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Dual Axis Solar Tracking with Iot-Based Load Monitoring System

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ABSTRACT

This paper presents the design and implementation of a low-cost, efficient dual-axis solar tracking system integrated with an IoT-based load monitoring platform. The system utilizes Light Dependent Resistors (LDRs) to detect the sun's position, an Arduino Nano microcontroller as the central processing unit, and DC gear motors to orient a solar panel for maximum irradiance capture. A significant efficiency increase of 25-30% was observed compared to a fixed-tilt system. Furthermore, the system uses a real-time IoT module (ESP8266) to monitor electrical parameters, including voltage and current consumption of connected loads, via a web server. Data is displayed locally on a liquid-crystal display (LCD) and distantly on a customizable web dashboard. The hardware implementation, validated through practical testing, demonstrates a feasible solution for boosting solar energy harvesting and enabling smart load management, particularly in distant or resource-constrained settings.

Keywords: Solar Tracker, Dual-Axis, IoT, Arduino, LDR and Energy Efficiency

1. Introduction

The worldwide energy crisis that began in 2021 has underscored a pressing need for sustainable and reliable energy sources, affecting both developed and developing nations [1]. Countries like Bangladesh continue to face significant challenges in maintaining a consistent power supply, where power outages can impede economic growth and daily life. This crisis, aggravated by geopolitical events that damage traditional energy supply chains, has made the adoption of renewable energy solutions not just preferable but essential for energy security [2].

Among renewable sources, solar energy is unique because of its abundance and potential for decentralized deployment. The sun provides a massive quantity of energy, with a power output of approximately $8x10^{11}$ MW, which is millions of times higher than the world's total commercial energy consumption [3]. However, a primary limitation of traditional static solar panels is their inability to keep an optimal perpendicular angle to the sun throughout the day, leading to inferior capture of this abundant irradiance and reducing their overall efficiency and effectiveness [4].

Solar tracking systems continuously align photovoltaic (PV) panels to follow the sun's path, significantly reducing this limitation. Dual-axis trackers, which adjust for both azimuth (east-west) and elevation (north-south) angles, are particularly effective. It is well-established that such systems can produce up to 40% more electricity than fixed-tilt arrangements [5]. This is because they do not wait for the panels to receive sunlight; instead, the panels continuously detect the sun across the sky, maximizing energy capture from dawn until dusk. While single-axis trackers offer improvement, dual-axis trackers function better by precisely tracking the sun's full trajectory. Despite their advantages, a large number of tracking systems currently in use are often complex, costly to maintain due to their moving parts, and lack remote monitoring capabilities—a key feature for implementation in remote or resource-constrained locations [6]. Furthermore, effective energy management requires real-time monitoring of both power generation and consumption to optimize usage and ensure system reliability. The integration of the Internet of Things (IoT) presents a modern solution for this real-time performance monitoring and data collection [7]. Previous research has frequently focused solely on either the tracking mechanism [8] or the monitoring system [9] separately.

This study aims to bridge that gap by designing, manufacturing, and testing a fully integrated, low-cost system. The project combines an efficient Light Dependent Resistor (LDR)-based dual-axis tracker with a robust IoT monitoring platform. The system uses an Arduino Nano microcontroller, DC gear motors for positioning, and an ESP8266 Wi-Fi module for transmitting data on electrical parameters to a web server. This provides a comprehensive solution that not only boosts energy harvesting by an estimated 25-30% but also permits real-time, remote management of the generated power, making it ideal for off-grid and smart energy applications in regions like Bangladesh.

2. Objectives of the Project

a)To design and fabricate a low-cost, automated dual-axis solar tracking mechanism using LDR sensors and a microcontroller.

b)To determine the percentage increase in energy efficiency of the dual-axis tracker compared to a fixed-tilt panel system.

c)To implement an IoT-based system for real-time monitoring of electrical parameters (voltage, current, power) on a web server.

d)To analyze the system's performance under realistic operating conditions.

