.9. This fact is linked to the acceptance angle of a CPV module, defined as the \( \text{STE} \) at which power generation decreases below 90% [45]. As seen in Figure 17, the NRP in the CPV cell is with the developed STS. On the one hand, with the mean \( \text{STE} \) achieved in sunny days (\( \text{STE} = 0.39^\circ \)), the NRP is equal to 0.96. On the other hand, with the mean \( \text{STE} \) of partially cloudy days (\( \text{STE} = 0.536^\circ \)), the NRP is to 0.91. In both cases, the mean NRP is greater than 0.9.
Figure 16. Collected irradiance flux on the cell surface: (a) STE = 0°, (b) STE = 0.3°, (c) STE = 0.5° and (d) STE = 1°.

Figure 17. Effect of the misalignment error on the radiative flux on the cell surface.

To estimate the DC electrical energy generated by two high concentration photovoltaic (HCPV) modules under different STEs, SAM software was used. The main parameters considered in the simulation were as follows: two 375.55 W HCPV modules of 20 cells with an efficiency of 37%, a concentration ratio of 700 suns, an optical error factor of 0.9, which takes into account the losses in the plane of array (POA) irradiance because of lens optical errors and a wind flutter factor of 0.01 m/s. There is a reduction in cell power value due to module motion caused by the wind; therefore, SAM reduces the cell output power each time step in the simulation according to 1-flutter loss factor × wind speed. The relative maximum powers of the CPV cells for different levels of STEs were obtained from the Tonatiuh simulation: 1, 0.98, 0.93, 0.67 and 0.31 for STE = 0°, STE = 0.3°, STE = 0.5°, STE = 1° and STE = 1.5°, respectively, (see Figure 17). It is important to mention that the STE or pointing error is the sum of different types of errors, some which are slowly time-varying, such as the misalignment error, and others of highly dynamic behavior,
such as those due to wind loads and the control system [12]. In the simulation, it was assumed that the errors due to the control system and misalignment errors were constant over time and its effect was considered in the SAM’s misalignment coefficient, which was determined, as shown in Figure 17. The only transient error simulated was that caused by wind loads at the location. The simulation was performed for Aguascalientes, Mexico (latitude N 21°50′39″ and longitude W 102°20′38″). Figure 18 represents the monthly DC electrical energy generated by the modules. It is important to note that when the absolute value of the STE is less than 0.6°, the energy generated by the CPV modules is greater than 90% of its capacity. On the contrary, when the absolute value of the STE is greater than 0.6°, the generation drops drastically. Therefore, the STS developed in this work will allow the CPV modules to reach at least 90% of their energy conversion efficiency both on sunny and partly cloudy days.

![Figure 18. Simulated DC electrical energy generated by two HCPV modules by different STEs.](image)

4.4. Cost Analysis

As mentioned in Section 2, the proposed STS consists of two main parts: the solar tracker and the monitoring and control panel. Table 4 shows the approximate cost of the solar tracker elements without considering import taxes and charges, which depends on each country. Note that the most expensive items are the steel pole structure and the slew drive; the latter can be easily exchanged for a low-cost actuator with lower precision and lower axial and radial load capacity. Similarly, the approximate cost of the control and monitoring panel was US $459, as detailed in Table 5; therefore, the total cost of the developed STS was US $3205.

From the energy analysis at SAM, it was estimated that the average daily DC energy generated by two fixed-tilt Perlight PLM-270-60 modules was 2.55 kWh and 3.50 kWh for modules with solar tracking: an improvement in efficiency of 37.5% was achieved. If it is considered that the solar tracker is fitted with its maximum payload of 15 PV modules, the system could produce 26.25 kWh compared to 19.12 kWh produced with a fixed system; there is a difference of 7.13 kWh. Taking into consideration that the annual average cost of electrical energy is 0.2 $/kWh [48], the price of the extra energy generated would be $1.426 per day. Therefore, it can be concluded that there is a requirement of 6.16 years to recover the US $3205 invested in the STS construction. As for the conventional PV systems with solar tracking, low and/or medium precision solar trackers could perform well at a lower cost since these can be built with actuators of lower precision and lower load capacity than the one used in this work [41]. On the contrary, as demonstrated in Section 4.3, the proposed
STS allows for achieving high energy conversion efficiencies in CPV systems, where a low and/or medium precision STS would not allow maximum performance to be obtained.

