

Article

A Novel Tracking Strategy Based on Real-Time Monitoring to Increase the Lifetime of Dual-Axis Solar Tracking Systems

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Abstract: Solar tracking systems allow an increase in the use of solar energy for its conversion with photovoltaic technology due to the alignment with the sun. However, there is a compromise between tracking accuracy and the energy required to perform the movement action. Consequently, the wear of the tracker components increases, reducing its useful lifetime and affecting the profitability of these systems. The present research develops a novel tracking strategy based on real-time measurements to increase the lifetime without reducing the energy productivity of the tracking systems. The proposed approach is verified experimentally by implementing the real-time decision-making algorithm and a conventional tracking algorithm in identical tracking systems under the same weather conditions. The proposed strategy reduces energy consumption by 14.18% due to the tracking action, maintaining a practically identical energy generation between both systems. The findings highlight a 53.33% reduction in the movements required for tracking and a 60.77% reduction in operation time, which translates into a 6.8-fold increase in the lifetime of the solar tracking system under the experimental conditions applied. The results are promising, so this research initiates and motivates the development of more complex models to increase the useful life of the tracking systems and their profitability and environmental impact concurrently.



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1. Introduction

Solar energy has become one of the most promising alternatives in the fight against climate change and high energy demand. Particularly, photovoltaic technology has had accelerated growth due to its low environmental impact and the recent reduction in technology costs [1]. In recent years, research groups have focused on increasing low conversion efficiency through the development of new materials [2–4], multi-junction configurations in solar cells [5,6], development of concentrating solar technology [7], and control strategies for generation capacity improvement [8,9], among others. The efficiency and generation capacity are related to the position of the solar collector; Solar Tracking Systems (STS) allow solar technology to follow the solar trajectory throughout the day [10], where the aim is to increase the amount of solar radiation received by the conversion technology. One classification of STS is according to the axes of movement into single-axis and dual-axis trackers. Studies have shown that dual-axis systems in an azimuth-elevation configuration are the most efficient and can increase the transformed energy by 67.65% compared to a fixed PV system [11], with the active tracker being the most common drive type with 76.42% [12], which determines the position of the solar path with pointing sensors. However, tracking systems have disadvantages such as complexity and size, which increase costs and complexity of maintenance, requiring special installations. In addition, the probability of failures increases due to the number of moving components required, which

causes losses of precision and profitability. These movements cause wear and tear on the physical components of the tracker, reducing the tracking accuracy or even stopping it from operating, which causes losses in energy production capacity and economics, affecting their performance and increasing energy consumption and tracking errors over a lifetime. Additionally, the complexity of tracking systems increases the probability of failures because they integrate electrical-electronic, electromechanical, and mechanical components. These devices are subject to drastic changes in weather conditions, mainly temperature ranges, rainfall, high humidity, and solar irradiance. Then, the tracking systems are subject to static and dynamic loads due to environmental conditions, and it is necessary to ensure continuous operation to harvest the greatest amount of solar energy. Therefore, it is essential to increase the reliability of the systems without affecting energy gain or increasing costs for additional devices. Consequently, much of the efforts of the scientific and industrial community are focused on improving the efficiency, reliability, and lifespan of solar harvesting systems to increase the energy gain during a period of 20 to 30 years and guarantee the best performance over time. There are multiple investigations focused on diagnosing the status of the photovoltaic system, which require additional devices such as DC-DC converters, charge controllers, power electronics, and processing devices that allow the implementation of algorithms. By estimating the current and voltage of the network [13], embedded devices detect faults by assessing and identifying, at the software level, the currents of the PV modules [14]. In [15], an approach is presented to detect faults in PV systems based on the processing of thermal images using a Support Vector Machine (SVM). The authors in [16] performed an analysis of the performance of a PV array by processing thermal images to detect faults. Finally, in [17], an extensive study of the various methods and techniques used for fault detection in PV systems is presented, including a classification and an approach for efficient maintenance. On the other hand, there is little to no research evidence regarding the lifetime of solar tracking systems, which considers the physical effects on the components due to the tracking action. In [18], a unified metric system is presented to evaluate the reliability of solar tracking systems in the software domain, estimating the convergence of faults of syntax errors, structural errors, and stuck-at-faults. However, structural and electromechanical faults are not considered, being elements subject to continuous wear due to the tracking action. Sorin and their team present in [19] a mathematical approach to estimate and improve the solar reliability factor (SRF), showing that factors such as prolonged exposure to sunlight and varying weather conditions significantly affect the failure rate. This research focuses on data errors in electronic components, not estimating the lifetime of the solar tracking system per se. In [20], the design of real-time test hardware for solar tracking is presented, considering electronic hardware failures of the open and short circuits without regarding failures in the moving components of the tracker. Experimental tests were performed, where the PV system generated a total output power of 10.76 W, and the tracker and monitoring hardware consumed 6.13 W, representing low energy gain. In [21], a technique is presented to test the software code of a solar tracking device, implementing a white-box testing approach through Wi-Fi communication. As a result, a coverage of 70.12% of the errors related to loopholes and possible breakpoints in the tracker software was achieved. In the structural domain, David Valentín et al. [22] presented an investigation of failures in a single-axis solar tracking system, which concludes that the tilt angle increases the probability of structural failures due to wind loads, generating a dynamic phenomenon called torsional galloping. They proposed a solution design of trackers with higher torsional resistance or the implementation of control of the tilt angle to move a safe position in dangerous situations. Additionally, recent research has indicated that monitoring systems are required to identify potential faults or existing damage as early as possible so that they can be corrected or prevented in advance [11]. This involves developing intelligent control strategies that allow decisions to be made to improve performance by recording extensive data on weather conditions and tracker characteristics [23–25]. In consequence, monitoring and online supervision are required and have a fundamental role in the solar

tracking system's lifetime improvement, allowing the decision-making process in real time through the implementation of strategies that increase global energy gain, characterizing the impact of solar and environmental parameters on energy generation with tracking, and diagnosis and prediction of hardware and software failures. Hence, the possibility of remote monitoring helps to control generating systems in distant locations through the transmission of data in real time for the detection and prevention of possible failures in photovoltaic technology or tracking systems, allowing the estimation of the levels of dirt due to dust and the detection of abrupt changes in energy generation, making it easier to implement preventive actions, reducing repair times and maintenance costs [26]. In summary, the literature on solar tracking systems mentions that there is still a need to develop trackers with high precision, low maintenance and low cost, and high reliability and robustness. Tests must be carried out outside the laboratory under realistic operating conditions, using methodologies for overall improvement [27]. Therefore, in two-axis solar tracking systems, it is essential to consider real-time monitoring parameters and energy consumption, and component lifetime estimation in the optimization strategies to increase the viability of these systems. The present research seeks to solve the challenges above across the development of a novel tracking strategy based on real-time measurements to increase the lifetime without reducing the energy productivity of the tracking systems, considering the tracking error and the energy consumption in the decisions. The impact of the research is verified through experimental testing and comparing the proposed tracking strategy with a conventional algorithm in identical tracking systems under the same weather conditions. The results are promising, so this research initiates and motivates the development of more complex models to increase the useful life of the tracking systems and their profitability and environmental impact concurrently. Finally, the main contributions of this work are listed below:

- A novel tracking strategy based on real-time monitoring to increase the lifetime of dual-axis solar tracking systems without reducing the energy productivity of PV systems due to the considerable reduction of operating time, and consequently, the reduction of maintenance requirements, less wear and fatigue in the tracking system, and increasing the profit and reliability during long periods.
- An approach to estimating the tracking system lifetime based on wear and tear and possible failures in the axes due to usage time of the tracking action.
- The energy consumption of tracking systems is reduced due to the decision-making algorithm considering the tracking accuracy and the gain of energy production in an integrated manner.
- An experimental analysis of two tracking strategies was performed by comparing the tracking errors, energy generation, and consumption of two solar tracking systems subject to the same climatic conditions.

The paper is organized as follows. The proposed tracking strategy for the decision-making process in real-time to increase the lifetime of solar tracking systems is presented in Section 2. The verification of the approach is developed through a case study in Section 3, where the proposed and conventional algorithms are tested under the same weather conditions, and the analysis of the results is presented. Finally, Section 4 presents some concluding remarks and research gaps for future work.

