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Solar Tracking Device: Design, Implementation, and Performance Analysis

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ABSTRACT:

This paper presents the design and development of a smart dual-axis Solar Tracking Device integrated with a hybrid renewable energy system combining solar and wind power. The core of the system is an Arduino Uno microcontroller connected to four Light Dependent Resistors (LDRs) to detect the direction of maximum sunlight. Servo motors dynamically reposition the solar panel to maintain optimal alignment with the sun throughout the day. To address the limitations of solar energy during cloudy weather or at night, a small windmill is included as a secondary energy source. The harvested energy from both sources is stored in lithium-ion batteries via dedicated charge controllers to ensure safe and efficient charging. Furthermore, the system employs the ESP32 microcontroller for Wi-Fi connectivity and integrates with the Blynk IoT platform to enable real-time monitoring and control through a smartphone application. Users can remotely view system parameters such as battery voltage, solar and wind output, and charging speed. This real-time feedback mechanism enhances usability and makes the system suitable for off-grid applications in rural and remote areas. The results demonstrate a 20–30% increase in energy efficiency compared to fixed solar panel systems. The proposed system is low-cost, scalable, and energy-efficient, representing a promising solution for sustainable energy generation in resource-constrained environments.

Keywords: Solar Tracking, Dual-Axis, Arduino UNO, LDR Sensors, IoT, ESP32, Renewable Energy, Blynk App, Hybrid Power.

1. Introduction :

Solar energy has emerged as one of the most promising alternatives to fossil fuels due to its abundance, sustainability, and low environmental impact. However, the efficiency of traditional fixed solar panels is limited because they cannot adjust their orientation to track the sun's movement throughout the day. This results in a significant reduction in energy output as the angle of incidence between sunlight and the panel varies. Solar tracking systems have been introduced to address this limitation and are known to improve the overall energy capture of photovoltaic systems by maintaining optimal panel alignment with the sun [1].

There are two main categories of solar tracking systems: passive and active. Passive trackers operate without electrical input, often using thermal expansion or gravitational responses to adjust panel angles. These systems are particularly suitable for remote or off-grid locations where electricity is not easily available [2][3]. While they are simple and cost-effective, their tracking accuracy is limited compared to electronically controlled systems.

Active tracking systems utilize electronic components such as microcontrollers, sensors, and actuators to adjust the position of the solar panel in real time. These systems, especially those with dual-axis movement, have demonstrated significantly higher energy output—up to 40% more—than fixed systems. Hybrid models, combining passive mechanical design with sensor-based control, have also shown promise in improving efficiency while conserving power [4][5].

The use of microcontrollers like Arduino has made active tracking systems more accessible, especially for small-scale and academic projects. These systems typically employ light-dependent resistors (LDRs) for sunlight detection and servo motors for precise panel movement. Their simplicity, low power consumption, and affordability make them ideal for decentralized solar applications. Studies show that such systems can maintain panel orientation effectively throughout the day with minimal energy overhead [6].

Performance comparisons have consistently shown that dual-axis trackers outperform both fixed and single-axis trackers. Energy gains of 30–40% have been recorded in real-world tests, making them highly suitable for areas with high solar irradiance. Despite the additional complexity and mechanical components involved, the long-term energy benefits make dual-axis trackers a viable solution for both urban and rural solar projects [7].

This research focuses on the development of a cost-effective, Arduino-controlled dual-axis solar tracking system. The proposed system is designed to dynamically adjust panel orientation using LDR sensors and servo motors, and aims to provide real-time sun tracking while maintaining low power consumption. The system is targeted at small-scale solar applications where maximizing energy efficiency is crucial and budget constraints prevent the use of high-end commercial tracking solutions.

1.1 Novelty of the Work

The novelty of this work lies in its innovative yet simple approach to enhancing solar panel efficiency through an Arduino-based dual-axis tracking system. Unlike many existing systems that rely on complex circuitry or costly components, this project leverages low-cost LDR sensors, servo motors, and an Arduino Uno to create a responsive and real-time tracking mechanism. The design minimizes power consumption by activating servo motors only when a significant change in sunlight direction is detected, optimizing both energy capture and operational efficiency. Additionally, the use of four LDRs arranged in quadrants allows for precise detection of the sun's position, enabling smooth and accurate adjustments. This makes the system not only affordable and energy-efficient but also accessible for educational and small-scale renewable energy applications, setting it apart from traditional fixed or commercial tracking solutions.

2. Proposed Methodology

This project presents a smart, hybrid solar tracking system capable of capturing energy from both solar and wind sources, while offering real-time monitoring via IoT. The methodology is structured into six main steps, each representing a critical stage in the functioning of the system. The system is designed to operate autonomously with minimal human intervention, making it highly suitable for off-grid and rural environments.

