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Design and Analysis of a Low-Cost Solar Panel Tracker

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Abstract: *Efficient operation of a photovoltaic system depends largely on how precisely maximizing photovoltaic efficiency depends primarily on keeping solar modules precisely oriented toward the sun's trajectory throughout the day. Traditional fixed-tilt systems cannot take advantage of continuous variation in solar angles and thus often result in efficiencies below the potential of their installed capacity. This deficiency is addressed in the present study, wherein a refined and cost-effective solar tracking system has been designed to enhance PV energy capture by enabling real-time positional adjustment of the PV module. The proposed tracking system integrates a microcontroller-based decision unit, a pair of precisely calibrated light- dependent sensors, and a dual-motor driving mechanism that, through mutual interaction, determines the direction of maximum irradiance and repositions the PV module accordingly. Unlike these traditional systems, reliant solely upon either preset angles or on astronomical calculations, dynamic light-intensity feedback is integrated into this design, allowing for more responsive and appropriate alignment under partially cloudy or rapidly changing environmental conditions. A series of controlled experimental trial for 7 days have been conducted, comparing the tracker's performance with that of a fixed panel of identical rating. The results showed substantial improvement in energy output, confirming that continuous solar alignment drastically enhances operational efficiency throughout the whole week (5th - 11th Dec. 2025). This study highlights how affordable, low-energy tracking systems can benefit localized green power grids, offering a scalable framework for evolving next-generation smart PV technology.*

Keywords: *Solar Panel, Arduino Uno, Light Sensor, Servo Motor.*

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Introduction:

Solar Power has proved to be one of the most promising areas of sustainable power infrastructure development due to the ever- rapid advancements that have been taking place in this field. However, even in spite of all these advancements in the field of Solar Power infrastructure development, the total efficiency of a Photovoltaic (PV) system is still fundamentally influenced by the angle of incidence of the surface of the PV panels. The inherent progression of the sun across the horizon results in constant shifts in both its azimuthal and elevational coordinates, (Ghassoul M. 2021), creating a dynamic target for fixed panels. This difference leads to a reduction in the total amount of irradiation of the panels, hence a reduction in their overall electricity generation.

To overcome this challenge, solar tracking technology has become an increasingly prominent focus of research. By dynamically adjusting the PV module direction to always point towards the sun in the most optimal fashion, solar tracking technology can significantly enhance daily electricity generation capacity without having to improve the underlying solar technology being used (Ramful *et al.*, 2022). Dual-axis mechanisms stand out among various tracking methods for their superior ability to capture maximum solar energy, as they account for both seasonal declination and daily sun paths. This contrasts with single-axis solar tracking technology in which only one axis of rotation is used to track solar movement instead of two as in dual-axis technology (Marcos *et al.* 2024).

Despite this, the widespread use of dual- axis solar track systems has various limitations. Typically, traditional commercial systems can be very costly, mechanically complicated, or require sophisticated sensors/algorithms for astronomical tracking (Alessandro *et. al.* 2022). These types of systems can be too expensive for miniature applications or for use within an academic setting when employing cheap solutions or alternatives related to this project. In this regard, the development of innovative mini-tracking systems that consider efficiencies concurrently offers an obvious market demand.

In a bid to meet this challenge, the present research introduces an innovative dual-axis Solar Panel tracking prototype specifically engineered for affordability and economic viability.

Methodology:

At the heart of this architecture lies the Arduino Uno, an integrated, budget-friendly microcontroller platform chosen for its compact design and hardware efficiency. It is very simple to program since it is open-source and the programming environment is very simple. The other components include the LDR sensors, the servo motors, and the solar panels shown in Fig.1. In this system, there is solar tracking that is performed by four LDR sensors. The sensors are linked to pins A0 to A3 of the Arduino-Uno microcontroller. The four LDR sensors determine the amount of light they receive and relay this data to the Arduino Uno microcontroller.