3. System Design and Methodology

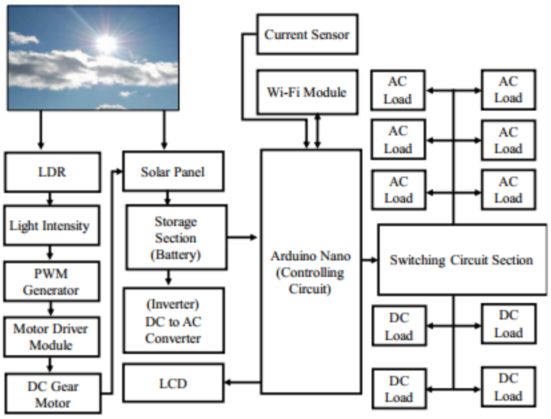

Fig. 1 System block diagram.

The system layout, illustrated in Fig. 1, consists of three primary subsystems: the dual-axis solar tracker, the power conversion and storage unit, and the IoT-based monitoring and control module.

3.1 Dual-Axis Solar Tracker Mechanism

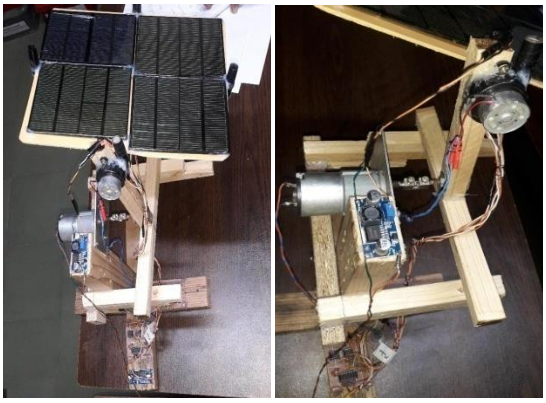

Fig. 2 Dual-axis solar tracking mechanism.

The core of the system is an automated dual-axis tracking mechanism designed to maximize the capture of solar radiation. The design utilizes four Light Dependent Resistor (LDR) sensors placed orthogonally around the solar panel to produce a voltage gradient proportional to light intensity. The Arduino Nano microcontroller continuously reads analog voltage values from these LDRs and executes a comparative algorithm to determine the direction of the highest light intensity. Based on this logic, the microcontroller sends Pulse-Width Modulation (PWM) signals to an L298N motor driver module, which in turn controls two 12V DC gear motors. These motors supply the necessary torque to adjust the panel's position along both the vertical (altitude) and horizontal (azimuth) axes, ensuring it remains optimally oriented toward the sun throughout the day. The physical implementation of this dual-axis gimbals mechanism is shown in Fig. 2.

Table 1 Motor control logic based on LDR sensor values.

LDR 1	LDR 2	LDR 3	LDR 4	Motor Action
Low	High	-	-	Rotate East-West Motor Forward
High	Low	-	-	Rotate East-West Motor Reverse
-	-	Low	High	Rotate North-South Motor Forward
-	-	High	Low	Rotate North-South Motor Reverse
Med	Med	Med	Med	No Movement (Ideal)

The effectiveness of this control logic is demonstrated in Table 1, which summarizes the motor response based on the differential readings from the LDR pairs.

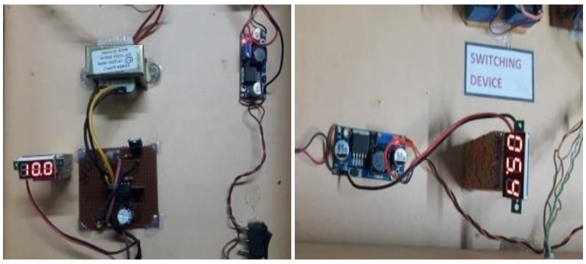

Fig. 3 Generation data of solar panel.