Table 4. Approximate cost of the solar tracker.

| Pieces | Element                              | Cost (USD) |
|--------|--------------------------------------|------------|
| 1      | PDE3 slew drive                      | $976       |
| 4      | Industrial limit switch              | $55        |
| 1      | Connection accessories               | $30        |
| 1      | Steel pole structure and frame       | $1115      |
| 4      | Aluminum profiles                    | $50        |
| 1      | Concrete isolated footing            | $350       |
| 1      | ISS-A60 analog solar sensor          | $170       |
|        | Total                                | $2746      |

Table 5. Approximate cost of the control and monitoring system.

| Pieces | Element                              | Cost (USD) |
|--------|--------------------------------------|------------|
| 1      | Arduino Mega 2560                    | $50        |
| 2      | BTS7960 H-bridges                    | $11        |
| 1      | Nextion touch screen NX8048T070      | $75        |
| 1      | Basic electronic elements            | $30        |
| 1      | Four-channel 5 V relay module        | $50        |
| 1      | Control panel and connection accessories | $210  |
| 1      | 24 VDC and 5 VDC power supplies      | $33        |
|        | Total                                | $459       |

5. Discussion

An on–off control algorithm is used in approximately 57% of the STSs reported in the literature because of its ease and low-cost implementation [12]. This algorithm, however, has several disadvantages such as low tracking precision, low attenuation of the effect of disturbances, as well as requiring a large tracking hysteresis to avoid instability that could cause excessive electrical consumption and wear in the actuators. Because of the characteristics of the slew drive used in the developed STS, the on–off control showed a good performance, achieving high precision solar tracking with robustness against climatic disturbances.

Section 4.4 detailed the construction cost of the proposed STS, which is higher than most of the STS reported in the literature. This cannot, however, be objectively compared with the cost of prototypes of solar trackers since the presented system reached a TRL 7–8. In other words, it has been validated in relevant environments, is low maintenance, can work outdoors, among other advantages. In addition, the axial and radial load capacity of the developed STS is much higher than that presented in prototypes. The cost analysis was performed to estimate the return on investment of the STS if a conventional PV system is considered as the payload. The developed STS, however, is focused on CPV modules, which require greater precision and accuracy of solar tracking. In such systems, small deviations can considerably reduce the performance of the modules, as analyzed in Section 4.3; therefore, a high precision tracking system is vitally important.

On the other hand, Table 1 shows that high precision and low-cost solar trackers have been reported in various works. Typically, however, the characterization of their precision was not performed using a standardized methodology, or only the error measured in the
control system is reported, which does not consider the errors caused by other factors [12]. On the contrary, the developed STS achieved an average solar tracking precision of 0.390° on clear sky days, which was measured using a procedure adapted from the IEC 62817 standard, so the reliability is relatively high.

6. Conclusions

This work presented the design and construction of a high precision dual-axis pedestal type solar tracker with a TRL of 7–8. The STS is capable of moving both manually and automatically. Videos of the system’s functions and its range of motion were presented. A closed-loop on–off control was implemented in a low-cost embedded system based on Arduino. The Arduino-based control system proved to be a technically and economically feasible alternative to be implemented in STS for CSP and CPV systems where high accuracy is required. If higher reliability is desired, however, it is recommended to use a controller with a higher processing capacity and a more advanced control algorithm.

The tracking accuracy was experimentally evaluated using test procedures adapted from the IEC 62817 standard. The total mean ISTEs with the DSS-MEMS and the PPS on a sunny day were 0.37° and 0.52°, respectively. The total mean RSTA measured with the DSS-MEMS on a sunny day was 0.390°, and 0.536° on a partially cloudy day. The energy analysis showed that the developed STS can increase the generation of a PV system up to 37.5% in relation to a fixed PV system. In addition, through an optical-energetic analysis, it was validated that the proposed tracker allows for maintaining energy conversion efficiencies greater than 90% in a CPV system. With the tracking precision achieved, it is possible to use the developed STS in solar energy harvesting systems with an acceptance angle greater than 0.6°.

Finally, a cost analysis of the developed system was presented: the approximate cost of the control and monitoring panel was US $459 and US $2746 USD for the solar tracker. Despite employing low-cost electronic elements in the construction of the control panel and an on–off control algorithm, the solar tracking precision achieved was high enough for the system to be implemented with CPV modules.

