SOLAR ENERGY HARVESTING: AN ASTRONOMICAL APPROACH TO SOLAR TRACKING SYSTEM DESIGN

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ABSTRACT

A solar tracking system is an electromechanical system designed to orient solar panels towards the sun to maximise energy capture. It is applied in renewable energy production to improve the efficiency of solar panels. Most solar energy systems make use of fixed solar panels, which have limitations in capturing maximum sunlight due to their inability to align with the sun's position throughout the day. To overcome the identified limitations, this work developed a dual-axis astronomical-based solar tracking system that integrates real-time astronomical calculations using geographical data to adjust the solar panel orientation throughout the day, thereby improving solar energy production. A microcontroller-based control system, coupled with servo motors and a GPS module, was used to implement the tracking mechanism and the system was evaluated against fixed and sensor-based solar tracking configurations in terms of energy output and tracking accuracy. The results showed that the astronomical tracker achieved a 32% increase in energy output compared to fixed systems and outperformed sensor-based systems by 8% in terms of alignment precision and reliability, particularly under suboptimal weather conditions.

Keywords: Astronomical method, Dual-axis tracker, Photovoltaics, Renewable energy, Solar tracking

1 INTRODUCTION

Over the years, renewable energy generation has been an area of great interest due to the need to shift from dependency on fossil fuels to address global energy demands while mitigating their environmental impacts [1, 2, 3, 4, 5]. Solar energy is one of the most promising sources of renewable energy. With the help of research and development, solar energy has been captured over the years with the use of fixed photovoltaic (PV) systems. Still, these systems have proven to be inefficient due to their inability to align the solar panel with the sun's angle of incidence all day, leading to significant energy losses [6]. Solar tracking systems have been introduced to address this issue by continuously adjusting the panel's orientation to follow the sun's motion. Solar tracking systems can be generally classified by their axis of movement (single-axis or dual-axis) and control strategy (sensor-based, passive or astronomical-based) [7, 8]. Sensor-based systems are widely used tracking systems that utilise light-dependent resistors (LDRs) for sensing and aligning with the position of the sensed sunlight, but are highly susceptible to performance drops, especially in cloudy, low-light, dusty, or shaded conditions [9]. In contrast to the sensor-based tracking system, the astronomical-based tracking system determines the sun's position using algorithms that utilise input data such as the time, date and geographical coordinates of its present location to enable consistent tracking accuracy regardless of weather conditions. This paper presents the development, implementation and testing of a microcontroller-based dual-axis astronomical solar tracking system, where energy output and tracking accuracy are key performance metrics for evaluation and validation. The efficiency and reliability of solar tracking systems have been the focus of extensive research in recent years. Several studies have compared different tracking mechanisms and explored their potential to optimise solar energy capture. Racharla and Rajan [6] provided a comprehensive review of tracking technologies, analysing the performance of single-axis, dual-axis, and fixed photovoltaic (PV) systems. Their findings showed that dual-axis trackers can increase efficiency by up to 40% compared to fixed installations, making them attractive for large-scale solar farms. However, they also emphasised the trade-off between higher energy yields and the increased energy consumption of actuators, which remains a challenge in sustaining overall system efficiency. Banerjee [9] examined astronomical tracking systems that rely on pre-programmed solar position algorithms rather than sensor inputs. The study demonstrated that such systems are less susceptible to environmental factors, such as cloud cover or dust, thereby offering more consistent tracking. However, the research identified a gap in evaluating the performance of astronomical trackers under extreme environmental conditions such as dust storms, snow, or prolonged cloudiness. This highlights the need for adaptive control mechanisms that can optimise performance across diverse climates. More recent advancements in intelligent solar tracking were presented by Kumba et al. [10], who investigated the application of artificial intelligence (AI) in astronomical tracking. Their work proposed the use of machine learning algorithms to adapt to seasonal variations and optimise panel orientation dynamically. Results indicated that AI-driven astronomical tracking could enhance solar energy capture by an additional 10–15% compared to conventional astronomical methods. Despite these promising outcomes, further studies are required to validate the integration of AI within purely astronomical tracking frameworks. Tiwari and Lakra [11] explored the use of Internet of Things (IoT) technologies in solar tracking. Their research developed a system that integrates astronomical tracking with IoT-enabled remote monitoring and control. The system improved operational flexibility and reliability, suggesting that IoT-based solutions could be particularly effective for large-scale solar installations. Future research directions include the integration of astronomical trackers into smart grid infrastructures for automated energy distribution and optimisation. In addition, Priyam [12] analysed the economic aspects of solar tracking, comparing single-axis, dual-axis, and astronomical systems. The study concluded that while dual-axis trackers have higher initial costs, they offer significant long-term returns through increased energy generation. Astronomical tracking was highlighted as a cost-effective solution due to its independence from sensor components, although the relatively high initial cost and maintenance costs remain barriers to adoption in resource-constrained regions. Research into modular system designs, cost-effective materials, and financing mechanisms could help address these challenges and make the technology more accessible. Collectively, these studies illustrate the technical, economic, and environmental considerations influencing solar tracking system development. They also point toward ongoing opportunities for improving astronomical tracking through AI integration, IoT connectivity, and cost reduction strategies.