2. Methodology

The lifespan of tracking systems recommended by investors is 20 years to 30 years on average [28], and the system profitability can be expressed as the relationship between energy gain and investment. One way to analyze is through the return-on-investment (ROI) indicator, which can be used as a priority factor and can be increased by:

1. Improving the productivity of the tracking system, transforming the biggest amount of solar energy with the least amount of energy loss due to the tracking action.
2. Increasing the service life of the tracker through maximizing reliability, reducing maintenance, and prolonging the useful life of the robotic system.

However, improving the productivity of trackers with current techniques and methods implies a reduction in their service life due to the wear caused by the tracking movement. Therefore, a concurrent tracking strategy is presented to find the balance between maximizing the energy gain and the system's service life in an integrated manner. A decision-making process is proposed based on real-time monitoring of the environmental, tracker, and energy parameters.

2.1. Productivity of Tracking Systems

The function of solar tracking systems is to position the energy transformation technology (photovoltaic, concentration technology, and thermoelectric, among others) in a normal position towards the Sun throughout the day, maximizing the energy capture. The productivity of these systems can be defined based on the energy balance defined in general form by [29]:

$$E_{tot}(\tau) = E_g(\tau) - E_c(\tau) \quad (1)$$

where $E_g(\tau)$ is the energy produced by the photovoltaic system and $E_c(\tau)$ is the required energy for tracking action and monitoring parameters, both in the period time τ . The increase in energy produced depends on the alignment accuracy throughout the day, defined as the tracking error. In this work, two-axis tracking systems in azimuth-elevation configuration are considered because they are the most efficient. According to [10], a mixed tracking method is recommended to increase the performance of the systems, which uses an algorithm to calculate the solar position and a solar pointing sensor to reduce the error. Tracking strategies define how the sun should be tracked to reduce the pointing error, which can be continuous or step-by-step tracking. The continuous strategy increases the energy required for the tracking action since it remains in constant motion. Therefore, the step-by-step tracking strategy is the most used. Additionally, the accuracy adjustment is performed by a control strategy. Fuentes et al. presented in [30] an extensive study of the different tracking control strategies, where the most common controls for two-axis solar tracking systems are On-Off, Proportional-Integral-Derivative (PID), and Fuzzy PID. Hence, the tracking accuracy can be expressed as tracking error, which is defined by the difference between the desired position and the actual position of the axis. In a two-axis system, the mixed tracking error is expressed by [29]:

$$\epsilon_m^2 = \epsilon_\beta^2 + \epsilon_\gamma^2 \quad (2)$$

where ϵ_β and ϵ_γ are the azimuth and elevation errors, respectively. However, the tracking accuracy increases the conversion efficiency of the photovoltaic technology but increases energy expenditure and component wear due to excessive motion. The system energy consumption due to the tracking action depends mainly on the electronic and electromechanical components that compose the tracker and can be reduced by implementing energy-saving strategies, as presented in [29]. Based on [31], the profitability of the tracking system in terms of energy is assured when the consumed energy by the tracker is between 2% and 3% of the energy increasing due to solar tracking.

2.2. Service Life in Tracking Systems

The increased service life of solar trackers means that the system must operate in reliable conditions without failures for an extended period. For the present research, the two-axis solar tracking system in azimuth-elevation configuration is considered a two-degree-of-freedom robotic system in an open kinematic chain. Hence, the common failures in industrial robotic systems occur in the joint mechanisms, which generally limits the service life [32]. Failures depend on characteristics such as transmission type, tooth geometry, and environmental conditions. Typically, expected life is based on transmission errors due to increased backlash and bearing deterioration, intensifying the stresses due to friction. Consequently, the lifetime analysis of the trackers will be carried out based on the wear and failure of the robot joints and processing hardware, where the critical devices in

the tracker are the axis, mainly the gearboxes, where their service life (L_h) in the robotic joints is determined by speed and torque. Each axis includes the motor driver, rotational position sensor, DC motor, gearbox, mechanical transmission, link, and housing. According to [32], it can be calculated as:

$$L_h = K \cdot \frac{N_o}{N_m} \left(\frac{T_o}{T_m} \right)^{\frac{10}{3}} \quad (3)$$

where K is the rated service life at rated torque and at rated output speed, N_o is the rated output speed, N_m is the average output speed, T_o is the rated output torque, and T_m is the average output torque. The service life and the rated output torque and speed are parameters defined by the reducer model in the datasheet. In addition, the path of each axis must be segmented based on the defined maximum tracking error as presented in [29] due to the tracking strategy will be step by step, obtaining the steps β_i for $i = 1, \dots, n_\beta$ and γ_j for $j = 1, \dots, n_\gamma$, for the azimuth and elevation axis, respectively.

Therefore, the solar path can be expressed in terms of the required time to move from one step to the next on each axis, defined as an operation time (t_{op}) when the axis is moving and as idle time (t_{id}) when the axis is waiting or stopped [29]. Figure 1 shows the segmented path of the azimuth and elevation axis where each movement is independent, and they do not necessarily arrive at the position at the same time. In other words, the operation time period is independent due to the solar path, where $t_{op,i} \neq t_{op,j}$. Therefore, the wear that exists on each of the axes depends on the operating time, which affects the lifetime. Then, based on [32], the average output speed and average output torque for the azimuth path are defined by the following expressions:

$$|N_m|_{avg} = \frac{\sum_{i=1}^{n_\beta} t_{op,i} |N_{m,i}|}{\sum_{i=1}^{n_\beta} t_{op,i}} \quad (4)$$

$$|T_m|_{avg} = \left(\frac{\sum_{i=1}^{n_\beta} t_{op,i} |N_{m,i}| |T_{m,i}|^c}{\sum_{i=1}^{n_\beta} t_{op,i} |N_{m,i}|} \right)^{\frac{1}{c}} \quad (5)$$

where c is equal to $\frac{10}{3}$. In the case of the elevation path, the Equations (4)–(6) are modified for the number of elevation steps for $j = 1, \dots, n_\gamma$ and with the mechanical transmission parameters. Consequently, the Equation (3) is modified as:

$$L_h = \frac{\lambda_h}{|N_m|_{avg}} \left(\frac{1}{|T_m|_{avg}} \right)^c \quad (6)$$

where $\lambda_h = K \cdot N_o \cdot T_o$.

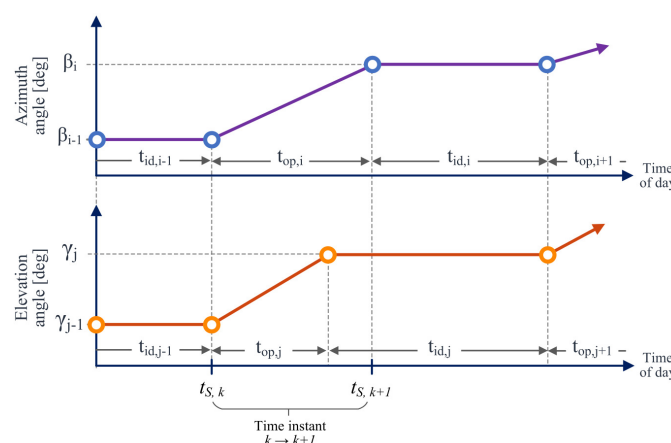


Figure 1. Schematic of the solar path segmentation in the time domain.

2.3. Proposed Tracking Strategy

The present proposal increases the useful life of solar tracking systems by measuring parameters and making decisions in real-time, where the integrated system must consist of a two-axis solar tracker in azimuth-elevation configuration, a monitoring device, and a photovoltaic system. Figure 2 shows the flow chart of the tracking strategy. The monitoring device is responsible for recording the real-time energy parameters of the photovoltaic system and the tracking process. In addition, it calculates the energy balance with the recorded data. The solar tracking system is responsible for maximizing energy capture by the photovoltaic system due to its alignment with the sun's position throughout the day and the reduction of tracking error by implementing control strategies and actual measurement with a solar pointing sensor. Based on real-time measurement, the decision-making process allows for maximizing the energy gain and reducing the number of steps to move simultaneously, considering the energy consumption due to the monitoring and tracking action.