The Arduino Uno platform transforms incoming analog data from the sensors into digital format using its integrated Analog-to-Digital Converter (ADC) module. The digital signals are then used to control the servo motors using a PWM (Pulse Width Modulation) method. The sensor that detects the brightest light from the Sun indicates to the system the direction in which the solar panel should turn. Following this, the servo motor adjusts the solar panel's position to match the calculated direction of peak sunlight. The motor rotates in three major angles of 0°, 90°, and 180°. The LDR sensors are aligned in all directions, including down and up positions, in order to determine in which direction there is intense sunlight. When the Arduino Uno has processed all the light signals and produced digital signals, it then generates a signal to control the servo motors, which turns the solar panel to face the Sun (Kaur *et al.* 2016).

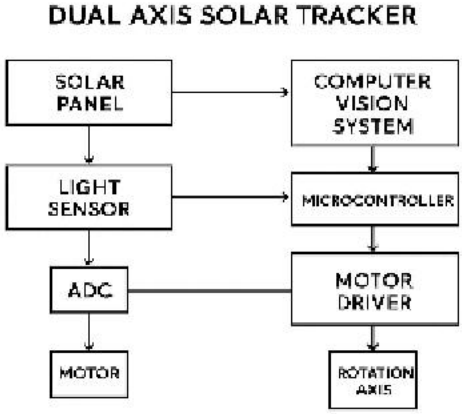


Fig. 1. Schematic representation of the hardware architecture for the proposed dual-axis solar tracker

Hardware Implementation: The dual-panel solar tracker includes a power supply, sensors, a microcontroller, motors, and a mounting frame. An Arduino Uno is used to read the light intensity from four LDR sensors set in a cross arrangement. The Arduino Uno, based on the difference in light falling on the sensors, drives two servo/DC gear motors through a motor driver to rotate the panels in both horizontal and vertical directions. A dual-panel mounting structure is built that can support both panels and move them with smooth motion. The system is calibrated and tested with appropriate Sun tracking and stable movement. The schematic arrangement of the hardware elements and their respective wiring is depicted in Fig. 2.

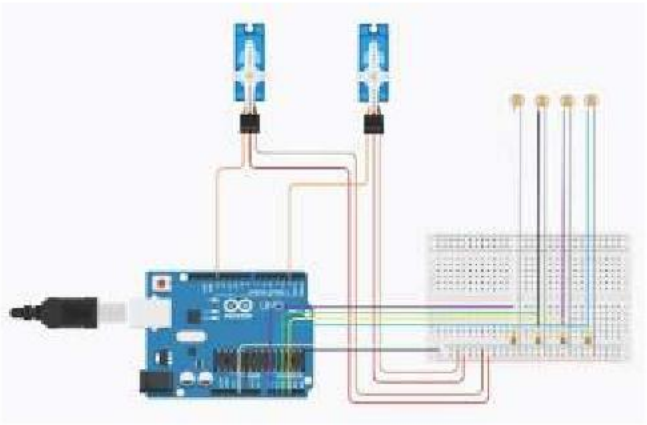


Fig. 2. Connection Diagram (Kaur T. *et al.*, 2016)

Software Implementation: In this project, we utilize a simple program created by writing code in the Arduino Uno to command the movement of the solar panels. This software commands the Arduino Uno to continuously check all four LDR sensors again and again. It is the role of the Arduino Uno to determine which LDR receives the maximum amount of sunlight.

Therefore, the software sends a signal to the motor and commands the motor to rotate the panel in the right direction. It is on the basis of this information that the position of the sun is determined. This software acts as if it were the brain of the whole system.

Circuit Design: The flowchart of Fig. 3 shows how the system keeps checking sunlight from all directions and moves the solar panels automatically to face the brightest direction.

