

IOT-BASED DUAL-AXIS SOLAR TRACKING SYSTEM WITH ENVIRONMENTAL MONITORING

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Abstract

The increasing demand for sustainable energy solutions has accelerated the adoption of solar photovoltaic systems. However, conventional fixed solar panels suffer from reduced efficiency due to their inability to maintain optimal alignment with the sun. This research presents an IoT-based dual-axis solar tracking system designed to maximize energy harvesting by continuously adjusting the panel orientation based on sunlight intensity. The system utilizes LDR sensors for detecting solar position, an ESP32 microcontroller for processing, and servo motors for actuation. Additionally, environmental parameters such as temperature and humidity are monitored using a DHT11 sensor and transmitted to a cloud platform for real-time visualization. Experimental results demonstrate a significant improvement in energy output compared to fixed-panel systems. The proposed solution is cost-effective, scalable, and suitable for residential and industrial applications.

Key Words: - Solar Tracking System, IoT, ESP32, Dual-Axis Tracking, Renewable Energy, LDR Sensor, DHT11, Energy Efficiency, Blynk, Smart Monitoring

1. INTRODUCTION

The increasing demand for energy and the depletion of conventional fossil fuels have made renewable energy sources more important than ever. Among these, solar energy is one of the most abundant, clean, and sustainable resources. However, the efficiency of solar photovoltaic (PV) systems is highly dependent on the amount of sunlight they receive. In conventional systems, solar panels are fixed at a particular angle, which limits their ability to capture maximum sunlight throughout the day.

As the position of the sun changes continuously from sunrise to sunset, fixed solar panels are only optimally aligned for a short period, leading to energy loss. To overcome this issue, solar tracking systems are used to adjust the orientation of the panel according to the sun's movement. Dual-axis solar trackers are more efficient than single-axis systems as they allow movement in both horizontal and vertical directions, ensuring better alignment with sunlight and improved energy generation.

With the advancement of technology, the integration of Internet of Things (IoT) in solar systems has made monitoring and control more efficient. IoT enables real-time data collection, remote access, and performance analysis through cloud platforms. This helps users track system performance and make informed decisions.

In this project, an IoT-based dual-axis solar tracking system is developed using an ESP32 microcontroller. The system uses LDR sensors to detect sunlight direction and servo motors to adjust the panel position accordingly. Additionally, a DHT11 sensor is used to monitor temperature and humidity. The data is transmitted to a cloud platform for real-time monitoring.

The main objective of this system is to improve solar energy efficiency, provide real-time monitoring, and develop a cost-effective and scalable solution for practical applications.

2. LITERATURE REVIEW

Several researchers have developed solar tracking systems using different technologies such as Arduino, PLC, and GPS-based tracking. Sensor-based systems using LDRs are widely used due to their simplicity and low cost. IoT

integration using platforms like Blynk and ThingSpeak has also gained popularity.

Table 1: Summary of Related Literature on Solar Tracking Systems

Sr. No.	Author(s) & Year	Paper / Book Title
1	Buswig et al. (2026)	Dual-Axis Solar Tracking System with IoT Monitoring using Arduino MEGA and Cayenne Platform
2	Achbi (2024)	Industrial Dual-Axis Solar Tracking System with SCADA-Based Web Monitoring
3	Vinodhkumar & John (2020)	Astronomical Dual-Axis Solar Tracking System using GPS and RTC Modules
4	Al-Sheikh (2025)	Validation of ESP32 and Blynk Platform for IoT-Based Solar Tracking Applications
5	Maharani (2025)	IoT-Based Dual-Axis Solar Tracking with DHT11 using ESP32 and Blynk
6	Atienza et al. (2024)	Single-Axis IoT Solar Tracking System using Arduino Uno and Blynk
7	Katyal et al. (2022)	Machine Learning-Enhanced Dual-Axis Solar Tracking with ThingSpeak IoT Integration
8	Rahaim et al. (2023)	Educational IoT Dual-Axis Solar Tracker using Arduino and Blynk
9	Esposito & Antonini (2022)	Photovoltaic Systems with Solar Tracking: A Review of Technologies and Performance

