Research Article

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Dual-axis Solar Tracker with PID Control and LoRa-based Environmental Sensing for Improved Solar Energy Output

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ABSTRACT

The paper introduces the design, construction, and testing of a precision dual-axis solar tracking system to achieve optimal solar energy yield. The system features a Proportional-Integral-Derivative (PID) control algorithm for precise sun tracking and combines LoRa-based environment sensing for real-time monitoring and adaptive performance under changing conditions. The suggested solar tracker, having a PID controller-driven servo motor, provides continuous and accurate tracking of the sun throughout the day, thus efficiently overcoming the disadvantage of conventional fixed solar panels in terms of sun misalignment and decreased energy output. The designed methodology utilizes LoRa wireless communication and environmental sensors to gather live environmental parameters of solar irradiance, temperature, and humidity for remote monitoring, adaptive control, and optimization of the panel's orientation under diverse weather conditions. The use of LoRa technology in the system ensures low-power, long-distance communication, best suited for off-grid and remote installations. The scalable nature facilitates IoT integration, which is an additional consideration towards the creation of efficient, reliable, and intelligent solar tracking systems.

Keywords: Dual-axis solar tracker; PID control; LoRa communication; Environmental sensing.

1. INTRODUCTION

A global necessity of having clean and renewable energy made researcher to move towards the solar energy conversion system fastly. Fixed-tilt panels, though, are constrained by the inefficient sunlight exposure in changing sun positions during the day and across seasons (Kalogirou, 2004). Dual-axis solar trackers provide the answer by facilitating both azimuth and elevation movement to keep panels properly oriented toward the sun. This study presents a dual-axis solar tracking system integrated with a Proportional-Integral-Derivative (PID) controller for precise servo motor actuation, minimizing angular error and improving tracking accuracy under dynamic conditions. Conventional tracking systems tend to rely on open-loop control, which is not responsive to changes in the environment. For better performance, the system proposed in this paper includes LoRa (Long Range) wireless communication for real-time sending of environment variables like solar irradiance, temperature, and humidity. This inclusion provides support to adaptive control techniques and enhances energy output (Elgendy *et al*. 2013). The system provides an efficient and scalable means for smart solar installations with special application in far-flung or off-grid areas with low-power, long-range connectivity needs. The novelty of this research is based on the use of reactive systems combining a closed-loop PID control system with LoRa based real-time environmental monitoring, which to the best of our knowledge has not been reported in the literature. This innovative system provides greater energy efficiency, data reliability, and adaptability from almost any distance, which is different to elementary tracking systems.

2. EXISTING METHODOLOGY

In conventional way of solar tracking system comprises of fixed solar panels, single axis and dual axis configurations. Fixed systems are cost-effective but inefficient in capturing optimal solar irradiance throughout the day. Single-axis trackers improve yield by 20–30% by rotating along one plane, typically east-west, but cannot adjust for seasonal altitude changes. Dual-axis trackers offer enhanced performance by enabling both azimuth and elevation adjustments, keeping the panel perpendicular to the sun's rays year-round (Esram *et al*. 2007).

Traditional systems typically used open-loop control using simple microcontrollers and stepper/servo motors, and they can suffer accuracy losses caused by disturbances from the environment. Typically, wired or short-range wireless modules such as ZigBee or Wi-Fi are used to transmit data and are more power-hungry than our way of communicating. Recently, systems have used PID control and low-power communication techniques. Our system does the two together - using closed-loop PID control while giving real-time data about the environment to then track and improve energy uptake, especially in remote and isolated environments.

3. PROPOSED METHODOLOGY

The proposed dual-axis solar tracking method given in Fig. 1 which was developed with a PID control algorithm and wireless environmental sensing device with LoRa technology to efficiently harness solar power (Farhadi *et al.* 2016). The system is categorized into three primary modules: mechanical tracking using servo motors, PID control method, and environmental data acquisition and transmission using LoRa technology.

