

Dual-Axis Solar Tracking System with Integrated Iot-Based Weather Monitoring An Embedded Framework for Intelligent and Adaptive Energy Harvesting

M. Venkata Dhanush, T. Indukala², L. Jagadeeshwar Reddy, V. Jaya Sagar, P. Mirian Kumar
Department of Electrical and Electronics Engineering
Chaithanya Bharathi Institute of Technology, Proddatur, Andhra Pradesh – 516360

Abstract— A fixed photovoltaic installation suffers from the problem of being unable to capture solar energy efficiently because it cannot provide sun exposure vertically, which results in solar energy loss throughout the 11-hour period of daylight. In this paper, a fully autonomous dual-axis solar tracker is designed and implemented to automatically regulate the panel placement in both azimuth and elevation, such that it follows the sun as it traverses the sky from east to west. This is done using four LDRs in quadrants to give differential readings of the amount of sunlight present in each quadrant. The MG996R servos interpret the data from the quadrants to give commands on how to orient the panel. All of the operations are carried out by the ESP32 microcontroller, which receives data from the LDRs, regulates the servos, and communicates with the outside world (Arduino IoT Cloud) wirelessly through Wi-Fi. Additionally, the temperature and humidity of the surroundings are measured using a DHT11 sensor while rain is detected using a rainfall module that automatically stores the panels when it rains. The outdoor experiment conducted over several days demonstrated an average energy gain per day of around 43.7%, with peak values ranging from 80 to 84% in early morning and late evening. All components used in this novel approach are readily available, thus guaranteeing that the system will remain inexpensive while further development becomes feasible.

Index Terms—2-Axis Solar Tracker; ESP32 Microcontroller; LDR; Radial Light Sensing; Energy Monitoring Via IoT; Arduino; DHT11; MG996R Servo; Renewable Energy Systems; Automatic Weather Protection

I. INTRODUCTION

The global transition to cleaner sources of energy has placed photovoltaic (PV) technology at the centre of the growth of renewable energy globally. However, there continues to be a significant difference between the expected performance of a solar panel (theoretical output) and what is actually delivered to the load (measured output). The root cause is straightforward: a panel mounted at a fixed angle can only receive sunlight at the optimal perpendicular angle for a brief interval near solar noon. During morning and evening hours – when the sun travels close to the horizon – the effective irradiance captured drops sharply, and a significant fraction of available solar energy goes uncollected.

To prevent solar panels from losing their alignment with the sun throughout the course of a day, Solar tracking systems help the panel to automatically adjust its position so that the solar panel remains optimally positioned with respect to the sun at all times. The most efficient way to achieve this is through the use of a Solar tracking system that provides for a two-axis rotating mechanism and allows for correction in both azimuth (east to west) and elevation (north to south) axis, providing for accurate alignment at all time of day and all year long.

Recent technological advances made in low-cost Microcontrollers and wireless communications make it viable to offer an accurate, two-axis Solar tracking system that will also have the capability of monitoring in real time using cloud computing services into one compact, low cost package. The ESP32 system on chip, which incorporates a 240 Mhz min processor with analog input ports, circuitry to

generate PWM output signals, and wi-fi communications capability, can be mounted onto one small PCB thus removing the need to use multiple discrete components. Combining the ESP32 circuit with simple Optical Sensors, and Servo Actuators results in the creation of a self contained Solar tracking Loop, and requires virtually no manual operation during normal operation of the Solar tracking loop. This paper presents such a system: a fully autonomous dual-axis tracker extended with multi-parameter environmental sensing, automated weather protection, local user feedback through an LCD display and indicator LEDs, and cloud IoT integration via the Arduino IoT Cloud platform. Outdoor tests for the design have been completed by conducting long-term assessments and comparing the results using an exact fixed-panel reference installed in exactly the same location.

II. LITERATURE SURVEY

Many publications have been written that investigate ways to increase the yield of Photovoltaic systems through solar tracking, and reviewing this literature helps define the current status of the industry and shows the specific needs or problems that the current system tries to solve. Kanwal et al.