Author Contributions: Conceptualization, A.D.-P. and I.S.-T.; methodology, M.A.-C.; software, M.A.-C. and C.P.-O.; formal analysis, S.K.; investigation, M.A.-C. and C.P.-O.; writing—original draft preparation, M.A.-C.; writing—review and editing, S.K. and A.D.-P.; supervision, I.T.-Z.; project administration, A.D.-P.; funding acquisition, I.T.-Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by Universidad Tecnológica de San Juan del Río and Centro de Investigaciones en Óptica, A.C.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Juan Margarito Sarabia Torres and Alan Adrián De Santos Martinez for their support in the design and construction of the control panel.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. IEC. IEC 62817: Photovoltaic Systems—Design Qualification of Solar Trackers; International Electrotechnical Commission, Geneva, Switzerland, 2014.
2. Nsengiyumva, W.; Chen, S.G.; Hu, L.; Chen, X. Recent advancements and challenges in Solar Tracking Systems (STS): A review. Renew. Sustain. Energy Rev. 2018, 81, 250–279. [CrossRef]
3. Mubarak, S.; Zhang, D.; Chen, Y.; Liu, J.; Wang, L.; Yuan, R.; Wu, J.; Zhang, Y.; Li, M. Techno-Economic Analysis of Grid-Connected PV and Fuel Cell Hybrid System Using Different PV Tracking Techniques. Appl. Sci. 2020, 10, 8515. [CrossRef]
4. Díaz, A.; Keshtkar, S.; Moreno, J.A.; Hernandez, E. Design and Control Strategy of a Low-Cost Parallel Robot for Precise Solar Tracking. In International Conference on Robotics in Alpe-Adria Danube Region; Springer: Cham, Switzerland, 2018; pp. 342–350.
5. Cammarata, A. Optimized design of a large-workspace 2-DOF parallel robot for solar tracking systems. *Mech. Mach. Theory* 2015, 83, 175–186. [CrossRef]
6. Shyam, R.A.; Ghosal, A. Path planning of a 3-UPU wrist manipulator for sun tracking in central receiver tower systems. *Mech. Mach. Theory* 2018, 119, 130–141. [CrossRef]
7. Jiménez, E.; Ceccearelli, M.; Carbone, G. A dynamic analysis of the robot CaPaMan (Cassino Parallel Manipulator) as solar tracker. In *Proceedings of the IFToMM-FelbIM International Symposium on Mechatronics and Multibody Systems MUSME*, Valencia, Spain, 28 October 2011; pp. 579–594.
8. Du, X.; Li, Y.; Wang, P.; Ma, Z.; Li, D.; Wu, C. Design and optimization of solar tracker with U-PRU-PUS parallel mechanism. *Mech. Mach. Theory* 2021, 155, 104107. [CrossRef]
9. Jeng, S.L.; Lue, B.H.; Chieng, W.H. Design and analysis of spatial parallel manipulator for dual axis solar tracking. *J. Chin. Soc. Mech. Eng.* 2014, 35, 221–231.
10. Wu, J.; Chen, X.; Wang, L. Design and dynamics of a novel solar tracker with parallel mechanism. *IEEE/ASME Trans. Mechatron.* 2015, 21, 88–97. [CrossRef]
11. Gómez-Uceda, F.J.; Moreno-Garcia, I.M.; Perez-Castañeda, Á.; Fernández-Ahumada, L.M. Study of the Dependence of Solar Radiation Regarding Design Variables in Photovoltaic Solar Installations with Optimal Dual-Axis Tracking. *Appl. Sci.* 2021, 11, 3917. [CrossRef]
12. Fuentes-Morales, R.F.; Diaz-Ponce, A.; Peña-Cruz, M.I.; Rodrigo, P.M.; Valentín-Coronado, L.M.; Martell-Chavez, F.; Pineda-Arellano, C.A. Control algorithms applied to active solar tracking systems: A review. *Sol. Energy* 2020, 212, 203–219. [CrossRef]
13. Wáng, J.M.; Lu, C.L. Design and implementation of a sun tracker with a dual-axis single motor for an optical sensor-based photovoltaic system. *Sensors* 2013, 13, 3157–3168. [CrossRef]
14. Fathabadi, H. Novel online sensorless dual-axis sun tracker. *IEEE/ASME Trans. Mechatron.* 2016, 22, 321–328. [CrossRef]
15. Saeedi, M.; Effatnejad, R. A New Design of Dual-Axis Solar Tracking System with LDR sensors by Using the Wheatstone Bridge Circuit. *IEEE Sens. J.* 2021, 21, 14915–14922. [CrossRef]
