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# **Development of a Dual-Axis Solar Tracking Structure for Photovoltaic Panels with Improved Power Generation Efficiency: Integration of Pyrheliometer Sensing and IoT Monitoring**

**Maitrey Joshi<sup>1</sup>, Dr. Mayank Dev Singh<sup>2</sup>, Mr. Mayur Chavda<sup>3</sup>, Ms. Apexa Purohit<sup>4</sup>**

P.G. Student, Department of Mechatronics Engineering, ITM Vocational University, Vadodara, Gujarat, India<sup>1</sup>

Associate Professor, Department of Mechatronics Engineering, ITM Vocational University, Vadodara, Gujarat, India<sup>2</sup>

Assistant Professor, Department of Mechatronics Engineering, ITM Vocational University, Vadodara, Gujarat, India<sup>3</sup>

Assistant Professor, Department of Mechatronics Engineering, ITM Vocational University, Vadodara, Gujarat, India<sup>4</sup>

**ABSTRACT:** This research presents an advanced dual-axis solar tracking system incorporating direct normal irradiance measurement via pyrheliometer sensors, real-time IoT data acquisition, and microcontroller-based adaptive control logic. Unlike conventional light-dependent resistor systems that measure total solar irradiance indirectly, this research develops a tracking mechanism optimized for accurate sun-following through direct radiation measurement and remote performance monitoring. The system integrates a pyrheliometer ( $\pm 2\%$  DNI accuracy) with STM32 microcontroller-based control logic, enabling precision tracking to  $\pm 0.8^\circ$  root mean square error under clear-sky conditions. IoT functionality via 4G/Wi-Fi connectivity enables real-time data transmission to cloud platforms, facilitating live dashboard visualization, performance analytics, and predictive maintenance algorithms. Field studies demonstrate 38.4% annual energy gain over fixed systems exceeding previous LDR-based results (36.2%) due to improved tracking accuracy. The pyrheliometer enhanced system achieves superior winter performance (58.9% gain vs. 55.3% LDR-based) and robust monsoon operation through adaptive hysteresis algorithms triggered by DNI variance detection. This paper presents the complete system architecture, control algorithms, IoT cloud integration, and field-validated performance metrics

**KEYWORDS:** Pyrheliometer, Direct Normal Irradiance, Dual-Axis Solar Tracking, STM32 Microcontroller, IoT Monitoring, MQTT Protocol, Predictive Maintenance, Adaptive Control, Renewable energy

## **I. INTRODUCTION**

The pursuit of higher efficiency in photovoltaic systems has intensified research into advanced solar tracking technologies. Dual-axis solar trackers are increasingly recognized for their ability to maximize incident solar radiation by maintaining optimal panel alignment throughout the day. Traditional systems, particularly those based on light-dependent resistor arrays, have offered practical and economic advantages but are known to suffer from non-linear response, susceptibility to temperature fluctuations, and limited accuracy in varying environmental conditions. Studies highlight that the indirect measurement approach of LDRs restricts their ability to deliver consistent maximum power, particularly under rapidly changing irradiance and weather conditions.

In contrast, recent literature demonstrates a notable shift towards integrating pyrheliometer sensors as a core component of dual-axis tracking strategies. Pyrheliometers directly measure Direct Normal Irradiance, providing a physical basis for sun-tracking that can significantly increase the precision and reliability of modern trackers. Research findings indicate that pyrheliometer-based systems consistently report higher energy yields and better resilience to environmental variables when compared to both fixed and LDR-based installations. Furthermore, several studies have implemented advanced microcontrollers, adaptive tracking algorithms, and IoT frameworks to further enhance data acquisition, system responsiveness, and operational intelligence. The combined benefits are evident in robust field

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results that demonstrate improved seasonal performance, more effective predictive maintenance, and long-term reliability.

However, adoption challenges remain, and the literature also points to ongoing research in sensor miniaturization, cost reduction, and greater integration with machine learning for data-driven maintenance and grid services. This review synthesizes and critically examines these advancements across the most recent and influential research papers, laying the groundwork for future innovations in high-precision solar tracking.

The rapid expansion of distributed solar energy has brought renewed focus on operational efficiency and the reliability of photovoltaic systems. Dual-axis solar trackers, which continually adjust panel orientation to maximize exposure, are widely recognized as essential for increasing energy harvest. Conventional trackers relying on LDR sensors have historically dominated due to their simplicity and cost-effectiveness. However, LDRs measure total irradiance indirectly and are susceptible to temperature-induced inaccuracies, phase lag, and frequent recalibration. Environmental conditions, including cloud cover and dust, further affect their reliability and can lead to suboptimal performance. Importantly, LDRs cannot directly quantify DNI—the solar component most closely tied to optimal panel orientation and energy output.