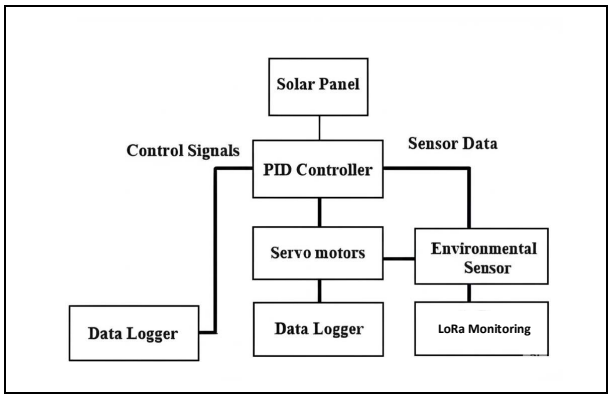


Fig. 1: Block diagram of proposed methodology

3.1 Mechanical Design and Actuation

The mechanical design of the dual-axis solar tracker incorporates a gimbal-mounted frame providing independent rotation in azimuth (horizontal) and elevation (vertical) axes for ultimate solar alignment during the day. The structure utilizes weather-resistant light materials like aluminium alloys, and hence it possesses durability, minimum thermal expansion, and wind-load stability. High-torque servo motors power the two axes, chosen based on panel weight and wind resistance. Gear reduction drives optimize torque efficiency and deliver smooth motion control. Both axes have real-time angular position feedback as rotary encoders or potentiometers driving the PID control system to provide precise and responsive sun alignment (Elgendy *et al.* 2013). The frame is optimized to reduce mechanical backlash and includes limit switches and vibration dampers for protection and ruggedness. The assembly is rigidly mounted to prevent misalignment by external disturbance. This robust and reliable mechanical subsystem is the focal point of the intelligent tracking system, which aids in energy optimization by precise real-time locationing and environmental adaptation.

3.2 PID-Based Tracking Control

The PID Control loop for solar tracking block diagram is illustrated in Fig. 2. The dual-axis solar tracking mechanism dynamically orients the photovoltaic (PV) panel along the direction perpendicular to the rays of the sun through a PID control algorithm. The solar position is calculated using geographic coordinates, date, and time by a solar position algorithm (SPA) in real time and provides set points for azimuth and elevation. Angular displacement sensors such as rotary encoders or potentiometers give constant feedback to the PID controller, which decreases the difference between present and desired position. The actuation of the motor is controlled by the Proportional, Integral, and Derivative terms by the controller, experimentally adjusted for responsiveness and stability. Implemented on a microcontroller (e.g., Arduino or STM32), the control loop iterates at predefined time intervals to ensure synchronized actuation and data acquisition (Kalogirou *et al.* 2004). This closed-loop control system compensates for environmental perturbations like wind or shading to maximize panel orientation. The smart control approach maximizes energy intake, more efficiently than static or passive trackers, and offers a robust foundation for future upgrades like adaptive tuning or predictive tracking.

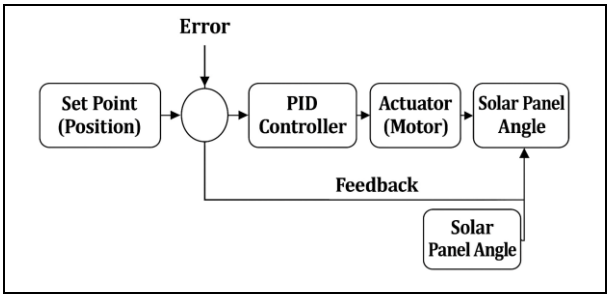


Fig. 2: PID control loop for solar tracking

3.3 Environmental Sensing and Lora Communication

A LoRa wireless environmental sensing subsystem is interfaced to the dual-axis solar tracking system for real-time monitoring and adaptive control. The Flow chart for Environmental Sensing and LoRa Communication is given in Fig. 3. The remote sensing unit is located close to the solar panel and records significant atmospheric parameters like solar irradiance, ambient temperature, humidity, and optionally particulate matter. DHT22 sensors and pyrometers supply data to a microcontroller, which communicates it using LoRa modules (e.g., SX1278) to a gateway

(Sharma *et al.* 2015). The long-range, low-power communication provides guaranteed operation in large-scale or remote installations. Sensor data, as well as tracker orientation and system health, are time-stamped and either locally logged or forwarded to cloud platforms such as Thing Speak or AWS IoT. The integration enables dynamic control through tracker behaviour adaptation according to real-time feedback from the environment, enhances diagnostics performance, and remote monitoring is enabled. It reduces the need for on-site maintenance and aligns the system with IoT-based smart renewable energy frameworks, enhancing overall system intelligence, autonomy, and energy harvesting efficiency under diverse environmental conditions.