10	Seme et al. (2020)	Analysis of Dual-Axis Solar Tracking Systems: A Comprehensive Review
11	Nadia et al. (2018)	Advances in Solar Photovoltaic Tracking Systems: A Review

A. Drawbacks of Existing Systems

- Lack of environmental monitoring (temperature, humidity)
- High cost and complexity in PLC-based systems
- Limited efficiency in single-axis trackers
- Absence of real-time monitoring in traditional systems
- Poor scalability and data analysis capabilities

3. PROPOSED SYSTEM

A. Problem Statement

Fixed solar panels do not efficiently utilize available sunlight due to their static position. Existing tracking systems lack IoT integration and environmental monitoring, reducing their effectiveness.

B. System Architecture

The proposed IoT-based dual-axis solar tracking system is designed using a layered architecture that integrates sensing, processing, actuation, and cloud communication components.

At the **input layer**, multiple sensors are used to collect environmental data. Four Light Dependent Resistors (LDRs) are placed in different directions to detect sunlight intensity and determine the position of the sun. A DHT11 sensor is also included to measure temperature and humidity, which affect solar panel performance.

The **processing layer** consists of an ESP32 microcontroller, which acts as the central control unit. It continuously reads data from the sensors, compares the light intensity values, and

calculates the required movement for optimal panel alignment. The ESP32 also handles Wi-Fi communication for IoT functionality.

The **actuation layer** includes two servo motors that control the movement of the solar panel along two axes. One motor adjusts the horizontal direction (east-west), while the other controls the vertical angle (north-south). Based on the processed data, the motors rotate the panel to face the direction of maximum sunlight.

The **communication layer** enables data transmission to a cloud platform using Wi-Fi. The collected data, including sensor readings and panel position, is sent to an IoT platform such as Blynk. This allows users to monitor system performance in real time through a mobile or web interface.

Overall, this architecture ensures efficient energy harvesting, real-time monitoring, and smooth system operation while maintaining a low-cost and scalable design.

C. Two-Step Agentic Workflow

The proposed system operates using a two-step agentic workflow that enables automatic decision-making and efficient solar tracking. This approach ensures continuous adjustment of the panel based on real-time environmental conditions.

The first step is the **Perception Phase**. In this phase, the system collects data from sensors. The LDR sensors detect sunlight intensity from different directions, while the DHT11 sensor measures temperature and humidity. The ESP32 processes this data by comparing the LDR values to determine the direction of maximum sunlight. This step helps the system understand its environment and identify the optimal panel position.

The second step is the **Action Phase**. Based on the analysis, the ESP32 sends control signals to the servo motors. The motors adjust the panel position along horizontal and vertical axes to align with the sun. At the same time, the system transmits sensor data and panel status to the cloud platform for real-time monitoring.

This continuous cycle of sensing and action allows the system to operate automatically, improving energy efficiency and reducing manual effort.

D. System Flowchart

The system flowchart represents the step-by-step working process of the IoT-based dual-axis solar tracking system. It describes how the system operates continuously to track sunlight and update data.

The process begins with **system initialization**, where the ESP32 microcontroller, sensors, and Wi-Fi module are set up. Once initialized, the system enters a continuous loop.

In the next step, the system reads data from sensors. The LDR sensors measure sunlight intensity from different directions, and the DHT11 sensor collects temperature and humidity data.

After data collection, the ESP32 processes the sensor values by comparing the LDR readings. It determines whether there is a difference in light intensity between different directions.

If a significant difference is detected, the system calculates the required movement direction. Based on this, control signals are sent to the servo motors.

The servo motors then adjust the position of the solar panel along horizontal and vertical axes to align it with maximum sunlight.

Simultaneously, the system sends data to the cloud platform through Wi-Fi for real-time monitoring.

If no significant change in sunlight is detected, the system maintains the current position.

Finally, the system repeats the process continuously, ensuring accurate tracking throughout the day.