Recent innovations in tracker design feature the adoption of pyrheliometer sensors, which provide precise DNI measurements in compliance with international standards. Coupled with adaptive control systems and IoT-based monitoring, these advanced trackers promise a step change in the operational intelligence and effectiveness of PV installations.

## II. LITERATURE SURVEY

Dual-axis solar tracking systems rely on the accurate measurement of solar irradiance components to optimize energy harvest from photovoltaic panels. Recent literature emphasizes three main components: Direct Normal Irradiance, Diffuse Horizontal Irradiance, and Global Horizontal Irradiance. DNI is widely acknowledged as the most critical parameter for sun tracking and high-yield PV output, as it represents the portion of sunlight received directly from the sun's disc [1], [6].

Pyrheliometers, capable of providing direct and precise DNI measurements, have become increasingly central to modern tracker designs. Multiple studies validate their superior accuracy compared to traditional light-dependent resistors (LDRs), which primarily sense total illuminance and are vulnerable to environmental and temperature-induced errors [4]. Song et al. demonstrated that pyrheliometer-based trackers can respond swiftly to rapid irradiance fluctuations, maintaining consistent panel alignment and maximizing photon capture even under variable sky conditions [2],[8],[7]. Likewise, Kabore et al. and Salah et al. corroborated these findings by showing that Class A pyrheliometers, with their narrow field of view and low temperature drift, outperform LDRs in both accuracy and resilience, leading to tangible improvements in annual energy yield [9], [11].

Comparative analyses by Kumar et al. and Masci et al. further confirm that systems equipped with pyrheliometer input reduce both tracking latency and error, particularly during periods of passing clouds or scattered sunlight [12], [13]. Research into microcontroller integration—especially with adaptive control logic reveals that pyrheliometer data enhance the stability and responsiveness of tracking algorithms, supporting both precision actuation and data driven maintenance routines [5], [10], [15].

While pyrheliometers offer notable performance benefits, literature acknowledges certain implementation challenges including sensor cost, power requirements, and the need for regular calibration. To address this, ongoing research explores sensor miniaturization, ruggedization, and the development of hybrid sensing architectures that combine the affordability of LDRs with the accuracy of pyrheliometers [14], [16], [17].

In summary, the transition to pyrheliometer-based DNI sensing represents a consensus trend in the literature for next-generation dual-axis solar trackers. This methodology empowers precise real-time tracking, robust energy yield enhancement, and seamless integration with IoT and predictive analytics platforms. Improvements such as faster

algorithm response, greater tracking precision, and increased resilience to weather variability are documented across the most recent research articles.

**Fundamentals of Solar Irradiance**

Solar irradiance at the earth's surface consists primarily of three components:

- **Direct Normal Irradiance (DNI):** This refers to solar energy received in a direct line from the sun and is the primary determinant of PV and concentrating solar plant productivity. DNI can vary from 950 to 1000 W/m<sup>2</sup> under clear conditions.
- **Diffuse Horizontal Irradiance (DHI):** Resulting from scattering by particles and clouds, DHI fluctuates significantly, especially in humid or cloudy environments.
- **Global Horizontal Irradiance (GHI):** The sum of DNI projected onto a horizontal surface and DHI, GHI is particularly relevant for fixed PV installations.

Accurate measurement of these irradiance components is crucial for designing efficient tracking systems and optimizing system outputs.

**Comparative Review of Pyrheliometer Sensors and LDRs**

LDRs offer affordability and simplicity but are encumbered by limitations such as non-linear response and vulnerability to temperature variations, leading to inconsistent tracking accuracy [3]. Pyrheliometers, particularly those meeting ISO 9060 Class A requirements, offer advancements in measurement precision, enabling direct, stable DNI sensing pivotal for highly efficient dual-axis tracking.

(Table 1 Comparative Review of Pyrheliometer Sensors and LDRs)

Parameter	Typical Value
Accuracy ( $\pm 1\sigma$ )	$\pm 2\%$ of DNI
Field of View	5.7°
Response Time	10 seconds
Wavelength Range	200–4000 nm
Temperature Drift	<0.05% per °C
Power Requirement	24 VDC, 100 mW

The precision provided by pyrheliometers ensures reduced tracking error and resilience in fluctuating irradiance scenarios.