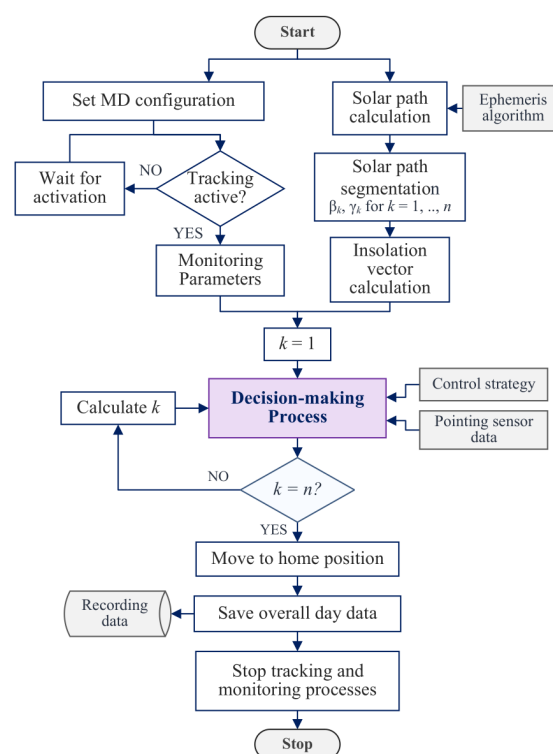


Figure 2. Flowchart of the proposed tracking strategy for lifetime improvement of solar tracking systems.

The decision-making process is described in Algorithm 1 and begins with the calculation of the solar path with an existing algorithm such as the Solar Position Algorithm [33], PSA [34], ENEA [35], and Cooper Equations [36], among others. In the general form, the location of the sun can be calculated in terms of azimuth angle (β) and elevation angle (γ), see Figure 3, expressed as follows:

$$\sin \beta = \cos L \cos \delta \cos H + \sin L \sin \delta \quad (7)$$

$$\sin \gamma = \frac{\cos \delta \sin H}{\cos \beta} \quad (8)$$

where L is the system latitude, δ is the declination angle, which varies from year to year, and H is the hour angle. The trajectory must be segmented into equal steps from sunrise to sunset as described in the previous section, according to [29]. The number of points will depend on the acceptance angle, based on [37], and the reduction of the electrical power at the maximum point can be neglected for angles of incidence less than 5° in photovoltaic technology. Thus, for the path segmentation is recommended to use 1° to 2° for each step.

Therefore, the segmented trajectory is expressed by the vectors $\vec{\beta} = [\beta_1, \dots, \beta_k, \dots, \beta_n]^T$ and $\vec{\gamma} = [\gamma_1, \dots, \gamma_k, \dots, \gamma_n]^T$, where n is the last point of the solar path. Figure 3 shows the solar path schematic considering the azimuthal and elevation angles for the k -point.

Algorithm 1 Decision-making process for solar tracking based on real-time measurement.

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1: Calculate solar path                                ► Solar Algorithm
2: Segmentation of solar path,
    $\vec{\beta} = [\beta_1, \dots, \beta_k, \dots, \beta_n]^T$ 
    $\vec{\gamma} = [\gamma_1, \dots, \gamma_k, \dots, \gamma_n]^T$ 
3: Calculate insolation vector,
    $\vec{I}_{tot} = [I_{tot,1}, \dots, I_{tot,k}, \dots, I_{tot,n}]^T$ 
4: Define time of day vector,
    $\vec{t}_S = [t_{S,1}, \dots, t_{S,k}, \dots, t_{S,n}]^T$ 
5: Define consumption constraint factor
    $\kappa_c$  for  $\kappa_c \leq 0.03$ 
6: Set monitoring device configuration
7: Initialize real-time monitoring process
8: Initialize  $k = 1$ 
9: for  $k = 1 : n$  do
10:  if  $k = n$  then
11:    Move to home position,  $(\beta_1, \gamma_1)$ 
12:    Save overall day data
13:    Stop tracking and monitoring processes
14:  else
15:    Move  $(\beta_k, \gamma_k)$  to  $(\beta_{k+1}, \gamma_{k+1})$ 
16:    while  $(\beta_{k+1,rt}, \gamma_{k+1,rt}) \neq (\beta_{k+1}, \gamma_{k+1})$  do
17:      Minimize  $|\varepsilon_{m,k}|$  until  $|\varepsilon_{m,k}| \leq |\varepsilon_{max}|$     ► Control strategy
18:    end while
19:    Stop tracking in position  $(\beta_{k+1}, \gamma_{k+1})$ 
20:    Save power reference value,  $P_{pv,ref}$ 
21:    if  $P_{pv,rt} \approx P_{pv,ref}$  or  $P_{pv,rt} > P_{pv,ref}$  then
22:      Hold tracking position  $(\beta_{k+1}, \gamma_{k+1})$ 
23:    else
24:      Measure insolation in real time,  $I_{tot,rt}$ 
25:      if  $I_{tot,rt} \approx I_{tot,k+1}$  or  $I_{tot,rt} > I_{tot,k+1}$  then
26:        Hold tracking position  $(\beta_{k+1}, \gamma_{k+1})$ 
27:        Send Alarm    ► Sunny with partly cloudy or damage
28:        Save Data      ► Future analysis and prediction
29:      else
30:        Send Alarm    ► Cloudy, dirty, or damage
31:        Save Data      ► Future analysis and prediction
32:        Compare  $t_{S,rt}$  with  $\vec{t}_S$ 
33:        Define new value of  $k$ 
34:      end if
35:    end if
36:  end if
37:  Calculate energy balance,
    $E_{tot}(\tau) = E_{pv}(\tau) + E_c(\tau)$ 
38:  if  $E_c(\tau) > \kappa_c \cdot E_{pv}(\tau)$  then
39:    Send alarm    ► Out of energy balance
40:    Save data      ► Future analysis and prediction
41:  else
42:    Send alarm    ► Within the energy balance
43:    Save data      ► Future analysis and prediction
44:  end if
45: end for

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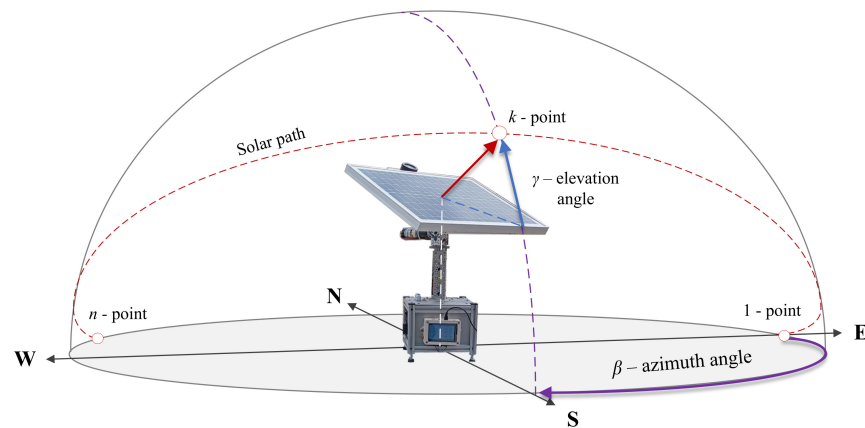


Figure 3. Scheme of the solar path, including the azimuth and elevation angles.

Subsequently, the total insolation vector $\bar{I}_{tot} = [I_{tot,1}, \dots, I_{tot,k}, \dots, I_{tot,n}]^T$ is calculated, where the k -point of the trajectory for two-axis solar tracking with clear sky is expressed by:

$$I_{tot,k} = I_{BC,k} + I_{DC,k} + I_{RC,k} \quad (9)$$

where $I_{BC,k}$, $I_{DC,k}$, and $I_{RC,k}$ are the beam, diffuse, and reflected insolation on the collector, respectively. In the general form, they are determined as follows:

$$I_{BC} = A \cdot e^{-\theta m} \quad (10)$$

$$I_{DC} = C \cdot I_{BC} \left[\frac{1 + \cos(90^\circ - \beta)}{2} \right] \quad (11)$$

$$I_{RC} = \rho \cdot I_{BC} \cdot (\sin \beta + C) \left[\frac{1 - \cos(90^\circ - \beta)}{2} \right] \quad (12)$$

where A is the apparent extraterrestrial solar insolation, θ the atmospheric optical depth, m the air mass ratio, and C the sky diffuse factor, which can be calculated for each day by:

$$C = 0.095 + 0.04 \cdot \sin \left[\frac{360}{365} (N - 100) \right] \quad (13)$$

