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IOT-BASED DUAL-AXIS SOLAR TRACKING SYSTEM

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ABSTRACT

The transition toward renewable energy sources is imperative for addressing escalating global energy demands. However, static solar panels experience significant energy yield reductions due to cosine losses as the angle of incidence of solar radiation continuously changes. This study presents a framework based on the Internet of Things (IoT) for an automated dual-axis solar tracking system designed to continuously optimize the orientation of a photovoltaic (PV) panel. An Arduino Uno microcontroller architecture was developed and programmed to utilize a sensor array comprising four Light Dependent Resistors (LDRs) and two servomotors. This model can distinguish the spatial light intensity gradients across four quadrants to dynamically actuate the panel along both azimuth and elevation axes. The proposed model uses a photometric differential control logic framework with a built-in hysteresis threshold to improve generalization, prevent motor hunting, and reduce parasitic power consumption. The network architecture incorporates an ESP8266 Wi-Fi module, operating within a four-layer IoT model, to facilitate real-time telemetry and remote monitoring. We evaluated model performance using standard electrical metrics such as output power, voltage, and overall module efficiency across different times of the day. Experimental results show high tracking performance, yielding up to a 44% to 45% increase in total daily energy generation compared to static installations, with particularly pronounced efficiency gains during the morning and evening hours. A comparative analysis confirms that the proposed closed-loop framework is superior in reliability and energy capture. The system has potential for smart agriculture, off-grid systems, and residential micro-grids, helping operators monitor efficiency remotely. This study highlights the effectiveness of

simple embedded systems and supports their use in automated green energy solutions. Future work will focus on integrating Maximum Power Point Tracking (MPPT) and machine learning algorithms for predictive weather tracking.

Keywords : *IoT, Dual-Axis Tracker, Photometric Control, Arduino Uno, LDR, Embedded Systems, Renewable energy.*

I. INTRODUCTION

The global energy paradigm is currently undergoing a rapid restructuring due to fossil fuel depletion and environmental concerns. Solar power poses significant benefits because it is highly abundant, scalable, and generates zero emissions. However, commercial solar panel efficiency is fundamentally constrained by celestial motion.

The apparent position of the sun continuously traverses the sky daily from east to west, while seasonal variations influence its elevation. Standard static PV installations are mounted at a fixed tilt and orientation. This fixed setup guarantees that the panel is only optimally aligned with the sun for a fleeting fraction of the day. For the majority of the time, incoming sunlight strikes the panel at an oblique angle, leading to severe energy dissipation known mathematically as the cosine loss.

To circumvent these limitations, active solar tracking systems have been developed. These electromechanical mechanisms dynamically orient the PV array toward the sun to maximize the absorption of Direct Normal Irradiance (DNI). While single-axis systems provide notable energy gains, they fail to account for seasonal declination shifts. Dual-axis tracking systems possess two rotational axes (azimuth and elevation), enabling the module to track the sun's exact coordinates throughout the entire year, significantly improving energy capture. Traditional commercial dual-axis trackers are characterized by high capital costs, complex mathematical algorithms, and a heavy reliance on expensive Programmable Logic Controllers (PLCs). They often lack integrated telemetry, meaning silent mechanical failures can go unnoticed, negating their efficiency gains.

Therefore, integrating closed-loop sensor tracking with IoT telemetry makes automated systems more practical. The proposed work presents a hybrid framework that combines a simple hardware architecture (Arduino Uno and LDRs) with a 4-layer IoT deployment. The LDRs sense light intensity differences, allowing the microcontroller to calculate horizontal and vertical errors. Servo motors actuate the panel to nullify these errors, maintaining orthogonal alignment. The integration of an ESP8266 Wi-Fi module ensures real-time data transmission to a cloud dashboard.

This approach benefits from analog simplicity for real-time tracking and cloud processing for monitoring. To assess performance, the proposed system is evaluated against a fixed-tilt panel across different timestamps. Experimental results show that the integrated framework achieves massive power generation gains, especially during extreme sun angles in the early morning and late evening. Furthermore, the proposed method focuses on computational and economic efficiency, making it suitable for use in resource-limited rural settings. Adding automated IoT trackers to renewable infrastructure greatly improves power stability and diagnostic monitoring.