2 MATERIALS AND METHODS

The system architecture, implementation of the astronomical tracking algorithm and the hardware and software components are discussed here.

2.1 Overview of System Architecture

The system developed is a dual-axis solar tracking device designed to maximise solar energy capture by continuously aligning a photovoltaic (PV) panel with the sun's position. The system has three main subsystems: the solar panel and mechanical tracking structure, the control unit, and the power management system. The mechanical structure consists of a lightweight acrylic frame fabricated using CNC machining, which allows both azimuthal (horizontal) and elevation (vertical) rotations. The frame securely holds the solar panel and is actuated by two servo motors, each dedicated to a specific axis. The control unit is built around an Arduino Nano microcontroller, which receives location and time data from a GPS module and processes solar position algorithms. The control signals generated by the Arduino are used to actuate the servo motors, thereby aligning the PV panel with the sun's trajectory. A 7.4V Li-ion battery serves as the primary power source, regulated by buck converters to provide stable 5V to both the Arduino and the servo motors.

2.2 Hardware Components

The hardware implementation integrates electronic and mechanical components, where the central control unit is an Arduino Nano microcontroller, chosen for its compact size, low energy consumption, and compatibility with the Arduino IDE. Solar position data is obtained with the GPS module, which supplies real-time geographic coordinates and time to the microcontroller. The actuation system makes use of two servo motors, each responsible for controlling one axis of rotation. Signal lines from the Arduino's digital pins D9 and D10 are used to drive the azimuth and elevation servos, respectively. To ensure stable operation and prevent voltage dips, the servo motors are powered through an external 5V supply with a common ground shared with the Arduino. A 7.4V Li-ion battery is used as the primary power source, stepped down to 5V using buck converters to supply both the logic and actuation components. The solar panel is mounted on a dual-axis acrylic frame, fabricated with precision CNC cutting (done at a CNC Workshop in Abuja, Nigeria) to ensure smooth motion and structural integrity. Finally, all wiring, converters, and the microcontroller are assembled on a veroboard and enclosed within a protective plastic junction box for durability and environmental resistance. The major hardware components used to construct the solar tracking system were purchased from Hub360, Nigeria, and some of the components include: A GPS Module, which was used to acquire the precise longitude, latitude, and UTC+1 timestamp data. Solar Panel (5W Polycrystalline) Model SK-203: The solar panel was the target device used for optimised energy harvesting. The defined specifications of the solar panel (Model: SK-203) used are shown below: Rated Power (Pmax): 1.5 Wp, Rated Voltage (Vmp): 4.9V, Rated Current (Imp): 309 mA, Short-Circuit Current (Isc): 334 mA, Open-Circuit Voltage (Voc): 7.0V, Max System Voltage: 8.0V, Standard Test Conditions: 1000 W/m² @ 25°C. Arduino Nano: This serves as the brain of the system, and it is responsible for executing astronomical calculations and controlling the servo motors. Two MG996R Servo Motors: They are used to control the movement of the dual-axis tracker. One for azimuth (to control horizontal tracking), and the other for elevation (to control vertical tracking). 7.4V 2200mAh DC-DC Buck Converters: Used to regulate voltages to supply appropriate power levels to the Arduino and servos. Panel Mount Structure: Custom dual-axis mount built with laser-cut acrylic sheets used to provide the physical structure for supporting and rotating the panel. Wires, Breadboards, and Connectors: used for electrical interconnections. Junction Box: Used for organised housing and wire management.