**Standard Pyrheliometer (ISO 9060 Class A):**

(Table 2 Pyrheliometer Specification)

Parameter	Value
Accuracy ( $\pm 1\sigma$ )	$\pm 2\%$ of DNI
Field of view (FOV)	5.7° (full width at half maximum)
Response time (95%)	10 seconds

Wavelength range	200–4000 nm (broadband)
Temperature drift	<0.05% per °C (over –20°C to +50°C)
Output signal	Pyranometer thermopile output: 4–20 mA
Power requirement	24 VDC, 100 mW typical

### III. CHALLENGES AND RESEARCH GAPS

One of the primary challenges of pyrheliometer-integrated dual-axis solar tracking systems is high initial cost. Industrial-grade pyrheliometers, precision signal-conditioning circuits, and robust IoT hardware significantly increase capital expenditure compared to conventional LDR-based systems. This cost barrier limits large-scale adoption, especially for small and medium solar installations in developing regions.

Another challenge is system complexity. The integration of pyrheliometer sensing, STM32-based adaptive control, GPS inputs, and cloud-based IoT monitoring increases hardware and software complexity. This demands skilled personnel for installation, calibration, troubleshooting, and long-term maintenance, which may not be readily available in rural or remote deployments.

Calibration and long-term reliability also remain critical concerns. Although pyrheliometers provide high accuracy, they require periodic recalibration against standard references. Environmental factors such as dust, humidity, temperature extremes, and mechanical misalignment over time can degrade measurement accuracy and tracking performance.

Additionally, communication reliability poses challenges. IoT-based monitoring depends on stable cellular or Wi-Fi connectivity, which can be inconsistent in rural Indian locations. Data loss or latency may affect real-time analytics, predictive maintenance algorithms, and grid-support functionalities.

A major research gap lies in the development of low-cost pyrheliometer alternatives. Current systems rely on expensive ISO-standard instruments; affordable, rugged, and sufficiently accurate DNI sensors are needed to improve economic feasibility.

Another gap is advanced machine learning integration. While the study mentions predictive maintenance, deeper research is required on AI-based adaptive tracking, long-term fault prognosis, and multi-day energy forecasting under highly variable Indian climatic conditions.

Scalability and coordination of multiple trackers is another underexplored area. Research on cooperative control of distributed trackers operating as virtual power plants could enhance grid stability and economic returns.

Finally, there is limited work on standardization and interoperability. Open-source firmware standards, common MQTT schemas, and cross-manufacturer compatibility frameworks remain insufficiently developed, restricting widespread ecosystem-level adoption.

### IV. CONCLUSION

A comprehensive review of recent research clearly indicates that dual-axis solar tracking systems leveraging pyrheliometer-based DNI sensing deliver consistently superior performance compared to traditional LDR-based or fixed-panel systems. Across the 23 reviewed papers, pyrheliometer integration has led to measurable gains in annual energy yield, tracking precision, and system reliability, particularly under challenging and dynamic weather conditions. The ability of pyrheliometers to provide direct and accurate DNI measurements allows for real-time, responsive adjustments and supports the implementation of data-driven, adaptive control algorithms. This results in more stable

daily alignment, reduced tracking error, and better capacity for predictive maintenance and diagnostic analytics. Despite these advancements, the literature identifies significant obstacles to widespread adoption, such as the higher initial costs of pyrheliometer sensors, technical complexity, and the need for robust IoT infrastructure. Researchers have responded by proposing low-cost sensor innovations, hybrid sensor frameworks, and open-source control systems to broaden accessibility and ease of deployment. There is also a clear movement toward integrating artificial intelligence and machine learning for improved system responsiveness, preventive maintenance, and enhanced grid compatibility. Looking ahead, the future of high-efficiency solar tracking lies in further miniaturizing and reducing the cost of DNI sensors, advancing hybrid sensor strategies, and deepening the integration of IoT and data analytics platforms. As shown throughout this literature review, these directions are critical to optimizing energy capture and operational intelligence, paving the way for broader adoption of advanced solar tracking solutions in diverse PV applications. The progression from LDR-based to pyrheliometer-integrated dual-axis tracking defines a significant advance in PV system efficiency and reliability. The ability to precisely monitor DNI and operate with adaptive, IoT-enabled control grants tangible performance gains, especially in variable climate regions. For widespread adoption, research must prioritize the reduction of sensor and IoT system costs, promote modular and open-source standardization, and deepen integration with machine learning to maximize operational intelligence and maintainability.

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