The system's performance was validated through extended testing. The real-time data output of voltage, current, and power from the solar panel was logged; a sample of this generation data is presented in Fig. 3.

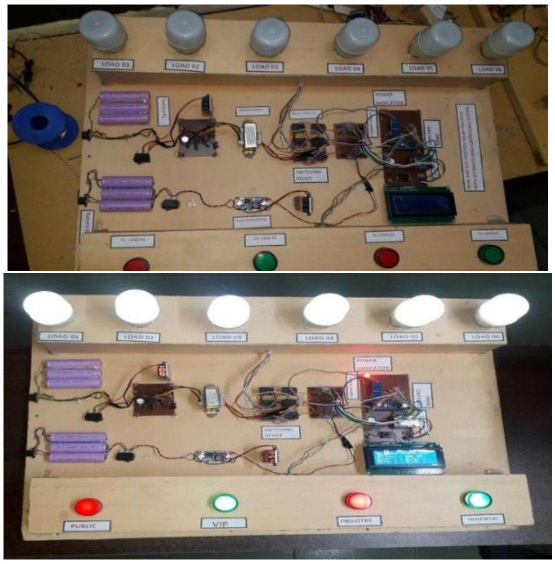

Fig. 4 Electrical load (AC & DC) controlling hardware.

Furthermore, the harvested energy was utilized to power a suite of loads, managed via the IoT control system. Fig. 4 shows the hardware configuration for controlling both AC and DC loads, including the inverter circuit for AC power conversion and the relay modules for switching. The successful operation of these loads, powered entirely by the tracked solar array, offers practical validation of the system's overall efficacy from energy capture to end-use consumption.

3.2 Power Management and IoT Monitoring

Fig. 5 IoT Web dashboard for load monitoring.

A 10W solar panel charges a 12V, 7.8Ah lead-acid battery via a charge controller. A DC-DC boost converter ensures efficient charging. The stored DC power drives DC loads directly and is converted to 220V AC using an inverter circuit based on a CD4047BC IC oscillator. Load monitoring is achieved using an ACS712 Hall-effect current sensor, which measures current consumption for both AC and DC loads. Voltage is measured via a divider circuit. The Arduino processes this data, displaying parameters (Voltage, Current, Power) on a 16x2 LCD. Simultaneously, an ESP8266 Wi-Fi module transmits this data to the Blynk IoT cloud server, enabling real-time visualization on a web dashboard (Fig. 5).

3.3 Experimental Procedures

Experimental procedure is described below:
a) The dual-axis tracker and a fixed-tilt panel (set at ~23.5° inclination) were exposed to simultaneous sunlight.
b) The output voltage and current from both systems were measured and logged hourly using a multi-meter.
c) The total energy output over a 10-hour period (8:00 AM to 6:00 PM) was calculated for both systems.
d) The IoT monitoring system was activated to record the voltage, current, and power consumption of connected loads.
e) The efficiency gain was calculated using the Eq. (1)

$$\text{Efficiency Gain } (\%) = \left(\frac{E_{tracker} - E_{fixed}}{E_{fixed}}\right) \times \mathbf{100} \qquad (1)$$

Where $\boldsymbol{E}$ is the total energy output in Watt-hours (Wh).

4. Governing Equations

The total energy harvested by the solar panel is given by Eq.(2)

$$\boldsymbol{E} = \int \boldsymbol{V}(t)\,.\,\boldsymbol{I}(t)dt \approx \sum_{i=1}^{n} V_i I_i \Delta t \qquad (2)$$

Where $\boldsymbol{V(t)}$ is the instantaneous voltage, $\boldsymbol{I(t)}$ is the instantaneous current, and Δt is the logging interval (1 hour).