2.3 Software Components

The following software tools, algorithms and libraries were used to integrate the astronomical tracking algorithm and implement the project. Solar Position Algorithm (SPA) based on the JDP10 SolarCalculator was used to compute the sun's azimuth and elevation based on date, time, and location. Arduino IDE was used to program and upload the tracking logic to the Arduino Nano. Gaisma.com and online solar position calculators were used to verify the accuracy of calculated sun positions. Microsoft Excel was used for data logging, analysis, and graphical plotting. The TinyGPS++ library was integrated to process the GPS data input. Servo.h library maps were used to calculate angles to the motor movements.

2.4 Hardware Design

Microcontroller System (Arduino Nano): This acts as the brain of the system, running solar position algorithms (NOAA-based via SolarCalculator library) to compute azimuth and elevation angles from GPS-provided location and time data. Power Management: A 7.4V Li-ion battery powers the system and buck converters step the voltage down to a stable 5V for both the Arduino and servos. During testing, USB power was used, but an external 5V source was adopted for deployment to avoid overload. Servo Motor Setup: Two servos handle azimuth (horizontal) and elevation (vertical) tracking. Signal wires were connected to

Arduino pins D9 (azimuth) and D10 (elevation). Power and ground rails were carefully separated to prevent dips and erratic behaviour. GPS Module Integration: The GPS provides automatic geographic coordinates. Connected via Arduino's digital pins D2 (RX) and D3 (TX), with VCC and GND linked to the 5V and ground rails. Circuit Assembly: All wiring was soldered on a veroboard for neatness and reliability. A common +5V rail and ground rail were shared across Arduino, servos, and the GPS module. Mechanical Structure: The mount was CNC-cut from acrylic for lightweight durability, allowing dual-axis movement. Servos were fixed to enable smooth azimuth and elevation control. A protective plastic junction box enclosed the Arduino and electronics. The circuit diagram and developed system are depicted in Figure 1 and Figure 2 respectively.