where N is the day number, with 1 January as day 1 and 31 December as day number 365. For more details on the calculation, consult [38]. Based on the trajectory and the solar algorithm, the time of day is defined for each k -point, expressed as the vector $\bar{t}_S = [t_{S,1}, \dots, t_{S,k}, \dots, t_{S,n}]^T$, see Figure 1. Additionally, considering the profitability of the tracker, where the energy consumption must be between 2 and 3% of the energy increase due to solar tracking [31], the consumption constraint factor $\kappa_c \leq 0.03$ is proposed, which helps in the decision-making and future prediction based on energy balance calculations. Then, we set the monitoring device and initialized the real-time monitoring process. The iterative process begins for each of the points of the trajectory ($k = 1, \dots, n$). The first step is the movement from point (β_k, γ_k) to $(\beta_{k+1}, \gamma_{k+1})$. The mixed tracking error ($\epsilon_{m,k}$) is calculated by comparison of the real-time position $(\beta_{k+1,rt}, \gamma_{k+1,rt})$, measured by the solar pointing sensor, with the desired position as defined in Equation (2). The acceptance angle of the photovoltaic technology defines the maximum admissible tracking error ϵ_{max} , and the tracking error $\epsilon_{m,k}$ is minimized by the selected control strategy for the tracking action. To ensure that the positioning is less than the maximum error, the selected control strategy will seek to minimize the error until it meets the condition, and the tracker stops the movement action while maintaining the achieved position $(\beta_{k+1}, \gamma_{k+1})$. In that position, a reference power value of the photovoltaic system $P_{pv,ref}$ is measured and stored as a reference for decision-making. The system will remain in position $(\beta_{k+1}, \gamma_{k+1})$ as long as the power generated in real-time ($P_{pv,rt}$) is similar or greater than or very close to the

reference value. This condition allows the reduction of the number of points to be tracked without affecting energy productivity and reducing the wear on the axis mechanisms. Otherwise, the insolation ($I_{tot,rt}$) is measured in real-time, compared with the estimated value of the insolation vector at the $k + 1$ step ($I_{tot,k+1}$) if the values are similar or greater, the robotic system maintains the position ($\beta_{k+1}, \gamma_{k+1}$), implying that the day continues sunny with possible PV-damage or partly cloudy, sending alarm and recording data for future analysis and failure prediction. If it is much less, it implies the sky was cloudy, the PV technology is dirty or has some possible damage. Then, the data are saved for future analysis. The period that the tracker does not perform the movement action due to fulfilling the two criteria (P_{pv} and I_{tot}) represents a reduction in energy consumption and wear of the mechanisms. Consequently, the time instant of the day ($t_{S,rt}$) is compared with the time of day vector t_S to define the new value of position k , and the tracker moves to the defined k -point of the trajectory for the next iteration. Simultaneously, with the recorded values and based on Equation (1), an energy balance calculation is carried out for the period τ , which is defined from the initialization of the movement from k -point until the taken decision of the new k -point to track. Lastly, a comparison is made between the energy generated and the energy consumed based on the consumption constraint factor, allowing the definition of the energy productivity of the energy harvesting system considering the tracking action and monitoring process. These actions are performed until the k -point of the trajectory is equal to the defined n -point, then the tracker moves to the home position, represented by β_1 and γ_1 , to be ready to continue tracking the next day. In addition, the data obtained during the day are saved for future analysis, and the monitoring and tracking processes are stopped. Finally, with the saved data, future strategies must be defined to improve the overall performance, identifying cases in which consumption increases or decreases, and analyzing the times in which the tracker mechanisms remain active to estimate the lifetime.

3. Case Study

The tracking strategy was experimentally validated through testing in an integrated system to verify the functionality of the decision-making process and to calculate the improvement of the lifetime by comparing the proposed algorithm with a conventional one under identical environmental conditions. The integrated system includes a solar tracking system, a monitoring device, and a photovoltaic system. Figure 4 shows the electrical power and data connections, including five GY-471 power sensors, one for each axis, another for measuring the generated power by the PV module, one more for the electronic hardware, and a last one for the monitoring device consumption. The technical characteristics of each system are briefly described below.

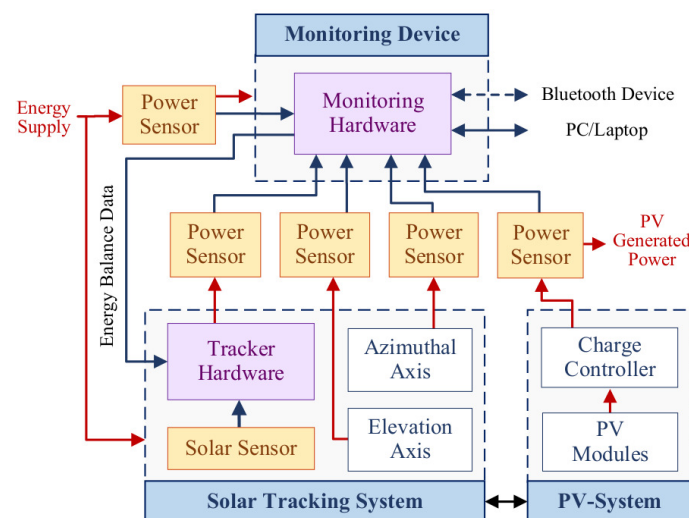


Figure 4. Block diagram of the integrated system, where the red and blue lines represent the electrical power connections and data buses, respectively.

1. **Solar tracking system:** The STS is a two-axis robot in azimuth-elevation configuration with an open architecture to freely configure the required tracking, energy saving, and control strategies. The azimuth axis has a parallel axis transmission with a 76:20 ratio gear, and the elevation axis has a worm gear mechanism with a 28:1 ratio gear, which allows the self-locking action to maintain the position without requiring energizing the actuator. Both axes have a DC gear motor with a planetary gearbox with a 188:1 ratio gear, a stall current of 9.4 A at a stall torque of 24.51 Nm, and a no-load speed of 30 RPM. Table 1 shows the rated output speed and torque of each axis. The angular position measurement is performed with an encoder integrated into the DC motor with a resolution of 5281 pulses per rotation at the output shaft. The system has an embedded Nucleo-F446RE board with 32-bit microcontroller and a VNH2SP30 driver for programming strategies (STMicroelectronics, Geneva, Switzerland). In addition, the tracker is equipped with a Solar Mems ISS-T60 solar pointing sensor, with a 120° field of view, two measurement angles, a precision of 0.06°, and measurement of direct irradiance and ambient temperature.
2. **Monitoring device:** An embedded system for energy monitoring in solar applications designed to be scalable, modular, and built with an open architecture was used for the tests. The device has a low energy consumption of just 0.326 Wh. It features a 32-bit microcontroller with 12-bit ADCs and an integrated Real-Time Clock (RTC) for real-time data logging through four channels. With compact dimensions of 104.5 × 74 × 36 mm, the device includes a 3.5-inch touchscreen for setting up parameters, configuring data logging operations, and visualizing measured values in display, graph, or table modes. It also supports wireless data streaming via Bluetooth and Wi-Fi and wire communication through USB or UART connections to external devices.
3. **Photovoltaic system:** The integrated system includes a PV technology module as an energy generation component with the following characteristics: an arrangement of 36 polycrystalline cells, a total dimension of 550 mm × 360 mm, a mass of 2.5 kg, maximum power in STC of 25 W, and an average conversion efficiency of 12.63%. In addition, it has a charge controller model PY-HP2410 (Prostar Solar, Jiangsu, China) with a maximum input solar power capacity of 170–340 W and a Solar Cale CL-31T/S-190M lead-acid battery (Enertec Mexico, Monterrey, Mexico) with a voltage of 12 V and capacity of 122 Ah. Additionally, the system can connect the output power to a charge inverter or a DC load to use the generated power.

Table 1. Rated output speed and torque of azimuth and elevation axis.

Axis	N_o [RPM]	T_o [Nm]
Azimuth	6.375	39.58
Elevation	0.865	343.14

3.1. Experimental Setup

The experimental procedure is realized on two identical integrated systems to compare the proposed decision-making algorithm (DMA) with a conventional algorithm (CA) under the same environmental conditions, where the CA employs a step-by-step tracking strategy, aiming to reach the position of each step of the segmented path and reducing the error with a Solar Mems pointing sensor and a control strategy. Figure 5 shows the conventional algorithm used in the experiment, where t_s is the time constant required for each step calculated with the quotient of total time from sunrise to sunset, and the total number of steps obtained from path segmentation, and $t_{s,k}$ is the time measurement at the k -point. The experimental setup is presented in Figure 6, where STS_1 is configured to operate with the DMA and STS_2 with the CA. The setup for both algorithms is described below:

- The location for the tests was in the Applied Dynamic Systems Laboratory of the UPIITA-IPN, in Mexico City, Mexico, with a latitude and longitude of 19.3014° and −99.0728°, respectively. The day was 17 May 2024, when sunrise was at 05:59:00, noon

at 12:32:00, and sunset at 19:06:00. The experimental tests began at 11:30:00 (UTC-6) and ended at 12:30:00 (UTC-6).