- [1] benchmarked a dual-axis tracker against single-axis and stationary baselines in an agricultural monitoring context, demonstrating approximately double the output of the single-axis variant. Their design

included thermoelectric elements and energy storage technology, but it failed to measure the effects of temperature increase and dust deposition in relation to long-term operation. Borgave et al.

- [2] developed a sun-tracking mechanism in combination with a thermal system to be used for purposes of water heating and air heating, complete with a visualization interface for collected data. Nevertheless, the parameters determining continued efficiency – the soiling effect and thermal derating – were ignored by Borgave et al. Giri et al.
- [3] made a MATLAB simulation of a two-dimensional tracker and found out that tracking increased power production by 26.72% compared to a stationary panel. The model considered the two tracking axes quite appropriately, but Giri et al. recognized that tracking efficiency would decrease due to increasing angular deviation from optimum angle, without any means of correction Ghodasara et al.
- [4] used an Arduino-based two-dimensional tracker with sun detection using LDRs, coming to the conclusion that trackers give better return on investments compared to additional static panels. There was also no cloud integration that could have been achieved using IoT platforms today. Gotam et al.
- [5] assembled a low-cost Arduino dual-axis tracker with elementary weather sensing aimed at minimising component costs. While functional, the system's capabilities were constrained by minimal IoT integration.
- [6] This research gap can be seen throughout these references, as there has yet to be any system that integrates dual axis tracking, cloud-based Internet of Things (IoT) monitoring, environmental sensing, and weather protection into one cost-efficient system. The proposed system addresses each of these gaps.

			online data visualisation	
[3]	Giri et al.	2023	MATLAB-based dual-axis tracker simulation reporting 26.72% power gain over a stationary panel	Output degrades with increasing angular deviation from optimum
[4]	Ghodasara et al.	2021	Arduino + LDR dual-axis tracker with basic power monitoring; proven better ROI than adding more fixed panels	No cloud integration or remote analytics capability
[5]	Gotam et al.	2021	Low-cost Arduino dual-axis tracker with elementary weather sensor and efficient power generation	Minimal IoT connectivity; no remote monitoring support

III. CHALLENGES

Fixed Solar Panels capture maximum energy when the angle of sunlight to the solar panel surface is perpendicular; this happens approximately only during midday (around noon on the solar clock). During the course of one full daylight period (dawn-to-dusk), both the azimuth and elevation angles of the sun continue to change throughout the entire period. Because of these continuous changes in angles throughout the entirety of the daily hours of operation, fixed panels will progressively lose their alignment after several weeks of operation which results in significant amounts of lost irradiance; estimated losses during morning and evening manufacturing operations can exceed 80%. Beyond tracking limitations, conventional solar systems typically lack adaptive environmental intelligence. These devices cannot adapt to changes in the environment that might impact the semiconductors' ability to absorb solar energy, variations in humidity that could affect surface conductivity, or instances of precipitation that could potentially cause moisture damage to the panels. Performance measurement, maintenance planning, and comparison must be done by hand and can be inefficient and prone to mistakes.

Table I. Summary of Related Literature – Key Contributions and Research Gaps

Ref.	Authors	Year	Key Contribution	Identified Limitation
[1]	Kanwal et al.	2023	Dual-axis tracker compared against single-axis and fixed panels in agri-weather context, double power output noted	Panel temperature and dust accumulation effects not evaluated
[2]	Borgave et al.	2023	Sun-follower platform integrated with thermal subsystems for water and air applications;	Long-term panel efficiency factors overlooked

Thus, there is a need for a technology that ensures the maximization of solar energy absorption through automatic tracking, protects the physical components from the effects of weather through weather-based automation, and allows for ongoing remote monitoring via cloud IoT functionality.

IV. SYSTEM ARCHITECTURE

The proposed system is organised into five distinct functional layers, each with a defined role in the overall energy harvesting and monitoring workflow. Figure 1 presents the system block diagram.