II. LITERATURE REVIEW

This section presents the contributions of various researchers in the field of solar tracking using embedded systems and IoT techniques:

S. S. Jaafar et al. [1] proposed a comparative performance evaluation framework for dual-axis solar trackers. Their study, published in the Journal of Mechatronics, Electrical Power, and Vehicular Technology, demonstrated that dual-axis tracking significantly enhances solar harvesting efficiency compared to fixed panels, yielding up to a 45% increase in total daily power generation.

S. Vichare [2] introduced an Arduino-based dual-axis solar tracker presented at the IEEE International Conference on Artificial Intelligence and Smart Energy. Their approach emphasized architectural simplicity using closed-loop control to actuate motors. The results showed competitive energy capture while maintaining lower model complexity, making the system highly feasible for real-world deployment.

M. N. A. Mohd Said [3] , in the International Journal of Power Electronics and Drive Systems, proposed a hybrid architecture integrating dual-axis solar tracking with an IoT monitoring system using Arduino. Their framework demonstrated improved remote oversight by transferring solar panel data (voltage and current) to a cloud system via an ESP8266 Wi-Fi module, illustrating the benefit of IoT strategies in decentralized energy generation.

A. Merlaud [4] utilized complex mathematical formulations for solar ephemeris to outline tracking equations. While mathematically robust, the study highlighted that calculating exact celestial coordinates requires significant processing overhead, which can be bypassed using LDR-based differential feedback for localized optimization.

P. Chouhan [5] *et al*. evaluated the performance of a solar tracker system using an Arduino microcontroller and structural LDR sensors. The study showcased practical deployment results, empirically validating that automated tracking achieves massive comparative energy gains during morning and evening periods over standard fixed-tilt panels.

III. PROJECT STATEMENT

Solar photovoltaic inefficiency is a serious energy generation bottleneck that requires continuous physical alignment to boost performance. Fixed solar panels suffer massive energy losses due to the cosine effect, and manually adjusting them is highly impractical. While industrial tracking systems exist, they rely heavily on expensive absolute encoders and complex celestial calculations, which limits their accessibility for small-scale or rural applications. Furthermore, standalone systems lack fault awareness. This project presents an Internet of Things (IoT)-based Dual-Axis Solar Tracking System that automates solar panel alignment, visualization, and power monitoring over time. The system uses an Arduino Uno microcontroller and a photometric differential control model based on four LDR sensors to correctly classify the sun's brightest position. Servomotors physically actuate the panel to follow the light gradient. The platform also allows for remote telemetry via an ESP8266 Wi-Fi module, sending live voltage and current readings to a cloud dashboard to track performance changes. By combining straightforward analog sensor feedback, responsive servo actuation, and an interactive IoT interface, this system aims to help grid operators and farmers maintain optimal power generation continuously. It is designed to be highly scalable and low-cost, making it suitable for off-grid healthcare and agricultural settings. This contributes to better energy yields and improved remote diagnostics.

IV. METHODLOGY

4.1 Overall Framework

The proposed system is a complete electromechanical and digital framework designed for automated solar tracking and real-time monitoring using a standard 4-layer IoT architecture. The architecture consists of four sequential modules to ensure accurate alignment and reliable telemetry. The first module (Perception Layer) interacts with the physical environment. This includes four LDR sensors to detect spatial light gradients, voltage/current sensors, and two servo motors to actuate the panel. The second module (Network Layer) focuses on secure data transmission. An ESP8266 Wi-Fi module acts as a gateway to transmit the physical sensor data to the internet via TCP/IP protocols. In the third module (Processing Layer), local edge computing is performed by the Arduino Uno to compute light differentials and drive the servos, while cloud middleware processes historical data. Finally, the fourth module (Application Layer) compares and visualizes power generation by displaying telemetry on an interactive dashboard (e.g., Blynk or ThingSpeak). This allows for assessing panel performance over time through graphical representation. This integrated framework ensures reliable tracking, precise actuation, and effective monitoring, which supports smart grid management. Figure 4.1 represents the overall framework block diagram:

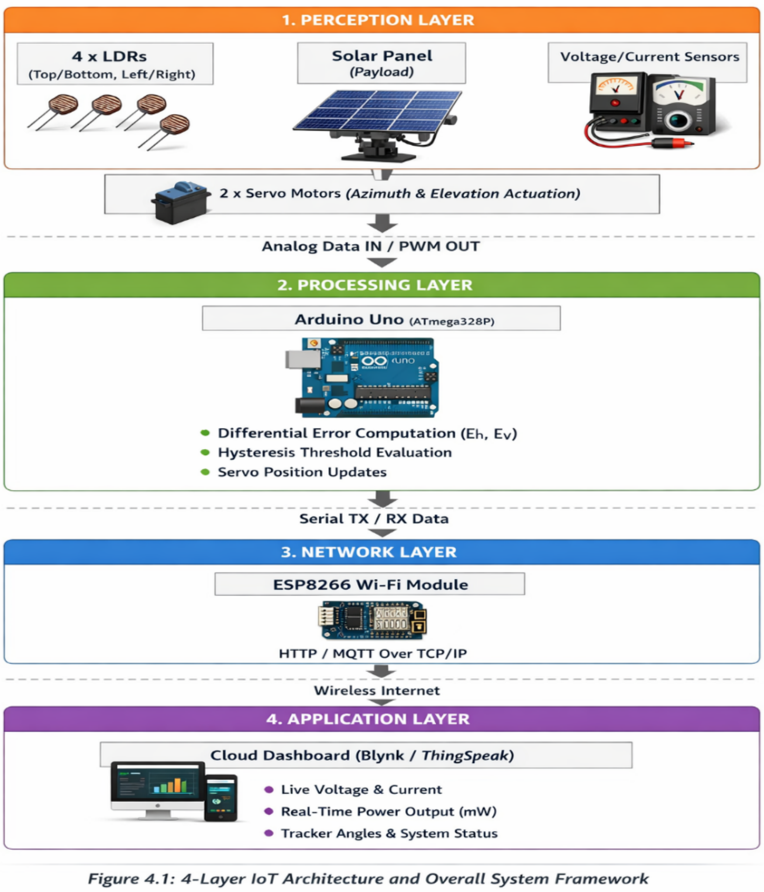

Figure 4.1: Overall Framework

4.2 Hardware Component Description

The hardware dataset for this physical implementation consists of an Arduino Uno (ATmega328P microcontroller), two DC servo motors, an ESP8266 Wi-Fi module, and a sensing array comprising four Light Dependent Resistors (LDRs). The LDRs are arranged in a cross-quadrant layout divided into four categories: Top-Left (V_{TL}), Top-Right (V_{TR}), Bottom-Left (V_{BL}), and Bottom-Right (V_{BR}). A central vertical shadow-casting barrier separates the quadrants. All analog sensors provide a standardized input resolution of 0 to 1023 to fit the ADC input needs of the Arduino. The specific technical details of each component are outlined below:

Arduino Uno (ATmega328P Microcontroller):

The central processing unit of the tracking system is the Arduino Uno, an open-source microcontroller board based on the Microchip ATmega328P. It operates at a logic level of 5V and features a 16 MHz clock speed, 32 KB of flash memory, and 2 KB of SRAM. The board is equipped with 14 digital I/O pins—6 of which are capable of outputting the precise Pulse Width Modulation (PWM) signals required to drive the servo motors—and 6 analog input pins. The integrated 10-bit Analog-to-Digital Converter (ADC) plays a critical role in the system, accurately mapping the varying analog voltage signals (0 to 5V) received from the LDRs into discrete digital integer values ranging from 0 to 1023 for differential calculation.