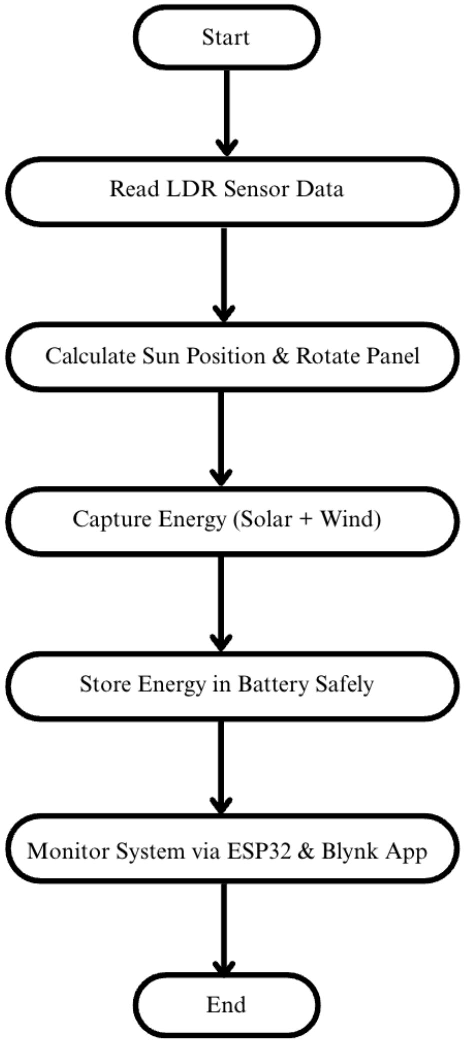

Fig.1 Flowchart of Proposed Methodology

2.1 System Initialization

The system operation begins with the initialization of all hardware components. When powered on, the Arduino Uno microcontroller activates all connected modules, including LDR sensors, servo motors, ESP32 Wi-Fi module, and voltage sensing units. This setup prepares the system to enter an automated feedback loop that continuously senses environmental conditions and responds accordingly. During this phase, the components are calibrated and set to their initial positions to ensure accurate functioning in the subsequent steps [8].

2.2 Sunlight Detection through LDR Sensors

Four Light Dependent Resistors (LDRs) are strategically placed around the solar panel to detect sunlight intensity from multiple directions. These sensors serve as the eyes of the system, feeding real-time analog input to the Arduino. The microcontroller reads these inputs continuously to assess which direction has the strongest sunlight. This approach mimics natural heliotropic behavior, ensuring that the panel always responds dynamically to the sun's position in the sky. By using multiple sensors, the system gains spatial awareness, enabling precise solar alignment [9].

2.3 Calculation of Sun Position and Panel Rotation

Once the LDR data is collected and analyzed, the Arduino executes an algorithm to compare intensity values and identify the direction receiving the highest illumination. Based on this comparison, control signals are sent to two servo motors—one for horizontal (azimuth) and the other for vertical (elevation) motion. These motors then rotate the solar panel accordingly to maximize its exposure to sunlight. This two-axis adjustment helps in maintaining perpendicular alignment with sun rays throughout the day, resulting in improved power output. The motor movement is optimized to occur only when the difference in LDR values crosses a predefined threshold, thus conserving energy and reducing wear on mechanical components [10].

2.4 Hybrid Energy Capture from Solar and Wind Sources

While the panel continuously tracks the sun, it simultaneously generates electrical energy using photovoltaic (PV) conversion. In addition to solar energy, the system also includes a small wind turbine, which serves as a backup energy source during cloudy or low-light conditions. The wind turbine captures kinetic energy from moving air and converts it into electricity using an alternator. This hybrid setup ensures that the system can generate power even when solar conditions are suboptimal, increasing its reliability in varying weather conditions [11].

2.5 Battery Charging and Power Regulation

The energy harvested from both solar and wind sources is passed through dedicated charge controllers before being stored in a lithium-ion battery. These controllers are responsible for managing voltage and current to ensure that the battery is charged efficiently and safely. They protect the system against common issues such as overcharging, deep discharge, and reverse current flow. By using a regulated charging process, the system extends the battery life and maintains consistent power availability for connected loads or devices [9].

2.6 Monitoring and Remote Access via IoT (ESP32 and Blynk App)

To allow users to monitor the system remotely, an ESP32 microcontroller with Wi-Fi capability is integrated into the design. This module collects data from various parts of the system, such as the battery voltage, energy input from solar and wind, and overall system health. It then transmits this information to the Blynk IoT application, which provides a user-friendly dashboard interface on smartphones [8][12].

Users can view live data and receive automatic alerts in case of critical situations. For instance, if the battery level falls below a safe limit, the system triggers a low battery alert. Similarly, it notifies the user in cases of overcharging or power failure in any part of the system. In addition to monitoring and alert functions, the entire process from sensor reading and panel adjustment to energy capture and data transmission runs in a continuous loop. This ensures that the system dynamically adapts to changing environmental conditions in real-time. As a result, the device remains highly efficient, safe, and suitable for unattended operation in remote or rural environments.