16. Mustafa, F.I.; Shakir, S.; Mustafa, F.F.; Natý, A.T. Simple design and implementation of solar tracking system two axis with four sensors for Baghdad city. In *Proceedings of the 2018 9th International Renewable Energy Congress (IREC)*, Hammamet, Tunisia, 20–22 March 2018; pp. 1–5.
17. Kuttybay, N.; Mekhilef, S.; Saymbetov, A.; Nurgaliyev, M.; Meirikhanov, M.; Kopzhan, Z. An automated intelligent solar tracking control system with adaptive algorithm for different weather conditions. In *Proceedings of the 2019 IEEE International Conference on Automatic Control and Intelligent Systems (ICACIS)*, Selangor, Malaysia, 29 June 2019; pp. 315–319.
18. Morón, C.; Ferrández, D.; Saiz, P.; Vega, G.; Díaz, J.P. New prototype of photovoltaic solar tracker based on arduino. *Energies* 2017, 10, 1298. [CrossRef]
19. da Rocha Queiroz, J.; da Silva Souza, A.; Guissoli, M.K.; de Oliveira, J.C.D.; Andrade, C.M.G. Construction and Automation of a Microcontrolled Solar Tracker. *Processes* 2020, 8, 1309. [CrossRef]
20. Skouri, S.; Ali, A.B.H.; Bouadila, S.; Salah, M.B.; Nasrallah, S.B. Design and construction of sun tracking systems for solar parabolic concentrator displacement. *Renew. Sustain. Energy Rev.* 2016, 60, 1419–1429. [CrossRef]
21. Yang, C.K.; Cheng, T.C.; Cheng, C.H.; Wang, C.C.; Lee, C.C. Open-loop altitude-azimuth concentrated solar tracking system for solar-thermal applications. *Sol. Energy* 2017, 147, 52–60. [CrossRef]
22. Das, S.; Chakraborty, S.; Sadhu, P.K.; Sastry, O.S. Design and experimental execution of a microcontroller (μC)-based smart dual-axis automatic solar tracking system. *Energy Sci. Eng.* 2015, 3, 558–564. [CrossRef]
23. Aipperspach, W.; Bambroke, S.; Trujillo, P.; Zech, T.; Berenguel, F.R. Evaluation of the IEC 62817 mechanical testing for the tracker validation. *AIP Conf. Proc.* 2015, 1679, 080001.
24. Martinez, M.; Calvo-Parra, G.; Gil, E.; de la Rubia, O.; Hillebrand, M.; Rubio, F.; Aipperspach, W.; Gombert, A. Environmental testing results over a tracker drive train. *AIP Conf. Proc.* 2014, 1616, 228–232.
25. Casajús, L.; Muñoz, I. Preliminary results after evaluating solar trackers based on IEC 62817: 2014 Ed. 1. *AIP Conf. Proc.* 2016, 1766, 110001.
26. Jamroen, C.; Komkum, P.; Kohsri, S.; Himananto, W.; Panupintu, S.; Unkat, S. A low-cost dual-axis solar tracking system based on digital logic design: Design and implementation. *Sustain. Energy Technol. Assess* 2020, 37, 100618. [CrossRef]
27. Sidek, M.; Azis, N.; Hasan, W.; Ab Kadir, S.; Shafie, S.; Radzi, M. Automated positioning dual-axis solar tracking system with precision elevation and azimuth angle control. *Energy* 2017, 124, 160–170. [CrossRef]
28. Gutierrez, S.; Rodrigo, P.M.; Alvarez, J.; Acero, A.; Montoya, A. Development and Testing of a Single-Axis Photovoltaic Sun Tracker through the Internet of Things. *Energies* 2020, 13, 2547. [CrossRef]
29. Yao, Y.; Hu, Y.; Gao, S.; Yang, G.; Du, J. A multipurpose dual-axis solar tracker with two tracking strategies. *Renew. Energy* 2014, 72, 88–98. [CrossRef]
30. Azizi, K.; Ghaffari, A. Design and manufacturing of a high-precision sun tracking system based on image processing. *Int. J. Photoenergy* 2013, 2013, 754549. [CrossRef]
31. Abbololahpour, M.; Golzarian, M.R.; Rohani, A.; Zarchi, H.A. Development of a machine vision dual-axis solar tracking system. *Sol. Energy* 2018, 169, 136–143. [CrossRef]
32. Sallaberry, F.; Pujol-Nadal, R.; de Jalón, A.G. Direct tracking error estimation on a 1-axis solar tracker. In *Proceedings of the EUROSUN Congress*, Aix-les-Bains, France, 16–19 September 2014.
33. Ferdaus, R.A.; Mohammed, M.A.; Rahman, S.; Salehin, S.; Mannan, M.A. Energy efficient hybrid dual axis solar tracking system. *J. Renew. Energy* **2014**, *14*, 629717. [CrossRef]