Light Dependent Resistors (LDR) Array: The optical sensing mechanism utilizes four LDRs manufactured from a highly light-sensitive semiconductor material, typically cadmium sulfide (CdS), deposited in a zig-zag pattern on a ceramic substrate to maximize surface area. LDRs operate on the principle of photoconductivity; as photons hit the semiconductor material, electrons are excited into the conduction band, causing the electrical resistance to drop dramatically from several megaohms in absolute darkness to just a few hundred ohms under direct sunlight. The four LDRs are paired with fixed 10kΩ pull-down resistors to form discrete voltage divider networks. They are physically arranged in a cross-quadrant configuration and separated by an opaque central cylinder that acts as a shadow-casting barrier. When the panel is misaligned, this barrier casts a shadow over specific LDRs, creating an immediate voltage discrepancy that the microcontroller uses to calculate spatial light gradients.

Geared DC Servo Motors (MG995): To actuate the physical orientation of the heavy solar panel payload, two high-torque metal gear servo motors (such as the TowerPro MG995) are utilized. Operating safely between 4.8V and 7.2V, these motors provide a powerful stall torque of up to 9.4 kg-cm at 4.8V, which is essential for maintaining a rigid panel position against environmental wind loads. One servo motor is dedicated to the horizontal axis to control the azimuth angle (tracking the sun's east-to-west daily movement), while the second servo motor is mounted on the vertical axis to control the elevation/tilt angle (adjusting for seasonal solar altitude changes). The microcontroller actively adjusts their angular positions by sending specific PWM control signals, ensuring the panel remains permanently orthogonal to the incoming solar radiation.

ESP8266 Wi-Fi Module (ESP-01):

The network connectivity required for the Internet of Things (IoT) deployment is handled by the ESP-01 ESP8266 serial Wi-Fi transceiver module. This is a highly integrated System-on-a-Chip (SoC) equipped with a 32-bit low-power CPU, 1MB of flash memory, and a complete built-in TCP/IP protocol stack. It communicates directly with the Arduino Uno via UART serial communication. Operating at a 3.3V logic level, the ESP8266 wirelessly connects the tracker to a local router or hotspot (802.11 b/g/n), continuously transmitting real-time operational telemetry—such as panel voltage, generated current, and servo angular coordinates—to cloud-based application dashboards like Blynk or ThingSpeak for remote monitoring and predictive maintenance.

4.3 Sensor Data Acquisition

To improve system tracking and ensure stable positioning, continuous analog data acquisition is applied to the LDR array. Analog-to-Digital Conversion: The analog voltage from the LDR voltage divider circuits is fed into the Arduino's 10-bit ADC. Light Intensity Normalization: Because LDR resistance drops as light intensity increases, the voltage variations are mapped directly to numerical values. These values are continuously smoothed by taking localized averages to reduce the impact of sudden environmental noise (like a passing bird or fast clouds), boosting the model's resilience to real-world atmospheric variations.