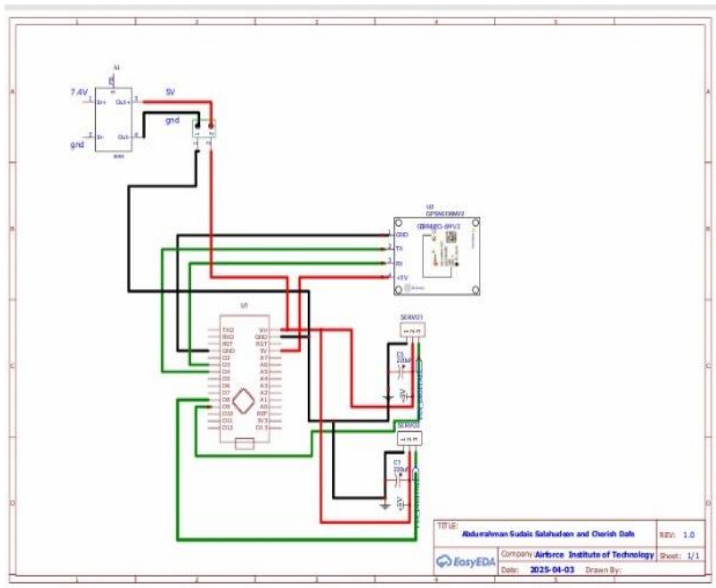

Figure 1. Schematic diagram of the system's circuit

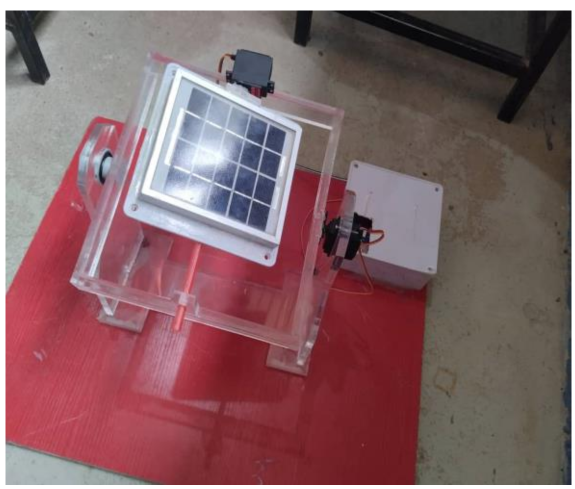

Figure 2. The developed structure of the solar tracking system

2.5 Astronomical Algorithm Implementation

Unlike sensor-based trackers, which depend on real-time sunlight detection, this system uses the astronomical method to compute the sun's position based on geographic coordinates, date, and time. The control unit implements the Solar Calculator library, which is derived from algorithms published by the National Oceanic and Atmospheric Administration (NOAA). These algorithms calculate solar declination, hour angle, azimuth, and altitude (elevation) angles with high accuracy. Specifically, the declination angle accounts for the tilt of the Earth's axis, while the hour angle is determined from the local solar time. Together, these parameters are used to compute the solar altitude and azimuth, which represent the sun's position in the sky. The Arduino Nano processes these calculations in real time and outputs control signals to the servo motors, ensuring that the solar panel maintains an optimal orientation throughout the day, even under cloudy or dusty conditions. An open-source solar tracking algorithm (JDP10 SolarCalculator) was adopted and modified for the Arduino. The algorithm used the Julian Day Number (JDN), Greenwich Mean Time (GMT), declination angle, and hour angle to compute the solar azimuth and elevation angles for the specified location (AFIT, Kaduna) and time (from dawn, 6:00 AM, to dusk, 7:00 PM). GPS Data Parsing was performed using the TinyGPS++ library to extract real-time location and UTC data. Once the angles were obtained, they were computed and mapped to the servo motor angles using the Servo library.h library. Programming was carried out using Arduino IDE with C++ as the programming language. A flowchart illustrating the software integration process for the dual-axis solar tracking system is presented in Figure 3. The system was calibrated using sun position data from Gaisma.com for the geographical coordinates of the test site (AFIT, Kaduna), and real-time motor positions were matched with these values to ensure accurate physical alignment of the panel.