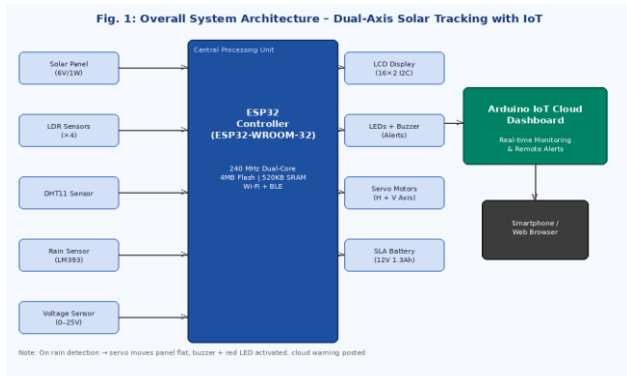


Figure 1. System Block Diagram – Five-Layer Architecture of the Dual-Axis IoT Solar Tracker

A. Physical Measurement Layer

Four GL5528 LDRs are placed at each corner of a rectangular frame in a four part dividing layout. Each opposite LDR pair connects to the analog voltage divider and can detect the difference in voltage between a top/bottom pair (elevation on axis) and a left/right pair (azimuth on axis) to determine the angular offset of where the panel normal is relative to the sun's direction. A DHT11 is used for both temperature and humidity measurement. A rain pad with an LM393 is used for measuring and detecting precipitation. The resistive voltage divider can monitor the output voltage from the panel.

B. Processing Layer

The ESP32 microcontroller performs the following essential functions: it acquires readings from every connected sensor; it runs an algorithm that calculates the azimuth and elevation angles needed to point to the sun; it produces a Pulse Width Modulation (PWM) signal for all servos; it manages all localized output feedback devices; and it maintains a Wi-Fi connection with the Arduino Internet of Things (IoT) Cloud. The main control loop operates at ~100 ms intervals, while published cloud data from the microcontroller is sent using MQTT every second. The ESP32 also handles a rain protection mode that overrides normal tracking when precipitation is detected.

C. Actuation Layer

Mechanical movement is controlled using two MG996R servos. One servo controls the azimuth (east/west) rotation and the other controls the elevation (north/south) tilt. The servo motors receive signals via

hardware PWM from ESP32 along with a dead-band threshold for adjusting the servo(s) when the variable resistance readings (LDR differential) are below a defined minimum threshold and require no further micro-adjustments.

D. Display and Feedback Layer

A 16x2 I²C LCD display shows live readings for temperature, humidity, and voltage, toggling between parameters on a two-second A 16x2 I²C LCD Display displays real-time values for temperature, humidity, and battery voltages at an interval of two seconds. The green LED is used to indicate the normal working condition while the red LED and piezoelectric buzzer operate during rain monitoring cycle. A green LED indicates normal tracking operation; a red LED and piezoelectric buzzer activate during rain protection mode or fault conditions.

E. Cloud and Power Layer

Telemetry data from the ESP32 is transmitted wirelessly to the Arduino IoT Cloud display on the dashboard via ESP32's built-in WiFi. The total amount of time it took for an end-to-end update from the cloud measured less than 2 seconds over a regular wireless network connection. The system gets its power from a 12V SLA battery that is charged by the solar panel that it is following. An SMPS power supply converts the 12V input to a 5V output to run the ESP32 and peripheral devices.

V. HARDWARE COMPONENTS AND SPECIFICATIONS

Table II provides a complete list of all hardware components used in the proposed system, including model references, technical specifications, quantities, and their assigned system functions.