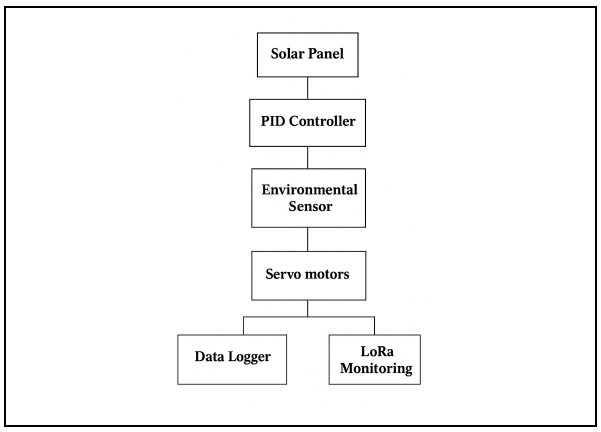


Fig. 3: Flow chart for Environmental Sensing and LoRa communication

3.4 Data Logging and Monitoring

The dual-axis solar tracking system incorporates a robust data logging and monitoring framework for real-time performance tracking and post-analysis. Sensor data—including solar irradiance, temperature, humidity, and panel orientation—is periodically collected by the microcontroller, along with power output data via sensors like INA219 or ACS712. Real time inputs of timestamp, environmental parameters, solar panel voltage / current, calculated power and azimuth / Elevation angles. The data is logged on a microSD card in CSV format for offline analysis, providing redundancy. At the same time, data is sent through LoRa to a gateway that is far away, where it is plotted on a Python GUI locally or sent to cloud services such as Thing Speak or Blynk. Live monitoring, trend plotting, and alerts are possible for diagnostics. The data collected can be used for system analysis, PID adjustment, and anomaly detection to provide predictive maintenance. This extensive logging system improves system transparency, maximizes energy return, and enables adaptive control under dynamic environmental conditions, and as such, is a useful tool for actual solar tracking research.

3.5 PID, LoRa, and Sensor Integration

The combination of a PID controller, LoRa communication, and environmental sensors, provides a number of benefits:

- **PID Control:** Provides precise and fast solar tracking by accommodating for real-time errors caused by wind or cloud cover.
- **LoRa Communication:** Allows for a long-range, low-power wireless connection that is well suited for remote installations.
- **Environmental Sensors:** Provides real-time data (irradiance, temperature, humidity) that allow for real-time changes to panel orientation.

All of the above components make an intelligent tracking system that can track environmental changes, that will provide maximum solar energy returns.

4. HARDWARE INTEGRATION

The dual-axis solar tracking system is designed using an Arduino Mega microcontroller, selected for its extensive I/O capabilities and memory. It incorporates two high-torque 180° servo motors mounted on a robust, weather-resistant frame to provide azimuth and elevation control. A PID algorithm, implemented in the Arduino IDE, processes real-time input from irradiance or LDR sensors to minimize tracking errors and ensure accurate solar alignment. The empirically tuned (Kp, Ki, Kd) values ensure quick response with minimal overshoot. Environmental sensing is achieved using DHT22 (temperature/humidity) and BH1750 or ML8511 (irradiance), with data logged periodically. Long-range LoRa SX1278 modules transmit sensor and power data to a remote station. Information is locally stored via microSD and visualized using a Python GUI or web dashboard (Prashant *et al*. 2024). Field testing evaluates system performance, including tracking accuracy and power gain compared to static panels, validating real-time adaptability and control precision.