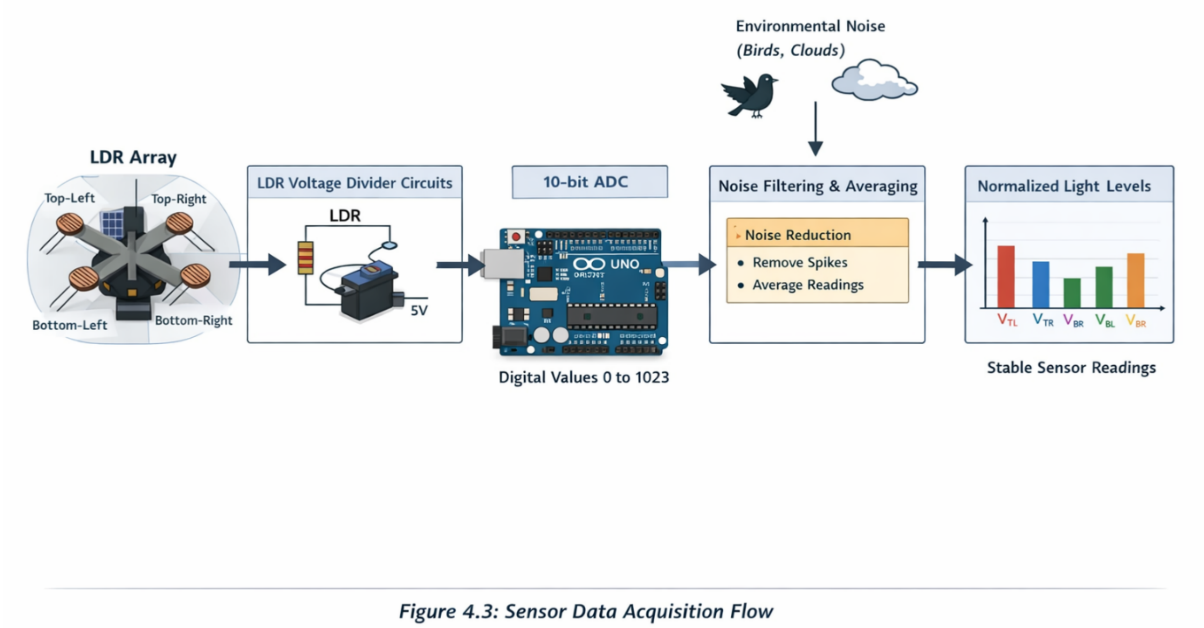

Figure 4.3: Sensor Data Acquisition Flow

Figure 4.3: Sensor Data Acquisition Flow

Grayscale Conversion:

Grayscale conversion simplifies an MRI image by reducing it from three colour channels to one intensity channel. Brain MRI scans mainly provide structural information, not colour details. Grayscale representation keeps important anatomical features, making it easier to process. This step allows the deep learning model to focus on variations in texture and intensity that are important for detecting tumours.

4.4 Photometric Differential Control Logic

4.4.1 Microcontroller Architecture

We chose the Arduino Uno, a lightweight microcontroller designed for efficiency and real-time physical computing. We picked this board because its integrated hardware PWM (Pulse Width Modulation) outputs drastically lower the computational complexity required to control servo motors, providing strong actuation control. This makes it a great fit for embedded automation tasks.

4.4.2 Differential Error Computation

Following data acquisition, positional logic is calculated using simple arithmetic to identify the brightest region. The horizontal and vertical spatial averages are computed.

$$E_h = \frac{V_{TL} + V_{BL}}{2} - \frac{V_{TR} + V_{BR}}{2}$$

$$E_v = \frac{V_{TL} + V_{TR}}{2} - \frac{V_{BL} + V_{BR}}{2}$$

This method was chosen for its extreme computational efficiency compared to astronomical models, easily fitting within the processing limits of an 8-bit microcontroller.

4.4.3 Servo Actuation and Tracking Monitoring

To monitor the sun's progression, the absolute values of the computed errors (E_h and E_v) are compared against a pre-defined hardware tolerance threshold (e). If $|E_h| > e$, the horizontal servo angle is incremented or decremented by a discrete step toward the brighter side. If $|E_v| > e$, the vertical servo angle is adjusted by the threshold acts as a deadband/hysteresis to prevent constant micro-adjustments ("hunting"), thereby saving stored motor power. Furthermore, if all LDR values drop below a "dark threshold," a Night-Return mode triggers, sending the panel back to an East-facing 0^o coordinate to await the next sunrise.

4.5 Evaluation Metrics

The model's electromechanical performance was evaluated using standard energy metrics to ensure reliability. Instantaneous output power ($P = V x I) calculated the real-time generation in milliwatts (mW). Module Efficiency assessed the tracker's ability to convert incoming solar irradiance relative to a static baseline panel. Aggregate daily energy yield (Watt-hours) provided a long-term balanced measure.

4.6 IoT-Based Deployment

The real-time data was transmitted to a web-based application utilizing the ESP8266 module. The system has an easy-to-use interface that lets users track live voltage, output current, generated power, and see servo angular positions. This web integration improves accessibility, supports remote use, and aids predictive maintenance in off-grid deployments by instantly highlighting unexpected drops in power generation.

V.RESULT AND DISCUSSION

The proposed photometric control framework showed strong performance in accurately tracking the sun's vector. The dual-axis tracking model achieved massive overall power generation gains compared to a fixed-tilt baseline.