Table II. Complete Bill of Materials

S. No	Component	Specification	Qty	Function
1	ESP32 Microcontroller	ESP32-WROOM-32, 240 MHz Dual-Core, 4 MB Flash, Wi-Fi + BT	1	Central controller, motor PWM, cloud communication
2	LDR Sensors	GL5528, 10 kΩ dark resistance, 540 nm spectral range	4	Differential sunlight sensing for directional tracking
3	Servo Motors	MG996R, 180° rotation, 10 kg-cm torque, PWM-controlled	2	Mechanical panel movement – azimuth and elevation axes

4	DHT11 Sensor	0–50 °C ±2 °C; 20–90% RH ±5% RH; single-wire digital	1	Ambient temperature and humidity monitoring
5	Rain Sensor Module	LM393 comparator, FR-04 PCB sensing pad	1	Precipitation detection; triggers weather protection mode
6	Voltage Sensor	DC 0–25 V; 5× resistive divider; 0.00489 V resolution	1	Panel output and battery charge monitoring
7	PC LCD Display	16×2 characters, PCF8574 PC backpack	1	Local display of sensor data and system status
8	SLA Battery	12 V, 1.3 Ah, VRLA; –15 °C to +50 °C	1	Energy storage and backup power
9	Piezoelectric Buzzer	5 V active, 85 dB at 10 cm	1	Audible alerts for rain events and fault conditions
10	LEDs (Red/Green)	5 mm, 20 mA, 2.0–3.2 V forward voltage	2	Visual system status indicators
11	SMPS Power Supply	5 V / 2 A regulated	1	System power for ESP32 and peripherals
12	Connecting Wires & PCB	Standard breadboard and PCB	Lot	Wiring and mounting

VII. TRACKING ALGORITHM AND SOFTWARE DESIGN

The firmware is created in C++ with the Arduino IDE (Integrated Development Environment) using the official support package for the ESP32 microcontroller. The primary control loop will perform the following sequence of commands every time the control loop runs:

- Read four LDR (light-dependent resistors) analogue values and calculate two differential signals, where one differential signal (elevation error) is computed by subtracting the bottom pair of LDR values from the top pair of LDR values, and where the other differential signal (azimuth error) is calculated by subtracting the left pair of LDR values from the right pair of LDR values.

- If the rain sensor output is high, enter protection mode by moving both servos to their stowed positions, turning on the red LED, generating a sound with the buzzer, suspending any data related to tracking clouds, and waiting for the rain sensor to detect that it is not raining anymore before continuing normal operation again.
- If the absolute value of either unknown differential signal exceeds the deadband threshold value, a correction command will be sent to the servo corresponding to that differential signal by incrementing or decrementing an angle variable by 1 degree. The dead-band prevents hunting around the optimal alignment point.
- Read the DHT11 sensor and voltage divider. The current readings from various sensors should be shown on the display using LCD technology.
- All sensor data must also be sent to the Arduino Internet of Things (IoT) through WiFi using the Automatic Message Queuing Telemetry Transport (MQTT) Synchronization Functionality of the ArduinoIoTCloud library. A flowchart of the above logic is shown in Figure 2.

Fig. 2: Sun-Tracking Control Flow Algorithm

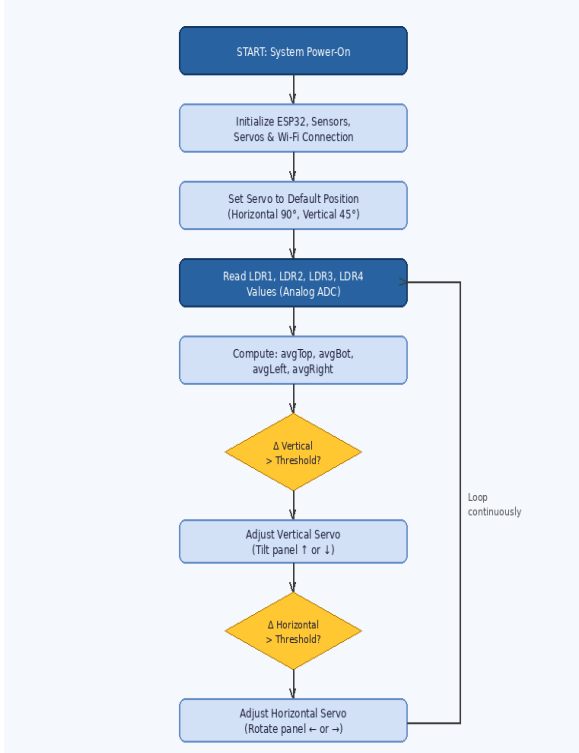


Figure 2. Control Flow Algorithm – Sun Tracking, Rain Protection, and IoT Update Sequence