- The experimentation was in mixed weather conditions with clear and partially cloudy conditions, where the periods of cloudiness were from 11:40:00 to 12:00:00 and from 12:05:00 to 12:22:00.
- The solar path was calculated using the Solar Position Algorithm (SPA) and segmented in intervals of 4 min, resulting in 151 steps for both axes.
- The power sensors calibration was using a Fluke 289 True RMS multimeter (Fluke Corporation, Everett, WA, USA), with a maximum error of 1.5%. The calibration procedure consisted of a zero adjustment to ensure the sensor reads zero when no current is flowing and a test with a constant electric load to compare the measured value with the multimeter value.
- The acceleration and velocity profiles at the robot joints are the same for both algorithms; for this reason, they were not considered in the lifetime analysis.
- The measurements of the monitoring device channels were configured to acquire 32 samples for each reading, considering an offset and measurement error correction factor.
- Each monitoring device connects to a computer with a USB cable and wirelessly using the Bluetooth module for real-time data transmission and recording. In addition, when the monitoring process starts, a file with *.csv extension is created to continuously record the data on a Micro SD memory card configured with the exFAT file system.
- Based on the results presented in [39], the selected control strategy for both systems is the PID controller due to a balanced relationship between the mixed tracking error and energy consumption, which ensures adequate performance for the case study. For more detail, in [39], a PID controller implementation in a two-axis solar tracker is presented.
- According to the experimental tests in [29], the proposed energy-saving strategy includes the activation of the sleep mode of the tracker control hardware during idle times and the parallel activation of the axes until the desired position is reached.

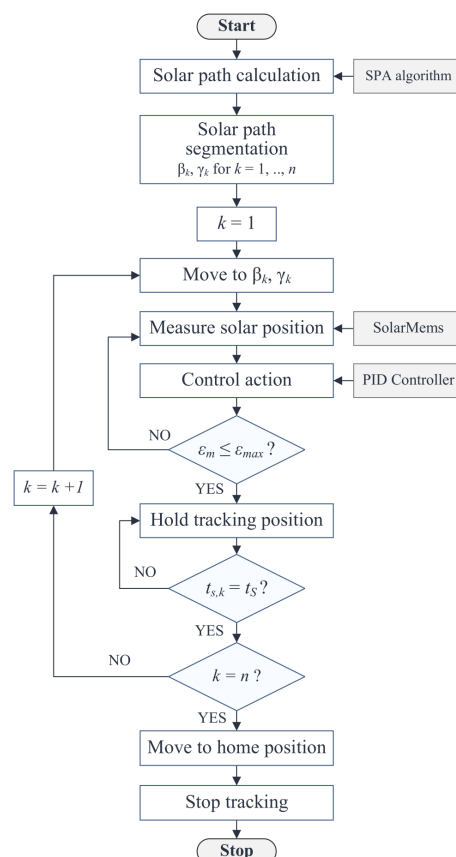


Figure 5. Flowchart of the conventional algorithm.

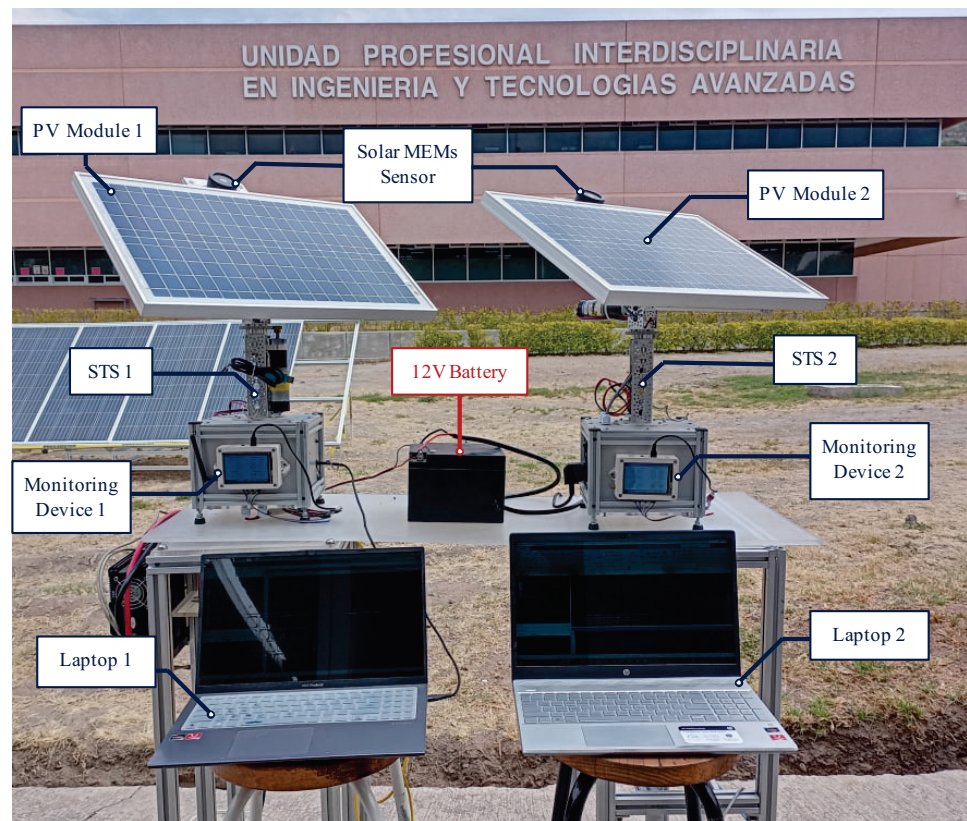


Figure 6. Experimental setup for the tracking strategy evaluation.

3.2. Experimental Results

Figures 7 and 8 show the tracking error results obtained for both strategies. The mean error in the azimuthal axis $\bar{\epsilon}_\beta$ is 1.43° and 0.27° for the DMA and CA strategies, respectively. For the elevation axis, a mean error $\bar{\epsilon}_\gamma$ of 4.39° and 1.00° for each strategy are measured. Therefore, a mixed tracking error is calculated using the Equation (2) obtaining a 4.61° for DMA and 2.04° for CA. The summarized results of the tracking error are presented in Table 2.

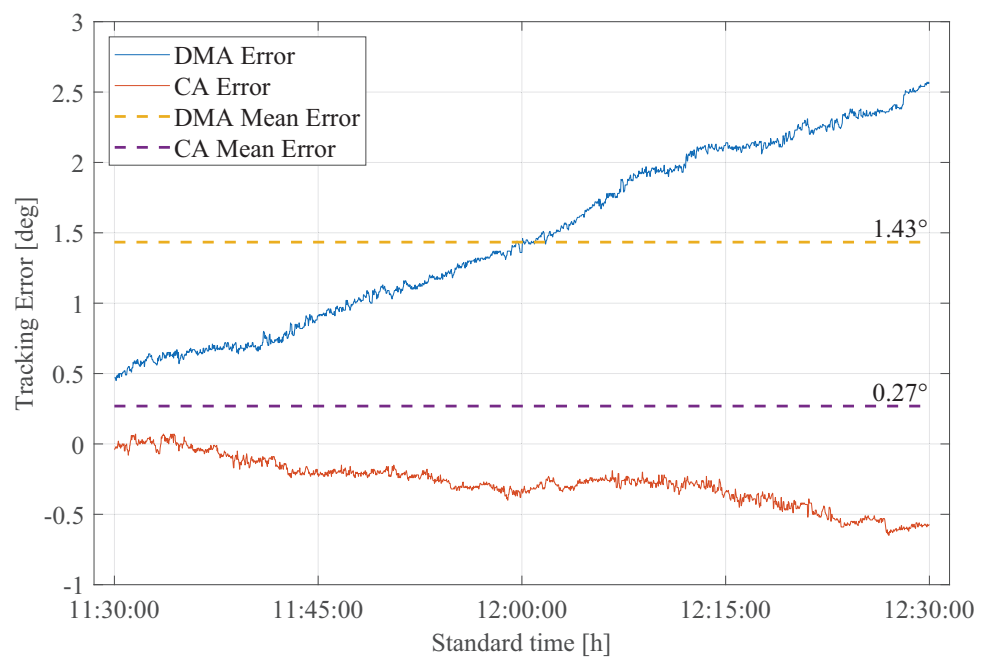


Figure 7. Tracking error measurements of the DMA and the CA for the azimuth axis.

