Implementation of Dual Axis Solar Tracking System for Enhanced Solar Energy Generation

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1. ABSTRACT

The rapid increase in global energy demand and environmental concerns associated with fossil fuels have accelerated the adoption of renewable energy sources such as solar power. However, conventional solar panels are installed in fixed orientations, which limits their efficiency because they cannot continuously face the sun as its position changes throughout the day. To overcome this limitation, this research presents the design and implementation of an IoT-based dual axis solar tracking system capable of automatically aligning a solar panel with the sun's position.

The proposed system utilizes LDR sensors, an ESP32 microcontroller, a stepper motor, and a servo motor to control the solar panel orientation along both azimuth and elevation axes. The system continuously monitors sunlight intensity using sensors and adjusts the panel direction accordingly to maximize solar energy capture. Additionally, IoT connectivity enables real-time monitoring and remote control through a mobile application.

Experimental results demonstrate that the dual-axis solar tracking system significantly improves energy generation compared to conventional fixed solar panels, achieving an efficiency improvement of approximately 30–45%. The proposed design provides an intelligent, cost-effective, and reliable solution for maximizing solar energy utilization in renewable energy systems.

Keywords:
Dual Axis Solar Tracking, Renewable Energy, ESP32, IoT Monitoring, Solar Energy Efficiency, Solar Energy, Dual Axis Solar Tracker, Photovoltaic (PV) System, Maximum Solar Irradiance Tracking, Microcontroller-Based Control, Light Dependent Resistor (LDR) Sensors, Renewable Energy Systems, Solar Panel Orientation Control, Energy Efficiency Enhancement, Embedded System for Solar Tracking.

2. INTRODUCTION

2.1 Back ground & Motivation:

The growing demand for electrical energy and increasing environmental concerns have led to the widespread adoption of renewable energy sources. Among these sources, **solar energy** is one of the most abundant, clean, and sustainable forms of energy available. Solar photovoltaic (PV) systems convert sunlight directly into electrical energy and are widely used for residential, commercial, and industrial applicationDespite their advantages, conventional solar panels are typically installed in fixed positions. Since the sun moves across the sky throughout the day and changes its elevation seasonally, fixed solar panels cannot maintain an optimal angle with respect to sunlight. As a result, a significant portion of potential solar energy is lost, especially during early morning and late evening hours. Solar tracking systems have been developed to address this limitation. These systems automatically adjust the orientation of solar panels to follow the movement of the sun, thereby increasing solar energy capture. Solar trackers are generally classified into **single-axis and dual-axis tracking systems**. Single-axis trackers follow the sun in one direction, typically east to west, while dual-axis trackers allow movement in both horizontal and vertical directions, ensuring maximum exposure to sunlight throughout the day. With the advancement of embedded systems and IoT technology, solar tracking systems have become more intelligent and efficient. Microcontrollers such as **ESP32** enable real-time sensor data processing, automated control of motors, and remote monitoring capabilities. This integration improves system efficiency, reduces manual intervention, and enhances the overall reliability of solar energy systems. In this research, an **IoT-based dual axis solar tracking system** is developed to automatically track the sun and maximize solar energy generation. The system uses LDR sensors to detect sunlight intensity, an ESP32 microcontroller for processing sensor data, and motors to adjust the panel orientation and these are monitored by Solar app.

2.2 Problem Statement:

Conventional solar photovoltaic systems generally use fixed solar panels, which cannot adjust their position according to the movement of the sun. As the sun changes its position throughout the day, the angle of sunlight on the panel varies, leading to reduced solar energy absorption and lower power generation. Additionally, many existing systems lack real-time monitoring, remote control capabilities, making it difficult to optimize performance. Therefore, there is a need for an efficient and intelligent solar tracking system that can automatically track the sun in both horizontal and vertical directions while also providing app-based monitoring and control to improve solar energy utilization.

2.3 Objectives:

The main objectives of the proposed Dual Axis Solar Tracking System with App Control are:

I. To design and develop a dual-axis solar tracking system that follows the movement of the sun throughout the day.
II. To increase the efficiency of solar energy generation compared to fixed solar panels.
III. To implement automatic solar tracking using LDR sensors, stepper motor, and servo motor.
IV. To integrate a mobile application for monitoring and manual control of the solar panel.
V. To develop a low-cost and efficient system suitable for small-scale solar power applications.