E. Objectives

The main objective of this project is to design and develop an efficient IoT-based dual-axis solar tracking system that maximizes solar energy harvesting. The system aims to improve the performance of conventional solar panels by ensuring continuous alignment with the sun.

The specific objectives of the project are as follows:

- To design a dual-axis solar tracking mechanism that adjusts the panel position in both horizontal and vertical directions.
- To implement LDR sensors for accurate detection of sunlight intensity and direction.
- To develop a control system using the ESP32 microcontroller for real-time decision-making.
- To integrate servo motors for smooth and precise movement of the solar panel.
- To monitor environmental parameters such as temperature and humidity using the DHT11 sensor.
- To establish IoT-based communication for real-time monitoring and data visualization.
- To improve overall energy efficiency compared to fixed solar panel systems.
- To design a low-cost, scalable, and user-friendly system suitable for practical applications.

4. METHODOLOGY

The methodology of the proposed system focuses on the systematic design, development, and implementation of the IoT-based dual-axis solar tracking system. It follows a structured approach to ensure proper integration of hardware and software components.

Initially, the requirements analysis is carried out to identify the necessary components such as sensors, microcontroller, servo motors, and IoT platform. Based on these requirements, suitable hardware and software tools are selected for the system.

In the next stage, the hardware design and setup is performed. The LDR sensors are arranged in such a way that they can detect sunlight intensity from different directions. The DHT11 sensor is connected to measure temperature and humidity. All components are interfaced with the ESP32 microcontroller, which acts as the central processing unit.

After hardware setup, the software development phase begins. The control algorithm is implemented using the Arduino IDE. The ESP32 reads sensor data, compares light intensity values, and determines the required movement of the solar panel. Servo motors are controlled using PWM signals to achieve accurate positioning.

The system is then integrated with an IoT platform, where sensor data is transmitted via Wi-Fi. A dashboard is created to display real-time information such as temperature, humidity, and panel orientation.

Finally, the system undergoes testing and evaluation under different environmental conditions. The performance is analyzed by comparing energy output with a fixed solar panel system.

This step-by-step methodology ensures efficient system operation, accurate tracking, and reliable data monitoring.

5. IMPLEMENTATION

The implementation of the proposed IoT-based dual-axis solar tracking system involves the integration of hardware components, embedded programming, and cloud-based monitoring. The system is designed to ensure efficient operation, accurate tracking, and real-time data communication.

A. Frontend

The frontend of the system is developed using an IoT dashboard platform such as Blynk. It provides a user-friendly interface to display real-time data including temperature, humidity, and panel position. Graphs and gauges are used to visualize system performance, allowing users to monitor the system remotely through mobile or web applications.

B. Backend

The backend is implemented using the ESP32 microcontroller programmed through the

Arduino IDE. It handles sensor data processing, decision-making, and control operations. The ESP32 continuously reads values from LDR sensors, compares light intensity, and determines the required movement of the panel. It also manages communication with the cloud platform using Wi-Fi.

C. Information

The system collects and processes multiple types of data such as sunlight intensity, temperature, humidity, and panel orientation. This information is used for both real-time decision-making and monitoring. The processed data helps in optimizing panel alignment and analyzing system performance.

D. Communication

Communication in the system is achieved through the ESP32's built-in Wi-Fi module. Sensor data is transmitted to the IoT cloud platform using APIs. This enables real-time monitoring and remote access. The system ensures continuous data flow between hardware and cloud services.

E. Security Mechanisms

Basic security mechanisms are implemented to ensure safe data transmission. These include secure Wi-Fi connectivity, authentication with the IoT platform, and validation of sensor data. These measures help in protecting the system from unauthorized access and data loss.

6. RESULTS AND DISCUSSION

A. Experimental Setup

The experimental setup of the proposed system is designed to test the performance of the IoT-based dual-axis solar tracking system under real-time conditions. The system includes an ESP32 microcontroller, four LDR sensors, a DHT11 sensor, and two servo motors mounted on a solar panel frame.