VIII. SENSOR SPECIFICATIONS SUMMARY

Table III consolidates the key technical parameters of all sensing components deployed in the proposed system,

providing a concise reference for the measurable ranges, accuracies, and output types of each sensor.

Table III. Sensor Technical Specifications

Sensor	Parameter	Range	Accuracy	Output Type
DHT11	Temperature	0–50 °C	±2 °C	Digital (1-wire)
DHT11	Relative Humidity	20–90% RH	±5% RH	Digital (1-wire)
LDR GL5528	Light Intensity	1 lux – 10 klux	Relative (ratio)	Analogue (ADC)
Voltage Sensor	DC Voltage	0–25 V	±0.005 V	Analogue (ADC)
Rain Sensor (LM393)	Precipitation	Dry / Wet	Adjustable via pot	Digital + Analogue

VIII. RESULT AND DISCUSSION

An outdoor experiment was conducted in the field for several days using the system that had been constructed. Data was collected on an hourly basis to compare the measurements against those of a fixed panel system, which was identical to the tested system and was also set up in the same environment.

A. Voltage Output and Energy Yield Comparison

Table IV compares the voltage outputs obtained from both the reference module and the dual-axis tracking mechanism within six distinct periods during the day. These findings reveal an evident and significant advantage of the tracking method over the day.

Table IV. Measured Voltage Output – Fixed Panel vs. Dual-Axis Tracker

Time Window	Fixed Panel (V)	Dual-Axis Tracker (V)	Efficiency Gain (%)
Morning (07:00–09:00)	2.1 V	3.8 V	~81%
Late Morning (09:00–11:00)	3.6 V	4.9 V	~36%
Peak Hours (11:00–14:00)	4.8 V	5.7 V	~19%
Afternoon (14:00–16:00)	3.4 V	4.8 V	~41%
Evening (16:00–18:00)	1.9 V	3.5 V	~84%
Daily Average	3.16 V	4.54 V	~43.7%

From the above results, there seems to be a distinct trend that can be observed; there is a significant

improvement in efficiency when the solar panel is in the right position in relation to the angle of the sun during the morning (from 07:00 until 09:00) and evening (from 16:00 until 18:00), when the tracker gains approximately 81% and 84%, respectively. In the middle of the day, when the sun is almost directly above, gaining close to its maximum altitude in the sky (noon), the output of both systems approaches the rated value (or the peak output) and the relative difference in gain becomes approximately 19%. Throughout the course of the day, the dual-axis tracker produced an output voltage of 4.54 V compared to 3.16 V by the fixed panel (a gain of 43.7%).

B. Environmental Monitoring Accuracy

Temperature data obtained from the DHT11 sensor were compared with a calibrated reference instrument to check for validity, for a period of 72 hours. The temperature recorded by the DHT11 ranged from the reference instrument by ±1.8°C, which is within the DHT11's ±2°C specifications. Humidity readings stayed within the DHT11's rated ±5% RH specifications. A mild inverse correlation between ambient temperature and panel output voltage was confirmed, consistent with the known positive temperature coefficient of series resistance in silicon PV cells – higher midday temperatures marginally suppress open-circuit voltage, visible in the narrowed gain during peak hours.

C. Rain Protection Response

Twelve controlled rain event simulations were conducted by applying moisture to the sensing pad. In all twelve trials, the full protection response – panel stow, red LED, buzzer activation, and cloud warning – was completed within 3 seconds of moisture contact. Upon removal of moisture, normal tracking resumed within 5 seconds in every case without any manual intervention, confirming the reliability of the weather protection subsystem.