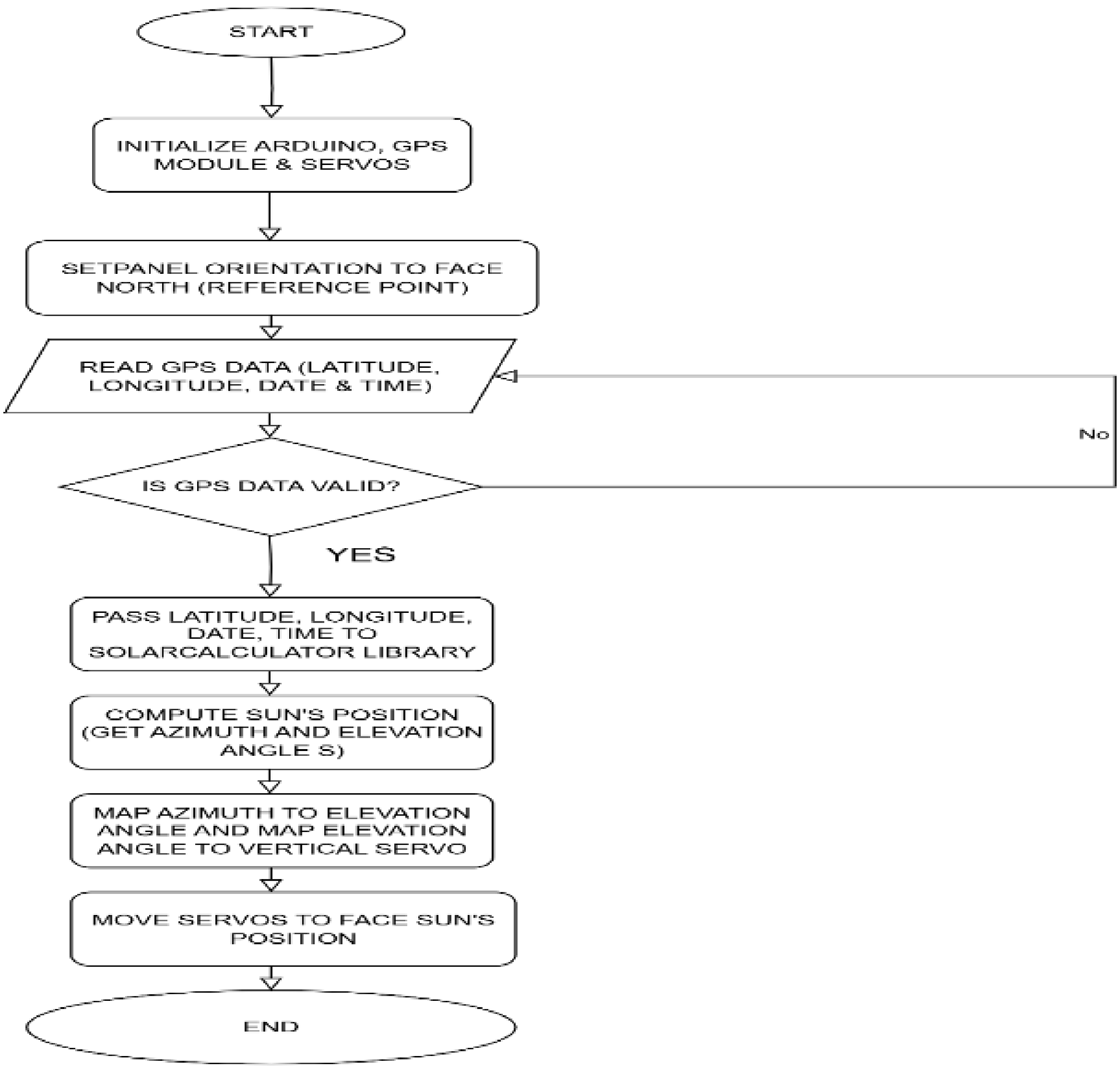

Figure 3. Flowchart of software implementation

2.6 System Testing and Validation

The testing and validation of the solar tracking system focused on evaluating its performance in terms of tracking accuracy and energy output. The system's operation was observed over several days, during which the sun's actual position was compared with the position calculated by the system. This comparison verified the accuracy of the dual-axis mechanism in maintaining alignment with the sun. Furthermore, the energy output of the tracking system was measured and compared with that of a fixed-panel and sensor-based setup under similar conditions. This validation process is crucial for determining whether the system meets the intended performance goals under real-world conditions. The energy output was measured at hourly intervals using a digital multimeter (for voltage and current), and power was calculated using the formula:

$$\text{Power (P)} = \text{Voltage (V)} \times \text{Time (t)} \tag{1}$$

The basis upon which the tests were carried out and validated is: Tracking Accuracy: This is defined as how closely the panel aligns with the actual sun position. Energy Output (Wh/day): This is the total power generated daily by each system.

3. RESULTS AND DISCUSSION

The results of the experiment are shown and analysed below.

3.1 Energy Output Results

Each system was tested over several days under similar sunlight and weather conditions, and the average daily energy output was calculated using the formulae:

$$\text{Output} = \text{STC Rating} \times \text{Peak hours of sunlight} \times 0.75 \tag{2}$$

Or

$$\text{Output} = \text{Panel Wattage} \times \text{Peak sunlight hours} \times \text{Efficiency} \tag{3}$$

Where; STC Rating = rated power under Standard Test Conditions, in watts. Panel Wattage = power rating of the solar panel. Panel efficiency = measure of the percentage of direct sunlight a PV panel receives that gets converted to electricity. 0.75 = standard value accounting for system losses or factors that decrease the solar panel’s electricity output (such as degradation rate, tilt angle, orientation, panel age, weather, and location). The efficiency of the panels (polycrystalline PV panels) is 14%, and the power rating is 1000 W/m, as indicated by the manufacturer. The percentage increase observed in the three systems was obtained using the formula:

$$\frac{\text{Increased Daily Output} - \text{Initial Daily Output}}{\textit{Initial Daily Output}} \times 100 \tag{4}$$

Where;

$$\text{Increased Daily Output} = \text{New wattage(Increased efficiency)} \times \text{Peak sunlight hours} \times \text{New (Increased)efficiency} \tag{5}$$