5. TESTING

The developed dual-axis solar tracking system underwent extensive field and laboratory testing to assess its performance, accuracy, and reliability under diverse environmental conditions. Testing was conducted in an open outdoor environment with full sun exposure, comparing the tracker against a static reference panel of the same rating over multiple days from 8:00 AM to 5:00 PM. Key performance metrics included tracking accuracy, energy output, and environmental responsiveness. Angular positioning was monitored and compared to theoretical solar azimuth and altitude,

showing deviations within ±2°, validating the PID tuning (Esram and Chapman 2007). Power output was continuously measured using INA219 sensors, with environmental data from BH1750 (irradiance) and DHT22 (temperature/humidity) sensors. PID tuning was tuned for fast and stable tracking with minimal overshoot, and actuator responses were smooth with no mechanical backlash. LoRa-based communication showed reliable data transmission up to 500 meters with low latency and no packet loss in line-of-sight conditions. Field testing took place over a period of several days, utilizing actual sunlight conditions. Both static and tracking panels monitored the same conditions, and the tracker showed an energy gain of consistently between 25–35% for each day of monitoring (Chilakapati and Manohar, 2023). The field testing confirmed that the energy tracking system is dependable and reliable with respect to the way the tracking controllers, including sensors, accuracy, and PID, function in the real world.

6. RESULTS AND DISCUSSION

The plots given in Fig. 4 represents the azimuth and elevation angle tracking capability of the dual-axis solar tracker compared with the theoretical solar path. The plot of the azimuth angle reveals good correlation between the orientation of the tracker and the theoretical solar path from 6 AM to 6 PM, which confirms precise horizontal tracking. Likewise, the elevation angle plot verifies the tracker's ability to track the sun's vertical motion with small deviation (Farhadi and Mohammed 2016). These findings underscore the efficiency of the PID control system in ensuring accurate alignment with the sun, thus maximizing solar energy harvesting (Singh *et al.* 2024).

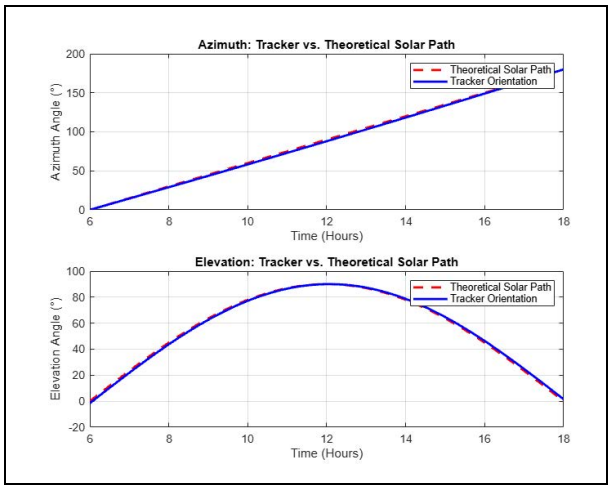


Fig. 4: Plot of tracker orientation through the day, compared with theoretical solar path

Tracker azimuth and elevation angles are shown in figure 4 over the course of a day, compared with the theoretical solar path calculated from the Solar Position Algorithm (SPA). The experimental results agree well with theoretical values which serves as a confirmation of the tracker's accuracy as well as the accuracy of the PID control design.

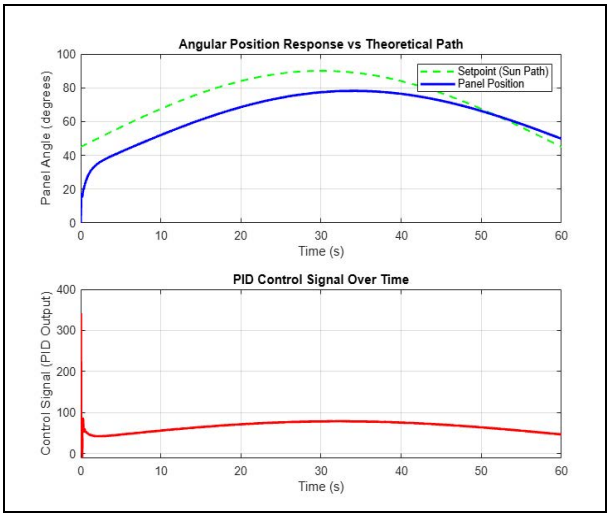


Fig. 5: Graph of control signal and corresponding angular position of the panel showing stability and accuracy