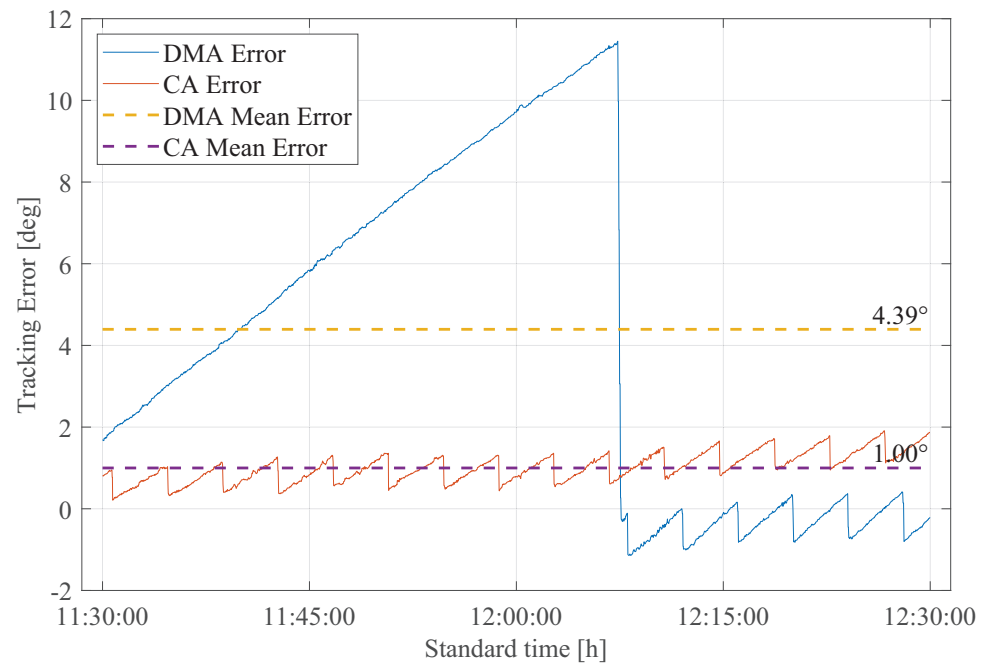


Figure 8. Tracking error measurements of the DMA and the CA for the elevation axis.

Considering the defined periods, the energy consumption on both axes is 0.26 Wh for the DMA and 0.47 Wh for the CA, and the total energy consumption is 1.27 Wh for the DMA and 1.48 Wh for the CA. Hence, the proposed algorithm demonstrates the reduction of energy consumption, representing a 14.18% reduction. The electrical power generated by the PV modules for DMA and CA is shown in Figure 9. The PV technology produces, during the tests, 19.87 Wh and 19.91 Wh with the STS₁ and STS₂, respectively. Therefore, the energy productivity for both strategies is practically identical, representing only 0.21% of difference between the strategies. Thus, the DMA simultaneously achieves a high energy conversion efficiency and reduces the number of tracking movements. For both strategies, two events of drastic reduction in the transformation of solar energy are presented in the measurements, and the reason is the cloudiness.

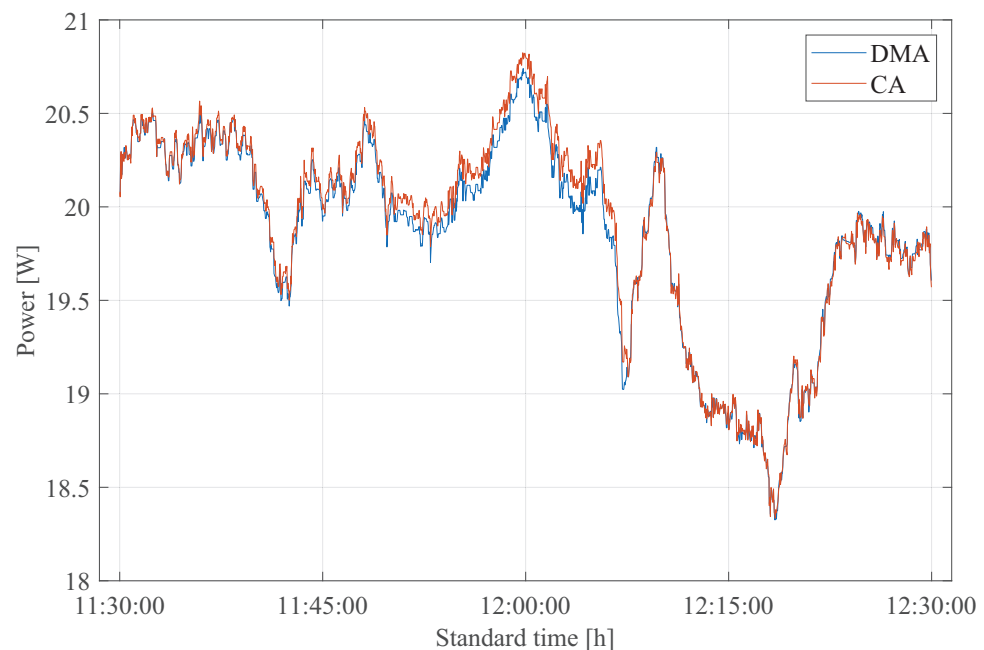


Figure 9. Electrical power generation by the PV modules with the DMA and CA strategies.

The operation states for the decision-making algorithm associated with the irradiance are shown in Figure 10, where the state 0 corresponds to the STS_1 turning to the home position and the state 1 is the movement to the next point of the trajectory, depicting the 8.33% of the tests time. In state 2, the system held position while the P_{pv} condition was accomplished, representing 90.24% of the experimentation duration. Finally, the system maintains its position while the I_{tot} condition is true in state 3, with 1.44% of the remaining time. In addition, five alarms were registered during the tests due to the partly cloudy condition.