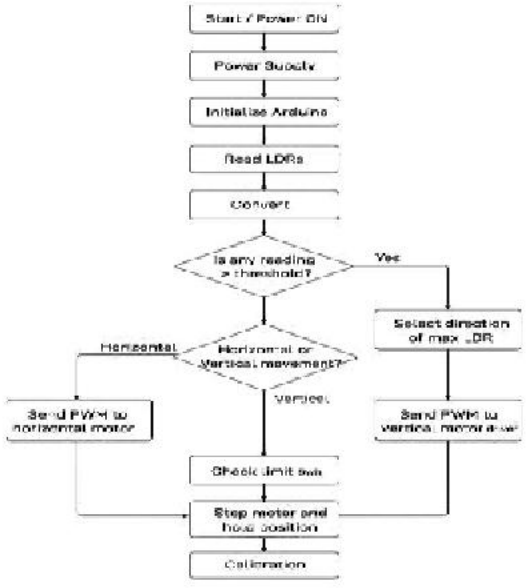


Fig. 3. Algorithm for dual-axis solar tracker

Explanation of flowchart:

1. **Start / Power On:** The system starts functioning when the power is turned ON.
2. **Power Supply:** Power for all the components, including the Arduino Uno board, LDR sensors, and motors, is also supplied.
3. **Initialize Arduino Uno:** The microcontroller, Arduino Uno, is where the programming starts and where the output pins are prepared.
4. **Read LDRs:** The Arduino reads the light intensity values from the LDR sensors that are mounted in various directions.
5. **Convert:** The values measured by the LDRs are then converted into digital values through the use of the Arduino Uno's Analog-to-Digital Converter.
6. **Check: Does any reading exceed the threshold value?**
   The process also checks if the sunlight intensity is sufficient for the movement of the solar panel.
   a. If NO, then the waiting loop continues.
   b. If YES, then it proceeds to the next step.
7. **Select direction of maximum LDR:** It is the role of the Arduino Uno to determine which LDR receives the maximum amount of sunlight. It is on the basis of this information that the position of the sun is determined.
8. **Decide Movement: Horizontal or Vertical?**
   From the identified or selected LDR, the system determines if the Panels needs:
   a. Horizontal movement (Left/Right)
   b. Vertical movement (up or down).
9. **Sending PWM Signal to Motor:**
   a. A PWM signal for horizontal movement is sent to the horizontal motor if horizontal movement is required.
   b. If there is a need to move vertically, a PWM signal will then be sent to the vertical motor driver.
10. **Check Limit Switch:** The system also checks the limit switch to make sure the panel will not travel past its safe mechanical positions.
11. **Stop Motor and Hold Position:** When the right position or the limit is attained, the motor stops to hold the panel fixed.

12. **Calibration:** The system self-calibrates to adjust the panel positioning and prepare for the upcoming sunlight interval.
13. **Loop Continues:** This repeats ceaselessly in order for the solar panel to track the Sun throughout the day.

Observation:

a. Even slight deviations in the angle can drastically impact how much energy is produced. We found that if the panel is off by just 5°-7° from the sun's direct path, there is a noticeable drop in the total power generated by the system.

b. **Cheap LDRs get confused easily:** The cheap LDR sensors suffered from problems of reflection, cloud cover, and sudden intensification of light.

c. **Servo motors consume additional power**: The servos continually made minute movements, wasting 4-6% of the consumed power.

d. **Lightweight frame bends in sunlight:** Cardboard/plastic frames that are slightly bent after hours of sunlight exposure.

e. **Big Power gain only in morning and evening hours:** The tracker 18-32% more power primarily during early and late hours, gain was minimal during mid-day.

f. **Dual axis is not much better than single-axis:** In the case of small panels, dual axis solutions could raise the power only by 3-5%, which isn't worth the cost.

g. **The system loses battery power during the night:** The Arduino Uno and the servos continued to drain the batteries even in the absence of sunlight.

h. **LDR shadow alignment is very important:** Small inaccuracies in LDR shading resulted in wrong motions of the tracker.

i. **Cloudy conditions result in too many movements:** The constantly changing nature of the clouds made the tracker overshoot and waste too much energy.