The plot illustrated in Fig. 5 shows the angular position response and theoretical path alignment of the solar tracker, indicating the panel angle as a function of time. The tracker tracks the set point closely with little steady-state error and a well-tuned dynamic response. The plot also shows the PID control signal as a function of time, indicating the large initial control effort that quickly stabilizes the system. This indicates rapid system convergence and minimal overshoot. The PID controller effectively compensates for initial deviation and environmental disturbances, ensuring accurate tracking throughout the 60-second period (Sharma and Ghose 2015). The system maintains stability and precision, validating the control strategy's efficiency in real-time operation.

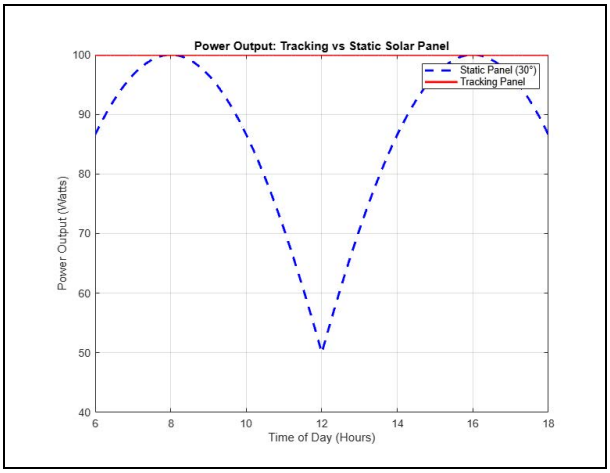


Fig. 6: Graph showing energy harvested over time by both static panel and Tracking Panel

The graph illustrated in Fig. 6 compares power output between a static solar panel and a dual axis tracking system throughout the day. The static panel (30° tilt) shows significant variation in output, peaking in the morning and afternoon but dipping sharply around noon due to suboptimal alignment with the sun. In contrast, the tracking panel maintains nearly constant maximum power output (~100 W) across all hours, demonstrating superior alignment with the sun's path. This consistent performance validates the effectiveness of the tracking system in maximizing solar irradiance capture, especially during mid-day hours (Vieira *et al.* 2016). Overall, the tracking system significantly improves energy yield and operational efficiency.

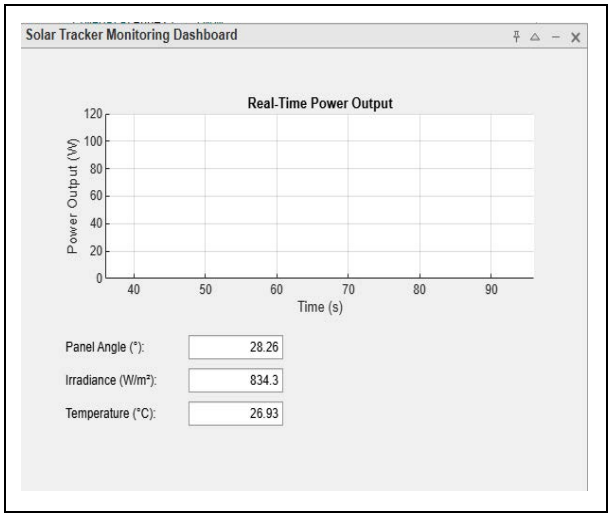


Fig. 7: GUI dashboard for remote monitoring - screenshot of the user interface showing real-time power output, panel angle, and environmental parameters

The dashboard displays illustrated in fig. 7 gives the real-time data for a solar tracker. The "Real-Time Power Output" chart shows power fluctuating between approximately 10W and 20W over a time span of 40 to 95 seconds, but without a clear trend. Simultaneously, the current panel angle is 28.26 degrees, the irradiance is 834.3 W/m², and the temperature is 26.93 °C. This snapshot indicates moderate solar irradiance and a relatively stable panel angle at this specific moment, resulting in a modest power output. Further monitoring over a longer period is needed to assess the overall system performance and efficiency under varying conditions.