The LDR sensors are arranged in four directions to detect sunlight intensity, while the DHT11 sensor measures temperature and humidity. The servo motors control the movement of the panel along horizontal and vertical axes. The ESP32 processes sensor data and connects to a cloud platform via Wi-Fi for real-time monitoring.

The system is tested under different weather conditions, and observations are recorded at regular intervals. The results are compared with a fixed solar panel system to evaluate performance improvement.

B. Sample Output Results

Table 1: Daily Energy Output Comparison of Fixed and Dual-Axis Solar Tracking System

Sr. No.	Weather Condition	Fixed Panel Output (mWh)	Tracked Panel Output (mWh)	Improvement (%)
1	Clear Sky	245	352	43.7%
2	Clear Sky	258	370	43.4%
3	Partial Cloud	189	267	41.3%
4	Partial Cloud	201	283	40.8%
5	Overcast	112	134	19.6%
6	Clear Sky	251	361	43.8%
7	Clear Sky + Haze	223	315	41.3%

C. Average Performance

Table 2: Average Performance Analysis of Solar Tracking System

Parameter	Value
Average Fixed Output	211.3 mWh
Average Tracked Output	297.4 mWh
Average Improvement	~43%

D. Discussion

The experimental results show that the proposed IoT-based dual-axis solar tracking system significantly improves energy efficiency compared to a fixed solar panel. The system was able to maintain better alignment with the sun throughout the day, resulting in higher energy output under most weather conditions.

From the observed data, the average improvement in energy generation was around 40–45% during clear sky conditions. Even under partially cloudy conditions, the system performed efficiently, although the improvement was slightly reduced. In overcast conditions, the performance gain was lower due to diffuse sunlight, which affects the accuracy of LDR-based tracking.

The integration of IoT technology proved useful for real-time monitoring and analysis. Users were able to observe system performance remotely, which enhances usability and system control.

Overall, the system demonstrates reliable performance, improved efficiency, and practical applicability. However, environmental factors and sensor limitations can affect accuracy, which can be improved in future enhancements.



7. APPLICATIONS

The proposed IoT-based dual-axis solar tracking system has a wide range of practical applications due to its efficiency, low cost, and real-time monitoring capability.

- **Residential Solar Systems:** It can be used in homes to improve energy generation from rooftop solar panels and reduce electricity costs.
- **Agriculture Sector:** The system can support solar-powered irrigation pumps and farming equipment, ensuring maximum energy availability for agricultural operations.
- **Rural Electrification:** It is suitable for remote and off-grid areas where efficient solar energy utilization is essential for reliable power supply.
- **Smart Cities:** The system can be integrated into smart city infrastructure for efficient energy management and monitoring.
- **Industrial Applications:** Industries can use the system to enhance solar energy production and

Use of **advanced sensors** for more accurate environmental monitoring.

- Implementation of **battery storage systems** for energy management.
- Enhancement of communication using **LoRa or GSM modules** for remote areas.
- Development of **large-scale solar tracking networks** for industrial applications.
- Improvement in mechanical design to reduce wear and increase durability.

reduce dependency on conventional energy sources.

- **Educational and Research Labs:** It serves as a useful project model for students and researchers to study IoT, renewable energy, and embedded systems.
- **Telecommunication Systems:** It can be used in remote telecom towers where continuous and efficient power supply is required.

8. CONCLUSION AND FUTURE SCOPE

The proposed IoT-based dual-axis solar tracking system successfully improves the efficiency of solar energy generation by continuously aligning the panel with the direction of maximum sunlight. Unlike fixed solar panels, the system dynamically adjusts its position, resulting in a significant increase in energy output. The integration of LDR sensors, ESP32 microcontroller, and servo motors ensures accurate tracking, while the DHT11 sensor provides useful environmental data.

The addition of IoT functionality enables real-time monitoring and remote access through a cloud platform, making the system more user-friendly and efficient. The experimental results indicate that the system achieves a noticeable improvement in energy generation, especially under clear weather conditions. Overall, the system is cost-effective, reliable, and suitable for practical applications in various fields.

Future Scope

- Integration of **machine learning algorithms** for predictive solar tracking.
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