3. LITERATURE & SURVEY

Figure3.1: LDR Sensor Module Layout

Several studies have explored solar tracking technologies to improve photovoltaic efficiency.
Researchers have developed various solar tracking mechanisms using microcontrollers such as Arduino, Raspberry Pi, and embedded systems. Many systems use light sensors such as LDRs to detect sunlight direction.
Dual-axis tracking systems have been proven to increase solar panel efficiency by **30-40% compared to fixed panels**.
Recent developments include IoT-based solar monitoring systems where solar parameters such as voltage, current, and power are transmitted through wireless networks.
However, many existing systems lack user-friendly interfaces or remote control capabilities. This project addresses these limitations by integrating a **custom Android application.**

A study by Abdallah and Nijmeh (2004) [1] proposed a two-axis sun tracking system using programmable logic controllers (PLC). Their research demonstrated that dual-axis tracking significantly improves the efficiency of solar panels compared to fixed installations. The system allowed automatic adjustment of panel orientation to maintain perpendicular alignment with sunlight.
A study by Clifford and Eastwood (2004) [2] introduced a passive solar tracking system that utilized mechanical structures and gravitational forces to follow the sun's movement. Although the system reduced the need for electronic control components, its tracking accuracy was limited under varying weather conditions.
A study by Barsoum (2011) [3] implemented a simplified solar tracking prototype using microcontroller-based control and light sensors. The proposed system used LDR sensors to detect sunlight intensity and automatically adjust the panel orientation. Experimental results showed improved power generation compared to fixed solar panels.
Recent studies have focused on integrating IoT technology and advanced microcontrollers to improve solar tracking performance. Bhuyan and Sheikh (2022) [4] designed an IoT-based dual-axis solar tracking system using microcontrollers and wireless communication technologies. Their system allowed real-time monitoring of solar panel performance through cloud-based platforms.
Another study by Mousazadeh et al. (2011) [5] reviewed various solar tracking techniques and concluded that dual-axis trackers provide the highest efficiency improvement among different tracking mechanisms. Their research highlighted that dual-axis systems can increase energy generation by up to 40% compared to fixed solar panels.
Although many solar tracking systems have been developed, several limitations still exist, such as lack of real-time monitoring, limited tracking accuracy, and absence of safety mechanisms during adverse environmental conditions. Therefore, this research proposes an IoT-based dual axis solar tracking system that integrates sensor-based tracking, automated motor control, and remote monitoring through a mobile application. The proposed system aims to improve solar energy harvesting efficiency while providing a reliable and cost-effective solution for modern renewable energy systems.

4. METHODOLOGY

4.1 System Overview:

The proposed system is a **dual-axis solar tracking system designed to improve the efficiency of solar photovoltaic (PV) panels by continuously aligning them with the position of the sun.** Unlike fixed solar panels, which remain stationary, the dual-axis tracker adjusts the orientation of the panel along two directions—horizontal (azimuth) and vertical (elevation). This ensures that the solar panel receives maximum sunlight throughout the day.

The system uses **light sensors, a microcontroller-based control unit, and motorized mechanisms** to automatically track the movement of the sun. The sensors detect variations in sunlight intensity and provide input signals to the controller. Based on the difference in sensor readings, the controller activates motors that rotate the solar panel until it faces the direction of maximum sunlight.

The design is suitable for **small-scale solar energy systems**, particularly in residential and educational applications. The proposed system focuses on improving energy output, reducing manual adjustment of panels, and providing a cost-effective solar tracking solution.