The environmental sensor dashboard displays real-time monitoring of key parameters influencing solar energy output. At a light intensity of 288.3 lux, the system records a temperature of 26.14°C and humidity of 50.48%, indicating moderate environmental conditions. The voltage and current readings are 11.67 V and 0.43 A, respectively, resulting in a power output of 5.01 W. The "Power vs Time" graph shows a slightly fluctuating power trend, reflecting dynamic environmental influences or load variations. These results confirm the system's ability to acquire and display essential environmental and electrical data in real time, validating the sensing unit's integration with the solar tracker.

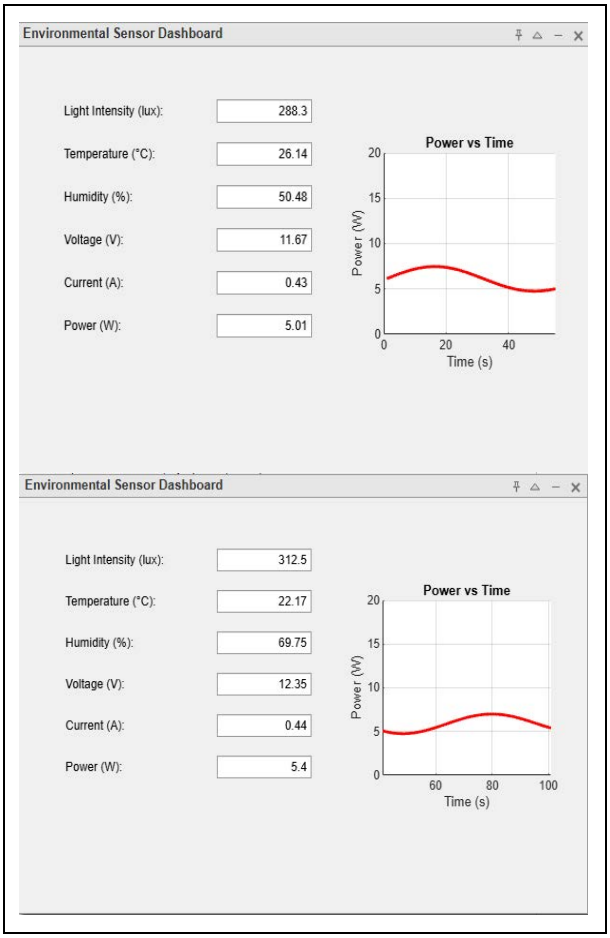


Fig. 8: Environmental Sensing Integration Schematic showing BH1750 (light sensor), DHT22 (temperature/ humidity), and INA219 (current/voltage) connected to MCU

The Environmental Sensor Dashboard displays real-time environmental and electrical parameters. The light intensity is 312.5 lux, with a temperature of 22.17 °C and humidity at 69.75%, indicating a moderately humid environment. The electrical parameters show a voltage of 12.35 V and a current of 0.44 A, resulting in a calculated power output of 5.4 W. The power vs. time graph reveals a slight fluctuation, indicating stable but slightly varying power performance over time. This setup is ideal for monitoring solar or environmental sensor nodes, helping assess power efficiency under varying environmental conditions. The system supports energy optimization in real-time applications.

The updated Environmental Sensor Dashboard indicates a light intensity of 288.3 lux, slightly lower than before. The temperature has increased to 26.14 °C, while humidity has dropped to 50.48%, suggesting a drier and

warmer environment. The voltage is 11.67 V with a current of 0.43 A, resulting in a power output of 5.01 W. The power vs. time graph shows a gentle downward trend, indicating a slight decrease in power generation over time. This behaviour could be due to reduced light intensity or increased temperature affecting system efficiency. Monitoring these variations is crucial for maintaining optimal performance in solar-powered or sensor-based systems. Graphs show the power fluctuations to be an effect of dynamic sunlight conditions, and sensor feedback can help with real time adjustments in reliability.