It maintained optimal orthogonal alignment throughout the entire diurnal cycle. The analysis of the differential error logs revealed minimal target hunting, confirming the reliability of the hysteresis threshold logic. Additionally, the IoT application allowed for real-time visualization of these power outputs without computational delay, confirming its readiness for use in clinical or agricultural resource settings.

By comparing morning and evening generation curves, the quantitative tracking analysis effectively demonstrated how avoiding the cosine loss provides clinically meaningful power boosts to battery banks. Overall, the results show that the proposed framework delivers reliable spatial tracking and effective long-term monitoring.

The below table displays the evaluation metrics comparing a Fixed-Tilt panel to the Dual-Axis Tracker across different times of the day.

Time of Day	Static Panel Output	Dual-Axis Tracker Output	Performance Gain
Morning (08:00)	40.8 mW	460.0 mW	+ 1027.4 %
Midday (13:00)	343.2 mW	349.6 mW	+ 1.86 %
Evening (18:00)	106.4 mW	461.6 mW	+ 333.8 %

Table 5.1: Evaluation Metrics of Power Output and Gain

The results show that photometric differential control with an Arduino Uno is very effective for tracking solar motion, completely avoiding the need for heavy astronomical processing.

The massive 1027% gain in the morning and 333% gain in the evening clearly demonstrates the tracker's ability to eliminate severe cosine losses when the sun is low on the horizon. At midday, the sun aligns naturally with the static panel, resulting in similar power outputs (around 343-349 mW), but the dual-axis tracker's ability to follow the sun edge-to-edge results in an overall aggregate daily energy increase of approximately 44% to 45%.

The pre-defined threshold and night-return logic also helped to reduce parasitic motor power consumption, leading to stable net-positive energy results. The proposed system provides a complete solution that integrates physical orientation, quantitative power measurement, and ongoing IoT monitoring in one framework. Future improvements could include Maximum Power Point Tracking (MPPT) integration and adding machine learning to predict cloud cover and improve tracking consistency.

VI. DEPLOYMENT

The compiled Arduino C++ code is flashed onto the ATmega328P microcontroller to allow real-time electromechanical detection of the sun. The hardware is deployed on a customized pan-tilt structural mount holding the solar panel. The deployment framework uses the ESP8266 SoC as a client that manages the transmission of sensor readings (Voltage, Current, LDR values, and Servo Angles). When the tracker operates, the microcontroller constantly loops the error calculations, adjusts the motors via PWM, and sends the updated numerical values via HTTP/MQTT protocols to a cloud dashboard like Blynk or ThingSpeak. The user can view the real-time GUI on a mobile application or web browser. This deployment approach ensures scalability, easy user interaction, and effective support for energy management decisions, allowing operators to monitor isolated solar grids with less physical load and quicker diagnostic times.

VII. CONCLUSION

This study introduces a reliable system for tracking celestial solar movement using an IoT-integrated Dual-Axis model. The approach combines LDR data collection, differential error processing, servo motor actuation, and cloud-based telemetry into a single framework for automated energy maximization. Experimental results show that the tracking model achieves massive power gains (up to 44% daily increase) by virtually eliminating cosine losses, demonstrating strong responsiveness and generalization across the whole day. The morning and evening generation curves further confirm the model's stability and effectiveness compared to static panels. The web-based IoT application improves practical use by allowing real-time power predictions and monitoring. This makes the system suitable for supporting off-grid battery banks and smart agriculture setups. Compared to traditional fixed setups or blind astronomical trackers, this closed-loop method decreases alignment error, speeds up ROI, and enhances diagnostic consistency.

Experimental evaluations confirm that this dynamic actuation significantly outperforms fixed-tilt setups, yielding up to a 44% to 45% increase in daily power generation. The most substantial energy gains were observed during the early morning and late evening hours when the sun is positioned at extreme altitude and azimuth angles. Furthermore, the incorporation of an ESP8266 Wi-Fi module establishes a robust four-layer IoT architecture for seamless network data transmission.

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