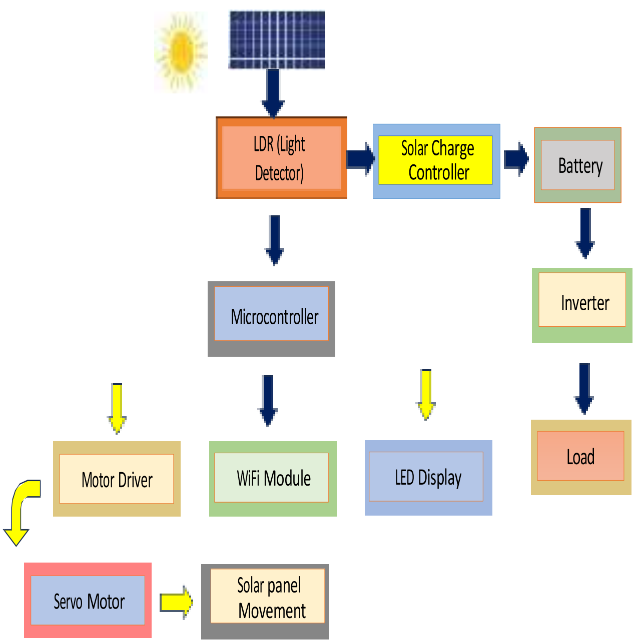

Figure *4.1*.Block Diagram of *Dual Axis Solar Tracking System*

4.2 SPECIFICATIONS:

Table :1 Compontent And Specifications

1	Microcontroller (MCU)	**ESP32 Development Board** – Dual-core processor up to 240 MHz with built-in Wi-Fi and Bluetooth
2	Light Sensors	**LDR (Light Dependent Resistors)** – Used to detect sunlight intensity and determine panel orientation
3.	Stepper Motor	**NEMA 17 Stepper Motor** – Used for horizontal rotation (azimuth axis) of the solar panel.
4	Stepper Motor Driver	**A4988 Motor Driver Module** – Provides precise microstepping control for the stepper motor
5	Servo Motor	**MG995 Servo Motor** – Used for vertical tilt (elevation axis) control of the solar panel
6	Solar Panel	**12V Photovoltaic Panel** – Converts solar radiation into electrical energy
7	Solar ChargeController	**PWM / MPPT Charge Controller** – Regulates charging of the battery from the solar panel
8	Battery	**12V Lead Acid Battery** – Stores generated solar energy for later use
9	Inverter	**DC to AC Inverter (12V–230V)** – Converts stored DC power into AC power for electrical loads
10	Sensors	**Voltage and Current Sensors** – Monitor solar panel output and system power generation
11	Diaplay	**16×2 LCD Display** – Displays system parameters such as voltage, power, and panel orientation
12	Communication	**Wi-Fi Module (ESP32 built-in)** – Enables IoT monitoring and remote control through mobile app

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4.3 HARWARE IMPLEMENTATION:

Figure 4.2 : Real-Time Hardware Implementation of Dual Axis Solar Tracking

The hardware implementation of the proposed Dual Axis Solar Tracking System was designed to automatically adjust the position of the solar panel so that it continuously faces the sun. This improves the efficiency of solar energy generation compared to conventional fixed solar panels.
The prototype consists of a 12V solar panel, Light Dependent Resistor (LDR) sensors, a microcontroller-based control unit, motor driver circuit, one stepper motor, and one servo motor. The LDR sensors detect the direction of maximum sunlight and send signals to the controller. Based on the sensor readings, the controller activates the motors to rotate the solar panel toward the direction of highest solar intensity.
The system enables automatic tracking of the sun in two directions, allowing the solar panel to maintain optimal alignment throughout the day.

Mobile Application Interface:

Figure4.3 : App interface

The system includes a **mobile application-based control system** that allows users to monitor and control the solar tracking system remotely. The mobile application provides the following features:

1. Monitoring of solar panel position
2. Manual control of panel movement
3. Real-time system status monitoring
4. Wireless communication with the microcontroller

The application communicates with the system through a **Bluetooth/Wi-Fi module**, enabling convenient and user-friendly control of the solar tracking system.

4.3.1 Working of Hardware System:

The hardware system operates based on automatic sunlight detection and mobile-assisted control.

The LDR sensors continuously measure sunlight intensity and send signals to the microcontroller. The controller compares these sensor values to determine the direction of maximum sunlight.The stepper motor rotates the panel horizontally to follow the sun's movement from east to west.The servo motor adjusts the vertical tilt of the panel according to the sun's elevation.The system automatically adjusts the solar panel position until optimal alignment with sunlight is achieved.

Additionally, the mobile application allows the user to monitor and manually control the system if required, providing greater flexibility and convenience.adjusts the solar panel position until optimal alignment with sunlight is achieved.

Figure4.4: Harware Working Model

5. RESULTS & DISCUSION

The results are presented in the following sections, showcasing the real-time operation, hardware implementation, and IoT-based monitoring of the system. A case study is included to illustrate practical applications.

5.1 Real-Time Operation of the System

The proposed system continuously measures the light intensity difference using multiple LDRs and adjusts the servo motor accordingly. When one LDR detects significantly higher light intensity than others, the servo motor moves in the respective direction. When no significant light difference is detected, the system remains stable. This process runs in a continuous loop to ensure real-time response to changing light conditions. If the environment turns completely dark, the system halts. These results validate the effectiveness of the servo motor control based on light intensity variations.