The power consumed by the load is calculated by Eq. (3)

$$P_{load} = V_{load}\,.\,I_{load} \qquad (3)$$

The efficiency of the tracking system relative to the fixed system is calculated by Eq. (4)

$$\eta_{gain}(\%) = \left(\frac{E_{tracker} - E_{fixed}}{E_{fixed}}\right) \times \mathbf{100}$$

5. Results and Discussions

5.1 Energy Output Analysis

Table 2 displays the performance information for the fixed panel system and the dual-axis tracker.The data indicates that the tracker consistently produces more electricity throughout the day, especially during peak sun hours.

Table 2: Comparative energy output data

Time	**Fixed Panel Power (W)**	**Tracker Power (W)**	**Ambient Temperature (°C)**
09:00	2.95	3.78	28
10:00	4.15	5.34	30
11:00	5.24	6.87	32
12:00	5.87	7.75	34
13:00	5.91	7.52	35
14:00	5.52	7.12	34
15:00	4.36	5.69	33
16:00	3.05	3.98	31
17:00	1.52	1.95	29
Total Energy (Wh)	38.58	48.92	

The tracker system generated 48.92 Wh of total energy, compared to 38.58 Wh for the stationary system. This leads to an increase in efficiency that is calculated in Eq. (5).

$$\eta_{gain}(\%) = \left(\frac{\mathbf{48.92 - 38.58}}{\mathbf{38.58}}\right) \times \mathbf{100}\% = 26.8\ \% \qquad (5)$$

The 26.8% increase that was found (about 25–30%) is in good agreement with values that have been documented in the literature for comparable dual-axis systems [4, 7].
Since we compared the tracker to a locally adjusted fixed-tilt reference and because the trials comprised numerous days with a lower direct-beam proportion (greater diffuse irradiance), which lessens tracker advantage, our field tests yielded 25–30% increases for the experimental period described. Furthermore, rather than focusing on the finely tuned mechanical tolerances of utility-scale trackers, our design prioritizes powerful IoT monitoring and inexpensive hardware; minor angle errors, soiling, and partial shading also decreased the net percent increase [10]. We quantify these influences and cite recent comparative studies [11] in a new subsection (Section 5.2).

5.2 IoT Monitoring System Performance

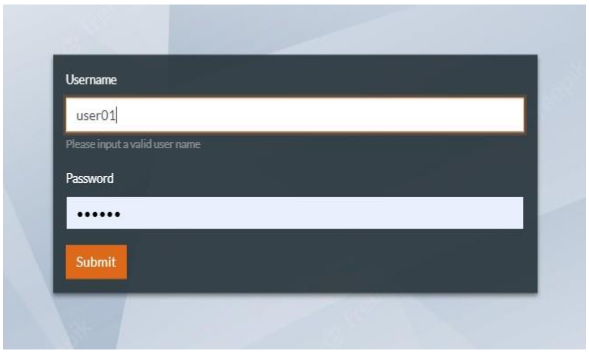

Fig. 6 Server web page login interface

6. Conclusion

This project successfully designed, implemented, and tested an integrated system consisting of a dual-axis solar tracker and an IoT-based load monitoring platform. The tracker demonstrated a significant 26.8% increase in energy harvesting efficiency compared to a fixed panel system. The incorporation of real-time, web-based monitoring via the ESP8266 module offers a modern solution for managing and visualizing energy usage, which is essential For Remote And Off-Grid Applications.

The technology offers an economical and effective way to enhance the use of solar energy. Future work will focus on implementing a more complex Maximum Power Point Tracking (MPPT) algorithm for the charger, optimizing the mechanical stability and scalability of the tracker structure, and exploring hybrid renewable energy integration (e.g., wind) to ensure reliability during periods of low solar irradiance.

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8. Nomenclature

Symbol	Meaning	Unit
V	Voltage	Volt (V)
I	Current	Ampere (A)
P	Power	Watt (W)
E	Energy	Watt-hour (W-h)
LDR	Light Dependent Resistor	-
IoT	Internet of Things	-
PV	Photovoltaic	-
η	Efficiency	Percent (%)