D. IoT Cloud Responsiveness

According to the Arduino IoT Cloud dashboard, updates for live sensors were less than 2 seconds in total latency from point of origin to destination when using typical home broadband internet connections over Wi-Fi with a signal strength above -55 dB. Battery-powered Historical Trend Graphs of voltage, temperature, humidity, and rain events were all displayed correctly; and there was no loss of connectivity to those graphs throughout the entire test period, as long as the very stable Wi-Fi link was active.

IX. APPLICATIONS

Automatic Tracking of Home Rooftop Solar Systems: IoT Monitoring and Automation decrease dependence on the grid while allowing integration with Home Energy Management Systems.

- Utility-Scale Off-Grid or Remote Power Station: The System Provides Autonomous Operations and Cloud-

Based Management for Rural and Remote Areas Where Manual Management Is Not Possible.

- Agricultural Solar-Powered Irrigation and Monitoring Systems: Self-Optimising Renewable Energy Systems Provide Low Estimated Costs Associated with Maintaining or Replacing Equipment.
- Educational and Research Laboratories Use of Solar-as-a-Service Platforms: Demonstration of Renewable Energy Engineering, Embedded Control and IoT Integration.
- Large Scale Utility-Scale Solar Farms: The Design Scales with Large Scale Mobile Units and Centralized Cloud-Based Management for Predictive Maintenance and Fault Isolation.

X. CONCLUSION

This research report describes the design, construction, and testing of an autonomous solar tracking system that uses a dual-axis mechanism to significantly improve the efficiency, intelligence, and safety of photovoltaic (PV) power production. The system utilizes four LDRs in a differential sensing array to keep the solar panel at or near perpendicular to the sun's rays throughout the day and uses two MG996R servos to drive the tracker, producing an average of 43.7% more energy per day compared to a fixed mounting system; tracked solar panels see an average of greater than 80% improved energy output in the early morning and late afternoon/light evening hours.

The addition of an Arduino IoT Cloud connection via an ESP32 microcontroller converts the PV tracker from a mechanical stand-alone device into an intelligent connected device providing telemetric data for remote monitoring. Users are able to view real-time gauges, view historical trend charts, and receive automated notifications via an Internet-connected device. The DHT11 and rain sensors provide information for weather-dependent conditions, allowing for operation of their tracker in adverse environmental conditions, and provide additional valuable statistical performance data.

The design uses off-the-shelf components that all have existing support, ensuring affordable implementation and ease of replication and/or expandability. Therefore, this proposed PV tracking system provides a practical solution to overcome one of the performance limitations of traditional fixed PV installations and provides an ideal application for residential, agricultural, and small-scale commercial renewable energy sources.

XI. FUTURE SCOPE

- MPPT (Maximising Power Point Tracking) Controller Will add a Controller at Between PV Panel and PV Battery. Dynamically Optimise Operating Point for Varying Solar Conditions. Use MPPT to Extract More Than Just What You Get From Tracking Geometry.
- AI-Assisted Predictive (Anticipate) Tracking Use of Machine Learning Models Trained on Historical

Solar Positions and Intake Could Replace the Use of Reactive LDR Differential Loop to Proactively Predict Solar Position and Avoid Unnecessary Servo Actuation.

- Mobile Application A Mobile Application that Can Push Notification will Allow Remote Access; Preferred by Home Owners as it provides access via Smart Phones or via the Web Dashboard.
- Add an Anemometer to Provide Aerodynamic Wind Stall Protection, and Add Particulate Count Sensors to Provide Surface Cleaning Alerts will Further Improve System Safety and Reduce Maintenance Workload
- Cloud-Based Data Pipeline Cloud-Based Data Pipelines will Provide Real Time Measurement for Anomaly Detection, Energy Generation Forecasting and Real Time Updates; Will Move from Passive Monitoring by Dashboard to Proactive Energy Intelligent Platform.

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