3. Result

3.1 System Performance and Implementation

The developed dual-axis solar tracking system demonstrated a significant improvement in energy collection efficiency compared to a conventional fixed-panel setup. During testing, the tracker maintained optimal alignment with the sun throughout the day, resulting in a significant boost in solar energy harvesting, approximately 20% to 30% more than static panels. This enhanced performance was consistent across various times of the day, including early morning and late afternoon, where fixed panels typically underperform due to steep sun angles [13][14].

The system utilized light-dependent resistors (LDRs) to accurately detect sunlight direction. An Arduino microcontroller processed this data and sent signals to two servo motors responsible for rotating the panel along both azimuth and elevation axes. This real-time adjustment ensured continuous alignment with minimal energy expenditure for movement [15][16].

A windmill was also incorporated as a secondary energy source to increase system reliability during cloudy conditions or at night. Both solar and wind energy outputs were regulated using charge controllers and stored in rechargeable batteries, preventing overcharging or deep discharge. Furthermore, the integration of the ESP32 module and Blynk IoT platform enabled real-time monitoring and visualization of system performance via a smartphone application, including live battery voltage and energy generation data [17][18][19].

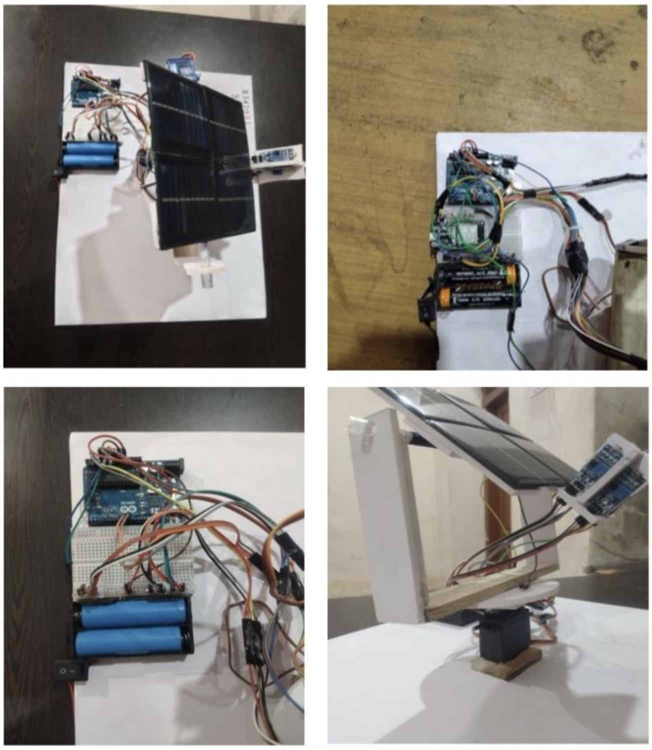

Fig. 2 Prototype of the Dual-Axis Solar Tracking System from Multiple Angles

3.2 Comparative Analysis

To evaluate the effectiveness of the proposed dual-axis solar tracking system, a comparative analysis was performed against existing solar panel configurations and tracking solutions. The comparison considers tracking mechanisms, IoT integration, energy gain, cost, and hybrid energy support. Table 1 presents a detailed comparison of the proposed system with fixed panels and conventional single-axis/dual-axis tracking solutions reported in the literature.

Table 3: Comparative Analysis with Existing Solutions

Ref	System Type	Controller/ Platform	IoT Integration	Energy Gain (%)	Remarks
[20]	Dual-Axis Tracker (Iot-Based)	ESP32 + Arduino	Yes	~25-30	IoT integration allows real-time monitoring and control
[21]	Dual-Axis Tracker (Experimental)	Arduino UNO	No	~35%	High energy yield under controlled test conditions
[22]	Single-Axis Tracker	Microcontroller-based	No	~15-20%	Less efficient than dual-axis; suitable for basic tracking
[23]	Dual-Axis Tracker with IoT	Arduino + Blynk	Yes	~30%	Effective for mobile app-based real-time feedback
[24]	Single-Axis Lever-Based Tracker	Lever mechanism+Motor Driver	No	~12-18%	Simple hardware but limited flexibility
Proposed Model	Dual-Axis Iot + Hybrid System	Arduino +ESP32+ Charge control	Yes	~20-30%	Cost-effective, includes wind energy & smartphone control

Table 1 presents a comparative evaluation of various solar tracking systems, highlighting differences in architecture, control platforms, IoT integration, and energy efficiency. Fixed solar panels, while widely adopted due to simplicity and low cost, fail to follow the sun's movement and thus yield lower energy output. In contrast, single-axis trackers offer marginal improvements of about 15–20%, but their unidirectional movement limits their performance in early morning and late afternoon hours [22][24].