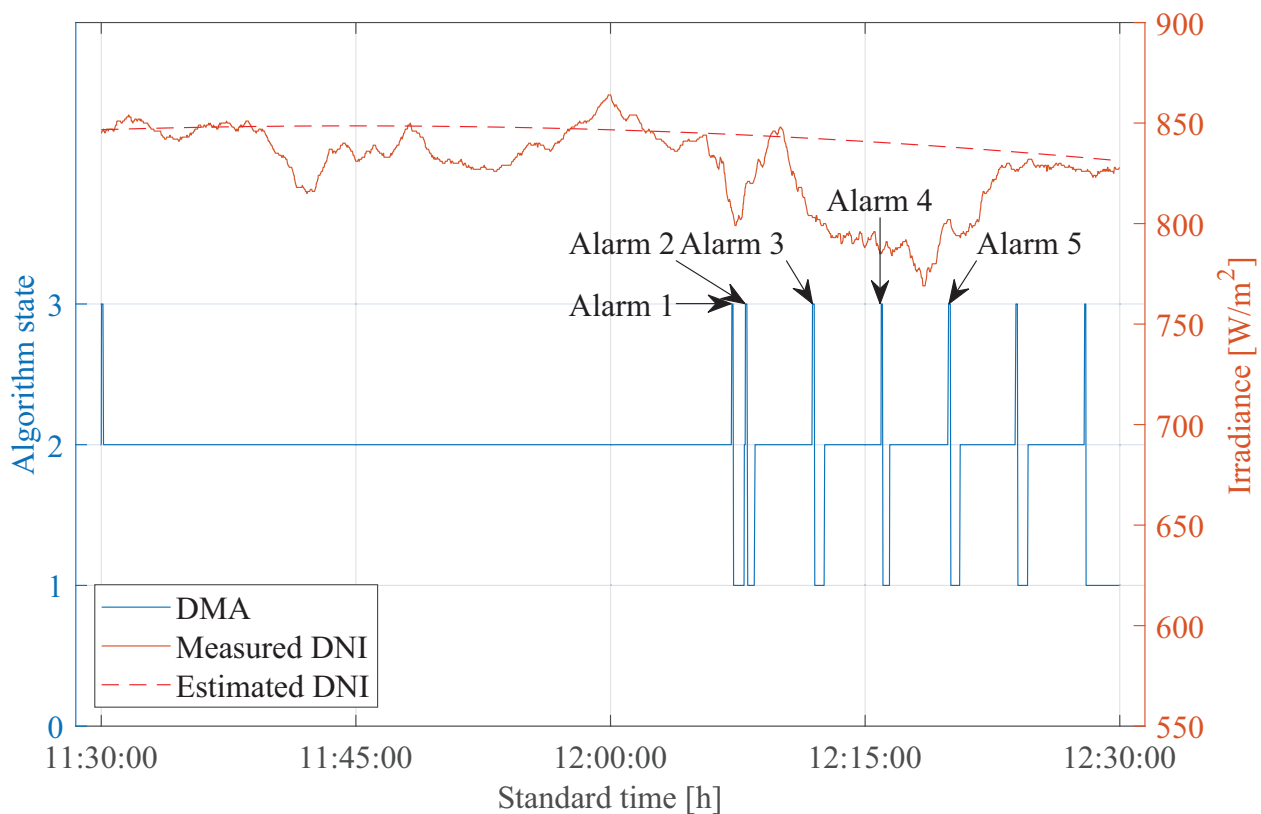


Figure 10. States of operation by the DMA and the measured irradiance variation.

Consequently, the productivity analysis for both strategies is performed with the experimental results obtained and shown in the bar graph in Figure 11, where $E_{c,a}$ and $E_{c,e}$ are the required energy for the azimuthal and elevation axis, respectively. $E_{c,m}$ is the energy consumption of the monitoring device and E_{PV} is the energy produced by the solar modules. In addition, the energy balance of the strategies is shown by calculating E_{tot} with Equation (1). Table 2 shows the summarized results of the energy productivity. Based on the experimental results, the CA strategy segments the trajectory into 15 steps and the DMA strategy into seven steps, as shown in Figure 8, which implies a 53.33% reduction in steps. Likewise, the total operation time for each axis of both strategies was determined (see Figure 12), obtaining a total time of 232 s for CA and 91 s for DMA, which implies a 60.77% reduction in operation time with the proposed strategy.

Table 2. Summary of the experimental results of tracking error and energy analysis.

Algorithm	$\bar{\epsilon}_\beta$ [°]	$\bar{\epsilon}_\gamma$ [°]	$\bar{\epsilon}_m$ [°]	E_g [Wh]	E_c [Wh]	E_{tot} [Wh]
DMA	1.43	4.39	4.61	19.87	1.27	18.60
CA	0.27	1.00	1.03	19.91	1.49	18.43

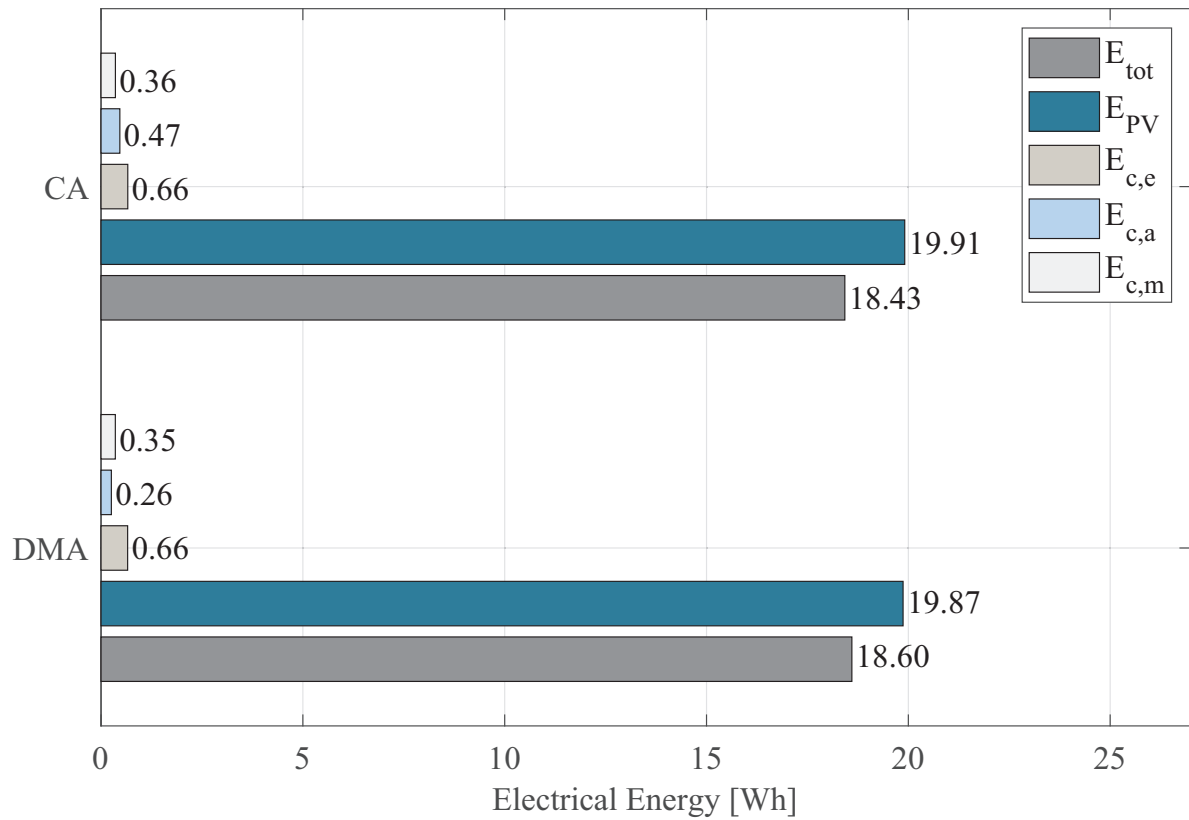


Figure 11. Bar graph of the energy balance of monitoring strategies.

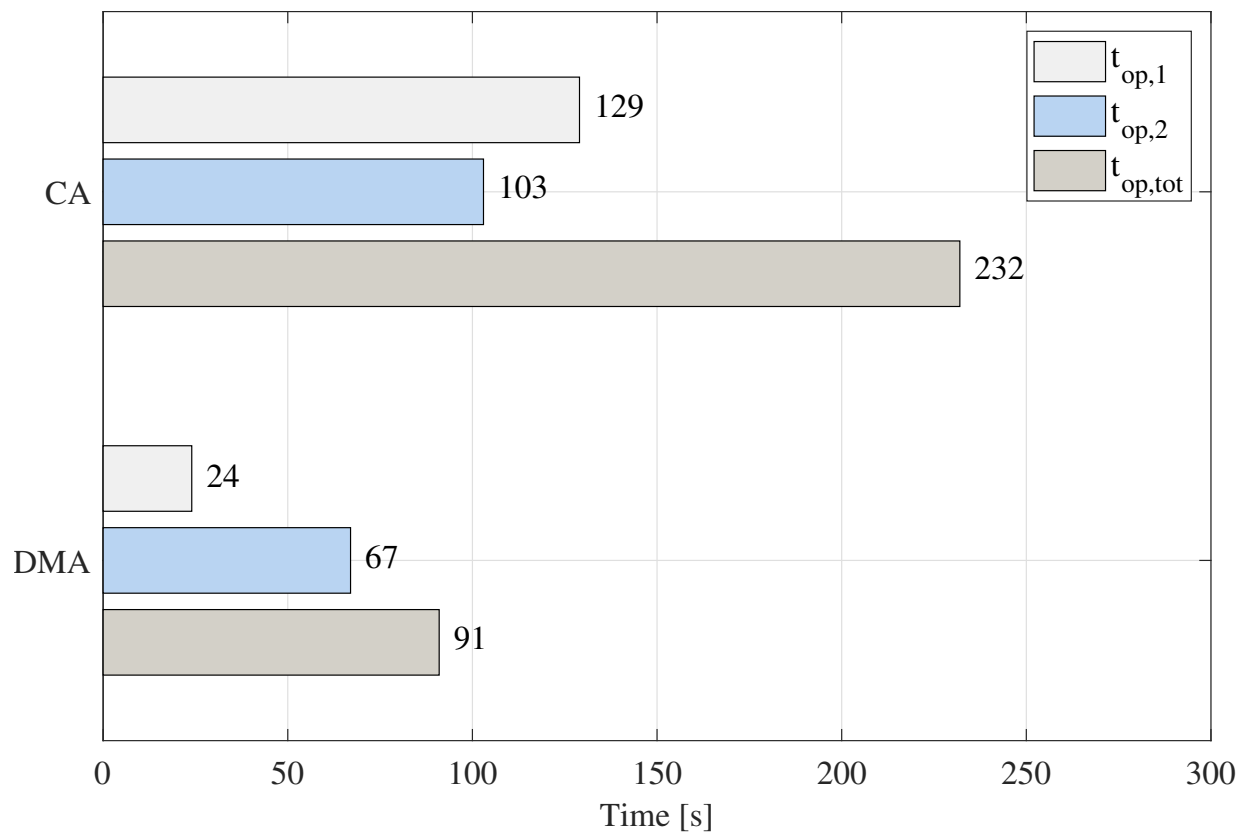


Figure 12. Operation times for the DMA and CA strategies.