Note: An increase in wattage or efficiency can occur as a result of improved panel orientation, more efficient tracking systems or a new panel with higher wattage. Using the formulae given above, the percentile increase in energy output of each system was calculated, and Figure 4 shows the average daily energy output represented in a bar chart, while Table 1 shows the average energy and percentile increase each system produced per day. From the results, the astronomical system gave the highest energy output, followed by the sensor-based system. The astronomical tracking system produced 32% more energy compared to the fixed system, while the sensor-based system produced 24% when compared to the fixed system. This agrees with earlier research, like Priyam [5], who found that dual-axis tracking systems can increase energy output by over 30%.

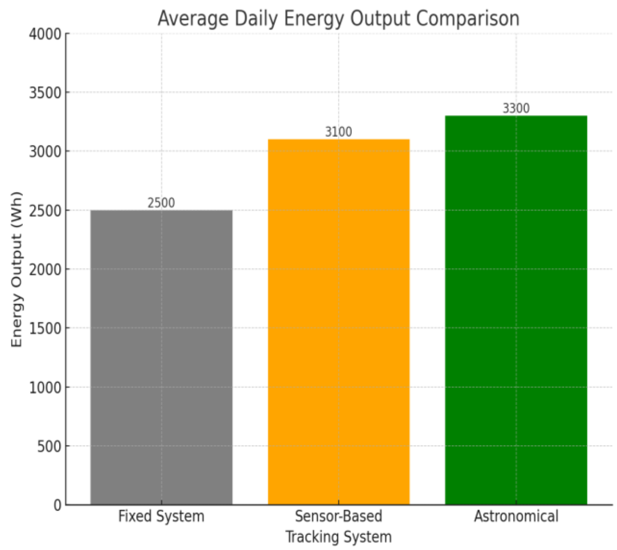

Figure 4. Energy Output Comparison (Bar Chart)

Table 1. Average Daily Energy Output

Tracking System	Average Daily Energy Output (Wh)	% Increase Overtime
Fixed System	2500	-
Sensor-Based	3100	24%
Astronomical	3300	32%

3.2 Tracking Accuracy Result

A reading obtained from the built astronomical tracking system for 18 June 2025, shows the azimuth and elevation angles of the day from sunrise to sunset for the Air Force Institute of Technology, Kaduna State, as presented in Table 2.

Table *2.* Azimuth and Elevation readings from the astronomical tracking system

Time	Azimuth (°)	Elevation (°)
6:10	65°	0°
7:00	67°	10°
8:00	68°	24°
9:00	68°	37°
10:00	65°	51°
11:00	56°	64°
12:00	29°	75°
13:00	332°	76°
14:00	304°	65°
15:00	294°	52°
16:00	290°	38°
17:00	291°	25°
18:00	292°	11°
18:54	294°	0°

When the values of the angles obtained from the tracking system were compared with real-time azimuth and elevation angles for the same location, obtained from a weather report website, the following values were obtained (Table 3).

Table 1. Azimuth and Elevation readings from Gaisma.com

Time	Azimuth (°)	Elevation (°)	Comment
06:10	65°	0°	Sunrise
07:00	67°	10°	
08:00	68°	24°	
09:00	68°	37°	
10:00	65°	51°	
11:00	56°	64°	
12:00	29°	75°	Approaching Noon
13:00	332°	75°	
14:00	304°	65°	
15:00	294°	52°	
16:00	291°	38°	
17:00	291°	25°	
18:00	292°	11°	
18:54	294°	0°	Sunset

The closeness of the values of both tables demonstrates the accuracy of the system when adjusting and orienting itself with the sun's position. The measurement of how accurately each system followed the sun throughout the day was observed and recorded (Figure 5). The accuracy level was determined by checking the angle difference between where the sun was and where the panel was pointing. That is, the angle of incidence. The astronomical tracking system had the lowest error all day, which means it stayed aligned with the sun the best. The sensor-based tracking performed well but had small errors, especially when the sun changed position quickly and there were cases of cloud coverage. As expected, the fixed system had the highest error because it does not move at all.