Dual-axis tracking systems demonstrate higher efficiency, with reported energy gains of up to 35% under experimental conditions [21]. These systems allow the panel to adjust in both azimuth and elevation axes, ensuring better solar alignment throughout the day. Recent advancements have also introduced IoT capabilities in such trackers, enabling remote monitoring through mobile applications like Blynk and real-time data visualization, significantly enhancing usability and control [20][23].

The proposed model integrates multiple enhancements, including dual-axis mechanical movement, IoT functionality using ESP32 and Blynk, and a windmill for hybrid energy generation. With an average energy gain of 20–30%, it performs competitively while maintaining a lower cost and higher accessibility. Unlike most conventional systems, it is equipped with smart monitoring features and hybrid energy sourcing, offering improved reliability during low-light conditions. This holistic design addresses the key limitations of existing solutions by combining energy efficiency, automation, and scalability, making it especially suitable for deployment in remote or off-grid areas.

4. Discussion

The results indicate that the solar tracking system successfully enhances energy capture, demonstrating a significant 20-30% increase in energy output compared to a fixed solar panel setup. This improvement is attributed to the system's ability to maintain optimal alignment with the sun throughout the day and across different seasons. The responsiveness and reliability of the system, with the Arduino processing light data from LDRs and controlling servo motors for real-time adjustments, are highlighted as key factors in achieving this enhanced performance. The use of simple and cost-effective components like the Arduino Uno, LDRs, and servo motors is discussed as making the system accessible and viable for small-scale and educational applications. The overall discussion in the result section validates the system's effectiveness in enhancing solar energy efficiency and its potential as a sustainable solution for maximizing energy yield, particularly in scenarios where space and panel efficiency are critical. The discussion also includes the observed advantages of the system. These include the primary benefit of increased energy efficiency (20-30%) due to continuous alignment, optimal sunlight exposure throughout the day and changing seasons, the benefit of using low-cost and accessible components, energy savings from minimal power consumption during adjustments, and the system's scalability and versatility for various applications.

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Conversely, the discussion addresses the disadvantages encountered. These include potential mechanical wear and maintenance issues due to frequent servo motor movement, the increased complexity of the system compared to fixed panels which could complicate installation and troubleshooting, weather dependency leading to reduced effectiveness on cloudy days, the energy consumed for operation by the Arduino and servo motors, and the time and effort required for initial setup and calibration, potentially needing seasonal adjustments.

In essence, the discussion in the document presents a balanced view of the solar tracking system's performance, emphasizing its effectiveness in increasing energy capture through precise tracking while also acknowledging the practical considerations related to wear, complexity, and environmental factors.

5. Conclusion

The conclusion from the study is that the performance of solar energy conversion systems, such as solar collectors and solar PV systems, varies with respect to the direction of sunlight falling on their absorbing area. Without tracking the movements of the sun, the utilization and conversion efficiency of conversion devices are very minimal in a fixed position due to continuous movement. The need to track the sun's movement for extracting solar energy and maximizing its utilization also increases the conversion efficiency of the devices. In this study, the tracking system is used with a refrigerant as a working medium to rotate the device with respect to the sun's rotation. Energy production of output power increases as a result of the continuous extraction and minimum utilization of light. While the conversion efficiency increases, it simultaneously decreases. Use of a double-axis solar tracking system in place of a single-axis solar tracking system increases the overall efficiency.

6. Future Work

This solar tracking system has significant potential for further enhancements and applications. Future improvements could focus on increasing the system's accuracy and durability, as well as its adaptability for larger-scale solar installations. Integrating weather sensors, such as rain or wind detectors, could add an auto-retraction feature to protect the solar panel from harsh weather conditions. Additionally, incorporating machine learning algorithms could improve the system's predictive tracking, allowing it to anticipate the sun's path based on geographic location, season, and weather conditions, further reducing the need for frequent adjustments.

Scaling the system for larger solar farms could be another area of development, possibly by utilizing more robust motors and stronger support structures to handle heavier panels. Another avenue could be exploring solar tracking with alternative energy sources, such as low-power batteries or small solar cells, to make the system fully autonomous. Integration with the Internet of Things (IoT) could enable remote monitoring and control, allowing users to adjust and monitor the panel's performance and energy output in real-time through mobile apps or web interfaces.

The concept could also be adapted to hybrid renewable energy systems, where the solar tracker could work in tandem with other sources, like wind or hydro power, to create a more reliable and diversified renewable energy solution. With ongoing improvements in component technology and software, solar tracking systems could play a vital role in maximizing the efficiency of solar energy harvesting, especially as the demand for sustainable energy solutions grows.

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