Prototype of Dual-axis solar panel tracker



Fig. 4. Dual-axis Solar Panel Tracker

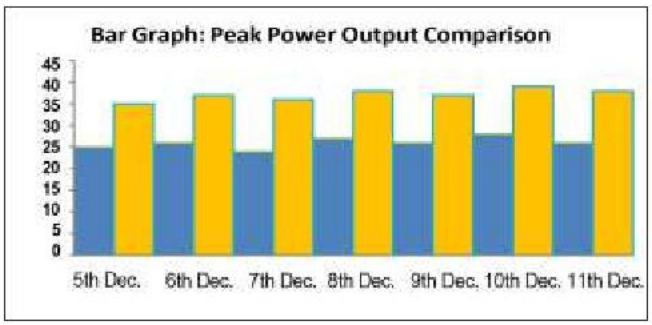
Fig. 4 illustrates the finished dual-axis solar tracker, showcasing the successful integration of both the physical hardware and the programmed software.

Weekly Comparison Table (5th December, 2025 to 11th December, 2025

Table 1. Comparison Table Peak Output Power of Fixed Solar Panel versus Dual-axis Solar Panel Tracker

Date	Fixed Panel Peak Output Power(W)	Dual-axis Panel Peak Output Power(W)	Difference (W)	% Improvement
5th Dec.	25	35	10	40
6th Dec.	26	37	11	42
7th Dec.	24	36	12	50
8th Dec.	27	38	11	41
9th Dec.	26	37	11	42
10th Dec.	28	39	11	39
11th Dec.	26	38	12	46

Weekly Comparison Graph (5th December, 2025 to 11th December, 2025)



Graph 1. Clearly shows that Dual-axis Solar Panel Tracker produced more power than Fixed Solar Panel

Result:

Based on the data collected from December 5th to 11th, 2025, it is clear that the dual-axis tracker consistently outperformed the stationary panel. Our findings show the tracker maintained a high output range of 35W to 39W, whereas the fixed setup lagged behind with a lower range of only 24W to 28W.

The two-axis tracker thus provided around 40-50% more power each and every day. Greatest difference was observed on 7th December, wherein the two-axis tracking system produced 12 W higher power in comparison with the fixed panel.

Analysis:

The two-axis tracker performs better because it is able to track the sun.

It implies that the sun's rays fall on the solar panel at the optimal angle throughout the day.

As a result, the panel receives more sunlight for a period of time, leading to an increased output of power. The graphs also show that the difference between the two systems was consistent and clear. In addition, regardless of the day, the dual-axis line was always above the fixed panel line. This ensures that the tracking system is not only efficient but also accurate.

The fixed panel, on the other hand, will accept full sun only at noon. In the morning and evening, the angle is not compatible with the sun, so the generated power will not be as much.

What is more evident from the graph is that when the sun is bright and sunny, the dual axis system works even better than the fixed panel system that loses efficiency in the afternoon.

Conclusion:

This research focused on developing an affordable dual-axis solar tracking system to evaluate how much more efficient it is compared to standard, non-moving solar installations.

Experimental observations over one week showed that the dual-axis tracking system produces about 40% to 50% more electrical power than the fixed solar panel under similar conditions. The data indicate that the power output of the fixed panel was much lower in the morning and evening because of the changing angle of sunlight. In contrast, the dual-axis tracker adjusted its angle both horizontally and vertically, staying nearly perpendicular to the sun's rays throughout the day. As a result, the tracker showed consistently higher voltage and current readings, especially during times when the sun was at a low angle. The average daily power output of the tracking system remained higher over all seven days of observation, confirming that this improvement was consistent, not just temporary.

This supports the principle of solar tracking and demonstrates that the most solar energy is collected when the panel is perpendicular to the sunlight.

In conclusion, the goal of boosting solar energy efficiency with a low-cost dual-axis tracking system has been successfully met. This system is practical, effective, and suitable for small-scale, budget-friendly solar setups that need greater output without increasing the size of the panels.

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