On the other hand, for the estimation of the service life, the following considerations are taken into account:

- For the calculation, the payload was evaluated as a constant value, only the load of the PV module; however, an increase in the applied load due to the wind force on the solar collection surface exists, affecting the study, and hence, it must be considered in future calculations.
- The analysis is carried out for the elevation axis because it is the critical element due to the configuration of the tracking robot, and the loads applied to the azimuthal axis are neglected since they are axial with a minimum impact on the bearing.
- The angular velocity is considered identical for each strategy, with an average value of 0.1067 RPM, which allows the service life calculation to focus on the impact on the operating time.
- The output torque for each step is calculated through the dynamic analysis of the system for each step in the trajectory, where the dynamic model is described by:

$$D(q)\ddot{q} + C(q, \dot{q}) + g(q) = \tau \quad (14)$$

where q , $\dot{q}$, and $\ddot{q} \in \mathbb{R}^2$ are the angular position, the velocity and acceleration of the azimuthal and elevation axis, respectively. The matrix $D(q) \in \mathbb{R}^{2 \times 2}$ represents the effective inertia matrix for the axis motors, $C(q, \dot{q}) \in \mathbb{R}^{2 \times 2}$ is the Coriolis matrix, $g(q) \in \mathbb{R}^2$ is the gravitational vector, and $\tau \in \mathbb{R}^2$ is the torque of each axis. The explicit model is defined as follows:

$$D(q) = \begin{bmatrix} m_2 l_2^2 C_2^2 + I_{y_1} + I_{x_2} S_2^2 + I_{y_2} C_2^2 & 0 \\ 0 & m_2 l_2^2 + I_{z_2} \end{bmatrix} \quad (15)$$

$$C(q, \dot{q}) = \begin{bmatrix} (I_{x_2} - I_{y_2} - m_2 l_2^2) C_2 S_2 \dot{q}_2 & (I_{x_2} - I_{y_2} - m_2 l_2^2) C_2 S_2 \dot{q}_1 \\ (-I_{x_2} + I_{y_2} + m_2 l_2^2) C_2 S_2 \dot{q}_1 & 0 \end{bmatrix} \quad (16)$$

$$g(q) = \begin{bmatrix} 0 \\ m_2 g l_2 C_2 \end{bmatrix} \quad (17)$$

where I_{x_2} , I_{y_1} , I_{y_2} , I_{z_2} are the tensor of inertia, m_2 is the PV module and link structure mass, l_2 is the distance of the elevation link, g is the gravity constant, and C_2 and S_2 stand for $\cos(q_2)$ and $\sin(q_2)$, respectively. For more detail, the dynamic model using the Euler–Lagrange procedure is presented in [40]. Since the load on the azimuth axis is absorbed by the bearing, the dynamic model is simplified and focused on the elevation axis, where the torque is expressed as follows:

$$T_m = m_2 \cdot l_2 \cdot g \cdot \sin(q_2) \quad (18)$$

where m_2 is equal to 4.081 kg, l_2 is 0.08 m, and q_2 is the angular position of the elevation axis with the horizon as reference for each step in the strategies path.

- The rated service life K of the system was defined as 60,000 h according to supplier recommendations for industrial robotic systems presented in [41].

Table 3 shows the torque and angular position data for each step and the strategy used for the calculation, where step 0 is the initial position for the experimental test and is calculated by the Solar Position Algorithm. Finally, based on experimental results and considering the Equations (4)–(6), the calculated service life for CA is 3.34×10^6 h and 22.77×10^6 h for DMA, representing an improvement of 682.10% of the lifetime with the proposed strategy (see Table 4).

Table 3. Angular position and torque and data for the CA and DMA strategies.

Step	Solar Time	CA		DMA	
		q_2 [°]	T_m [Nm]	q_2 [°]	T_m [Nm]
0	11:30	75.22	-	75.22	-
1	11:34	81.25	0.4878	80.13	0.5496
2	11:38	82.19	0.4357	-	-
3	11:42	83.13	0.3835	-	-
4	11:46	84.08	0.3307	-	-
5	11:50	85.02	0.2783	-	-
6	11:54	85.96	0.2259	-	-
7	11:58	86.90	0.1734	-	-
8	12:02	87.84	0.1208	-	-
9	12:06	88.78	0.0683	-	-
10	12:10	89.73	0.0151	91.43	0.0862
11	12:14	90.67	0.0375	92.37	0.1326
12	12:18	91.61	0.0901	93.31	0.1851
13	12:22	92.55	0.1427	94.25	0.2376
14	12:26	93.50	0.1957	95.19	0.2912
15	12:30	94.44	0.2482	96.14	0.3429

Table 4. Summary of the experimental results of service life analysis.

Algorithm	$ N_m _{avg}$ [RPM]	$ T_m _{avg}$ [Nm]	L_h [hours]
DMA	0.1067	1.8178	22.77×10^6
CA	0.1067	3.2337	3.34×10^6

4. Conclusions and Future Work

A novel tracking strategy for dual-axis solar trackers is presented, which increases the useful life of the mechanisms considering the required tracking precision and without affecting energy productivity. The algorithm significantly reduces the tracking operation time due to the reduction of the path steps without affecting energy productivity depending on decisions made during the real-time monitoring process. The proposed methodology was experimentally tested, comparing the decision-making algorithm with a conventional strategy under the same weather conditions and with identical tracking systems, reducing the energy consumption by 14.18% due to the tracking action while maintaining identical energy productivity between both strategies. Although the proposed algorithm does not manage time per se, the parameter is necessary for estimating the useful life of the components, so recording time and associating the actions performed in the decision-making process is essential to determine comprehensive strategies for reducing the wear of the tracking systems. The findings highlight a 53.33% reduction in the movements required for tracking and a 60.77% reduction in operation time, which translates into a 6.8-fold increase in the lifetime of the solar tracking system under the experimental conditions applied. In addition, the tracking strategy and the real-time data recording will allow effective identification of failure modes to determine critical states during the operation of the tracking system. The collected, filtered, and saved data can be processed in a cloud system to anticipate malfunctions, failures, and maintenance of the tracking systems. On the other hand, control strategies can increase tracker performance; however, even with the most precise control method, the fatigue limits of the robot's structural and mechanical components cannot be exceeded, considering torque, current, and temperature

limits. Hence, if the operation time and the tracking action aggressiveness are reduced, as a consequence, the lifetime of the tracking systems can be improved considerably.

Although life estimation of the tracker's lifetime is complex due to the variability in the weather conditions, the health of the PV system, and the wear or failure of the tracker components, the proposal presents an approach with promising results that require future research to develop more complex models based on the present strategy that allow defining with greater precision and in a comprehensive manner the improvement of the useful life of the trackers, considering the speed and acceleration profiles, wind loads, temperature, and control action, among others. In addition, a more extensive comparison can be made with state-of-the-art algorithms that allow the development of new strategies that improve the performance of tracking systems and increase their useful life simultaneously. Finally, the present research has the future perspective of helping in the development of solar tracking systems that are efficient for longer periods, reducing the required maintenance and extending the lifetime without affecting the performance in the conversion of electrical energy and integrating novel technology for solar harvesting energy.

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Abbreviations

The following abbreviations are used in this manuscript:

CA	Conventional Algorithm
DMA	Decision-Making Algorithm
MD	Monitoring device
PV	Photovoltaic
SPA	Solar Position Algorithm
SRF	Solar Reliability Factor
STS	Solar Tracking System
SVM	Support Vector Machine
PID	Proportional-Integral-Derivative
ROI	Return-on-investment
RTC	Real-Time Clock

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