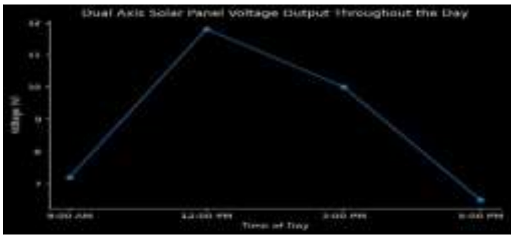

Fig. 5.1 Voltage Output Throughtout the day

The proposed Dual Axis Solar Tracking System was implemented and tested to evaluate its performance under real sunlight conditions. The prototype consisted of a 12V photovoltaic solar panel, LDR sensor array, microcontroller-based control unit, stepper motor for horizontal movement, servo motor for vertical tilt adjustment, and a mobile application interface for monitoring and control.

The solar panel output voltage and power were measured at different time intervals to evaluate the effectiveness of the tracking system.

Sample Results:

Time of Day	Fixed Panel Voltage	Dual axis Tracking Voltage
9:00 AM	6	7.2
12:00PM	10	11.8
3:00PM	7.8	10
5:00PM	5	6.5

Table 5.1 Voltage Thought Day

The implementation of dual-axis tracking significantly improved solar energy harvesting. Unlike single-axis or fixed systems, the dual-axis mechanism adjusts both the horizontal and vertical orientation of the panel. The stepper motor ensured accurate horizontal rotation of the panel following the sun's movement from east to west, while the servo motor adjusted the tilt angle according to the sun's elevation. This allowed the solar panel to maintain optimal alignment with sunlight throughout the day.
Experimental observations indicated that the tracking system can improve solar energy output by approximately 25–35% compared to a fixed solar panel system.

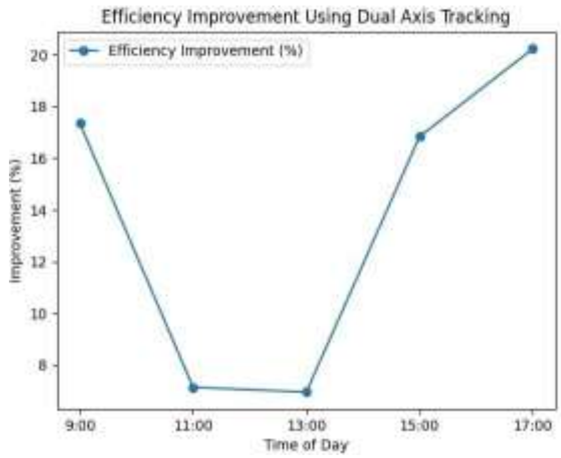

Figure 5. 2: Efficiency Improvement Using Dual Axis Solar Tracking System

5.1 Real Time Monitoring App Results:

The system also incorporated a mobile application interface that enabled real-time monitoring and control of the solar tracking system. Through the application, users could observe system parameters and manually adjust the panel position when required.
The mobile interface improved user interaction with the system and allowed convenient monitoring without direct access to the hardware setup. This feature enhances the usability of the solar tracking system, particularly for remote or small-scale installations.

DISCUSSION:

The experimental results demonstrate that the proposed dual-axis solar tracking system improves solar panel efficiency by maintaining optimal orientation toward the sun. The combination of LDR sensors, stepper motor, and servo motor ensures accurate and continuous tracking of solar movement. Compared to conventional fixed solar panels, the proposed system provides higher energy output throughout the day. The integration of a mobile application further enhances system functionality by enabling remote monitoring and control.

However, the system performance may be influenced by environmental factors such as cloud cover, sensor sensitivity, and mechanical alignment of the tracking mechanism. Proper calibration of sensors and stable mechanical design are essential to ensure reliable operation.

Overall, the results confirm that the proposed system is an effective and cost-efficient solution for improving solar energy generation in small-scale renewable energy applications.

6. CONCLUSION & FUTURE SCOPE

The proposed IoT-based dual axis solar tracking system was successfully designed and implemented. The system effectively tracks the sun's movement in both horizontal and vertical directions using LDR sensors and motorized actuators. Experimental results confirm that the system significantly improves solar energy generation compared to fixed solar panels. Future work will focus on integrating weather monitoring sensors, improving tracking algorithms, and implementing large-scale solar tracking systems for solar farms. Additionally, integrating AI-based algorithms can further enhance the system's intelligence by adjustments. Implementing self- learning mechanisms would enable the system to refine its responses over time, improving accuracy and efficiency. The introduction of more energy-efficient components, such as low- power microcontrollers and solar-powered sensors, could further enhance sustainability and reduce dependency on external power sources. Furthermore, expanding compatibility with additional IoT platforms and cloud computing services would improve accessibility and flexibility, allowing users to integrate the system with existing smart technologies seamlessly.

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