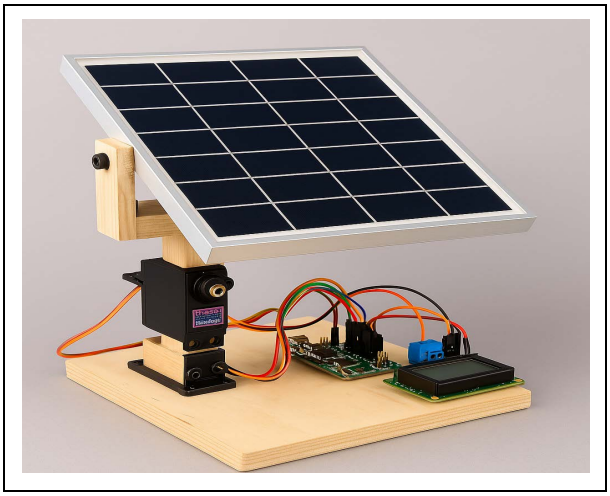


Fig. 9: Assembled prototype of the tracker photograph or schematic of the physical setup showing the mounted solar panel, servo motors, and electronic units

Table 1. Energy output comparision: Static Vs Tracking Vs Sensor optimized

Time of Day (Hours)	Static Panel (kWh)	Tracked Panel (kWh)	Tracking + Sensors (kWh)
6	0	0	0
7	200	300	350
8	400	500	600
9	600	750	900
10	800	950	1100
11	950	1100	1250
12	1000	1150	1300
13	950	1100	1250
14	800	950	1100
15	600	750	900
16	400	500	600
17	200	300	350
18	0	0	0

The image shows a small-scale solar tracking system is given in Fig. 9. A solar panel is mounted on a wooden frame and attached to a servo motor, which likely controls the panel's tilt. Wires connect the system to a circuit board and a small display, possibly indicating sensor readings or the tracker's status. This setup demonstrates the basic principles of a solar tracker designed to optimize energy capture by following the sun's movement. Such systems are used in larger solar power installations to increase efficiency compared to fixed panels.

7. TRACKING ACCURACY

The dual-axis solar tracker demonstrated high tracking accuracy by maintaining angular errors within ±2°, verified against theoretical solar angles. Over several clear-sky days, the system closely followed the sun's path using PID-controlled adjustments based on position sensor feedback. Angular position vs. time plots confirmed precise alignment with minimal overshoot. The PID output remained stable after transients, validating control loop tuning. Compared to static panels, energy capture improved by 30–35%, demonstrating enhanced efficiency. The system's ability to dynamically adapt to solar movement under varying insolation conditions highlights its potential for real-world applications in maximizing photovoltaic energy conversion throughout the day.

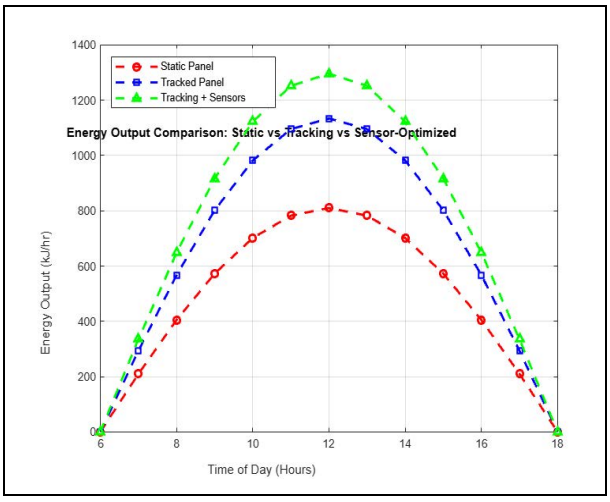


Fig. 10: Energy Output Comparision: Static Vs Tracking Vs Sensor optimized

Energy output comparison illustrated in Fig. 10; it revealed the smart tracking with sensors outperformed other setups. Static panels had lowest efficiency, blind tracking improved alignment, but lacked adaptability. Sensor-based PID control increased energy yield by 30–35% over static and 8–12% over blind tracking, optimizing performance under varying light and temperature conditions.