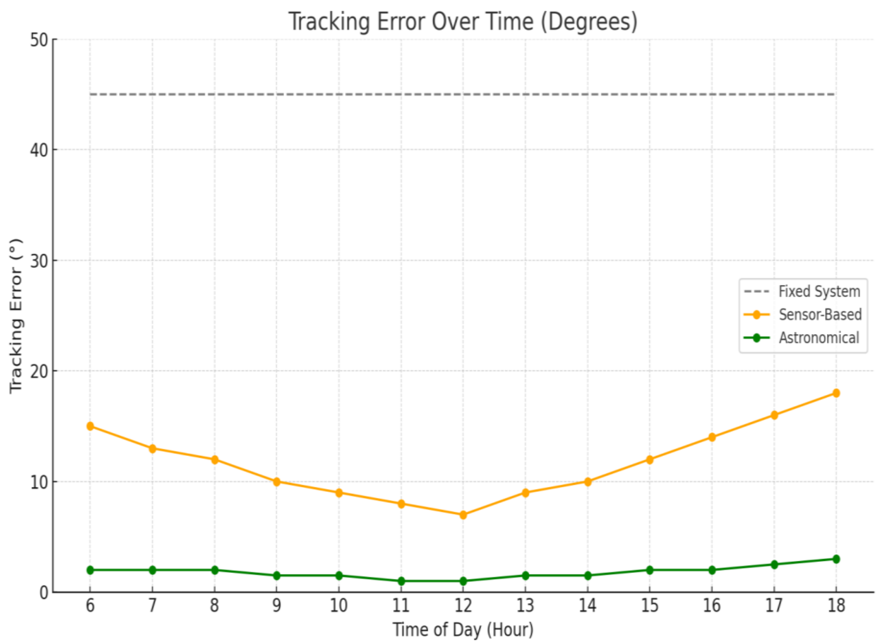

Figure 5. Average Tracking Error (Line Graph)

3.3 Energy Output Comparison

The results clearly show that energy output can be significantly improved once a tracking system is introduced to a solar panel. Both the astronomical and sensor-based tracking systems captured more sunlight than the fixed system because they were able to adjust their orientation to follow the sun's movement. Because the astronomical tracking system is sensor-independent and uses formulas to calculate the sun's exact position, moving accordingly, it performed better than the sensor-based tracking system, which depends on real-time light or sensors, thus yielding higher energy output. This happens because sensor systems can be affected by things like clouds and dust, which in turn reduce their performance. These results are supported by past studies. For example, Racharla and Rajan [1, 13] also showed that astronomical tracking systems improved solar panel performance by more than 30% in their tests.

3.4 Tracking Accuracy Comparison

Since the astronomical tracking system is centred on calculating the sun's position ahead of time, it produced the most energy because it can stay aligned with the sun's position throughout the day, making it the most accurate of the three systems. Sensor-based tracking systems are reactive; they respond to sunlight, which means that their response and performance can be slightly delayed. his also agrees with the research. Adsul et al [6] explained that astronomical trackers usually have better long-term accuracy because they are not affected by shadows or poor weather, like sensor-based systems can be.

4 CONCLUSIONS

This study aimed to design and develop a dual-axis solar tracking system using the astronomical method, and to compare its performance with that of fixed and sensor-based systems in terms of energy output and tracking accuracy. A solar tracking system was developed, and the astronomical algorithm was integrated to make the system more efficient. From start to finish, the goal was to enhance the way solar panels track the sun, ensuring they collect as much sunlight as possible throughout the day. After testing and comparing the systems, the astronomical tracker came out on top, producing about 32% more energy than the fixed system, and around 8% more than the sensor-based one. It also tracked the sun more accurately, staying closely aligned all day without needing sunlight sensors. Since the system relies on calculations of the sun's position rather than detecting light directly, it was not affected by issues like cloud cover or dirty sensors. Overall, the astronomical tracking system proved to be the most efficient. Even though it is a bit more complex and needs proper programming and setup, the performance makes it worth it, especially in applications where every bit of extra energy counts. A key contribution of this project is that it shows how the astronomical method, which is mostly used in theory and simulations, can be practically implemented using a microcontroller-based system. Many previous projects have focused on light sensors or simpler one-axis systems, but this work presents a working dual-axis setup that accurately tracks the sun using only calculated data.

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