34. Salgado-Plasencia, E.; Carrillo-Serrano, R.V.; Rivas-Araiza, E.A.; Toledano-Ayala, M. SCADA-Based Heliostat Control System with a Fuzzy Logic Controller for the Heliostat Orientation. *Appl. Sci.* **2019**, *9*, 2966. [CrossRef]

35. Salgado-Plasencia, E.; Carrillo-Serrano, R.V.; Toledano-Ayala, M. Development of a DSP Microcontroller-Based Fuzzy Logic Controller for Heliostat Orientation Control. *Appl. Sci.* **2020**, *10*, 1598. [CrossRef]

36. Huang, C.H.; Pan, H.Y.; Lin, K.C. Development of intelligent fuzzy controller for a two-axis solar tracking system. *Appl. Sci.* **2016**, *6*, 130. [CrossRef]

37. SunCalc. Computation Path of the Sun. Available online: [www.suncalc.org](http://www.suncalc.org) (accessed on 3 January 2022).

38. Solar MEMS Technologies S.L. *Sun Sensor ISS-AX: Technical Specifications*; Technical Report; Version: 1.07; Solar MEMS Technologies S.L.: La Rinconada, Spain, 2015.

39. Solar MEMS Technologies S.L. *Sun Sensor ISS-DX: Technical Specifications*; Technical Report; Version: 1.14.M; Solar MEMS Technologies S.L.: La Rinconada, Spain, 2013.

40. Gilman, P.; DiOrio, N.A.; Freeman, J.M.; Janzou, S.; Dobos, A.; Ryberg, D. *SAM Photovoltaic Model Technical Reference 2016 Update*; Technical Report; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2018.

41. Zsiborács, H.; Hegedűsné Baranyai, N.; Vincze, A.; Haber, I.; Weih, P.; Oswald, S.; Gützer, C.; Pintér, G. Changes of Photovoltaic Performance as a Function of Positioning Relative to the Focus Points of a Concentrator PV Module: Case Study. *Appl. Sci.* **2019**, *9*, 3392. [CrossRef]

42. Sarniak, M.T. Simulation Model of PV Module Built from Point-Focusing Fresnel Radiation Concentrators and Three-Junction High-Performance Cells. *Appl. Sci.* **2022**, *12*, 806. [CrossRef]

43. National Renewable Energy Laboratory (NREL). Chart of Best Research-Cell Efficiencies. 2022. Available online: [https://www.nrel.gov/pv/cell-efficiency.htm](https://www.nrel.gov/pv/cell-efficiency.htm) (accessed on 10 December 2021).

44. Fernández, E.F.; Almonacid, F.; Rodrigo, P.M.; Pérez-Higuera, P.J. Chapter II-4-A—CPV Systems. In *McEvoy’s Handbook of Photovoltaics*, 3rd ed.; Kalogirou, S.A., Ed.; Academic Press: Cambridge, MA, USA, 2018; pp. 931–985.

45. Luque-Heredia, I.; Quéméré, G.; Cervantes, R.; Laurent, O.; Chiappori, E.; Chong, J.Y. The sun tracker in concentrator photovoltaics. In *Next Generation of Photovoltaics*; Springer: Berlin/Heidelberg, Germany, 2012; pp. 61–93. [CrossRef]

46. Cardoso, J.P.; Mutuberria, A.; Marakkos, C.; Schoettl, P.; Osório, T.; Les, I. New functionalities for the Tonatiuh ray-tracing software. *AIP Conf. Proc.* **2018**, *2033*, 210010.

47. Blanco, M.; Amieva, J.; Mancillas, A. The Tonatiuh Software Development Project: An Open Source Approach to the Simulation of Solar Concentrating Systems. *ASME Int. Mech. Eng. Congr. Expo.* **2005**, *42142*, 157–164. [CrossRef]

48. Neven Valev. Global Electricity Prices. Available online: [www.globalpetrolprices.com](http://www.globalpetrolprices.com) (accessed on 3 January 2022).