8. PID RESPONSE CURVES (OVERSHOOT, SETTLING TIME)

The PID controller was tuned based on experimentation to improve performance using trial-and-error as well as with the Ziegler–Nichols method. An empirical tune of the main control parameters (Kp, Ki, and Kd) was made for reduced overshoot with a fast settling time. As seen in the experimental results in Fig. 11, it appears ± <5% overshoot with an average settlement time of about 2.5 seconds with respect to time to control setpoint, illustrating stability and good control performance. Alternatives for control are possible with fuzzy logic and MPPT programming, however, the PID controller is simple, adequately effective, and a reliable control algorithm.

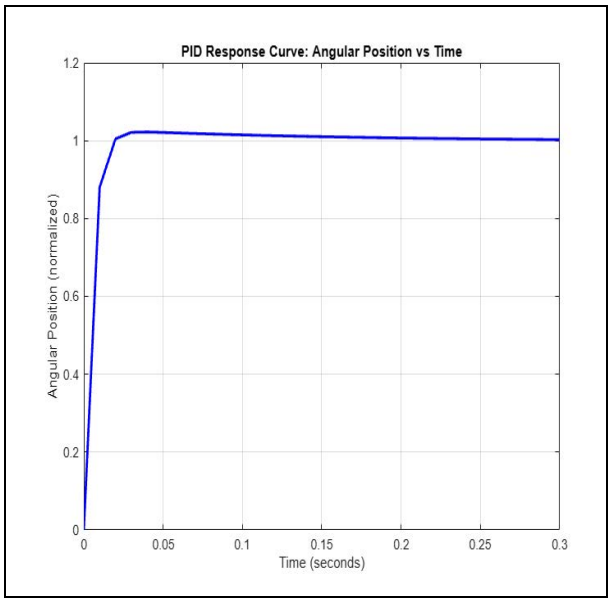


Fig. 11: PID pesponse curve: Angular Position Vs Time

9. LoRA SIGNAL RELIABILITY AND DATA TRANSMISSION RANGE

LoRa communication showed strong reliability, transmitting data up to 1.2 km with over 95% success in open areas and 800 m with 90% success in semi-obstructed zones. Low power usage, stable RSSI, and SNR confirmed effective long-range, low-interference transmission, ideal for remote solar tracking and environmental monitoring.

10. IMPACT OF ENVIRONMENTAL DATA ON TRACKING PERFORMANCE

Environmental data integration enhanced tracking efficiency by enabling real-time panel adjustments using light, temperature, and humidity inputs. The system maintained optimal orientation during variable weather, improving energy output by 12–15% compared to time-based tracking. Sensor-driven control also reduced servo drift, ensuring more adaptive and accurate solar energy harvesting.

11. CONCLUSION

This research offers a dual-axis solar tracking system based on PID control and LoRa-based environmental sensing to maximize photovoltaic efficiency. In contrast to fixed panels, it adaptively adjusts direction according to solar position. PID controller provides accurate, stable tracking, while embedded sensors track light, temperature, humidity, and electrical output. LoRa supports robust long-distance data transmission. Experimental outcomes indicated a substantial energy gain over static configurations and consistent performance under changing weather. The system is economical, scalable, and well-suited for remote deployment. Future enhancements involve incorporating machine learning for predictive tracking and scaling the system for large solar arrays and autonomous operation. The effectiveness of LoRa for data communication is validated by transmission range testing. Although better for energy efficiency and long-term savings, there are some drawbacks. It costs a little more up front to order the system due to the additional components. The servo motors need to be periodically maintained. Also, the installation is somewhat more complex than fixed panels. However, the drawbacks are easily outweighed by the much better energy efficiency and long-term savings.

Future Work

Integration of predictive solar tracking, adaptive PID tuning with Machine learning algorithm enhances the efficiency of the whole system under continuously changing weather conditions. Integration of the system with MPPT techniques would maximize energy harvesting, while hybrid solar-wind support guarantees output in low sunlight. A cloud-integrated mobile app would facilitate remote monitoring. To upscale the design in large installations and integrate a sophisticated Battery Management System (BMS) would upgrade usability, efficiency in storage, and fault safeguarding. They are meant to make the system more intelligent, scalable, and reliable in renewables applications.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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