

IOT BASED DUAL AXIS SOLAR TRACKING SYSTEM WITH WEATHER MONITORING USING RASPBERRY PI PICO.

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Abstract

The efficiency of solar power generation significantly depends on the orientation of solar panels and the intensity of sunlight. This project proposes an IoT-based Dual Axis Solar Tracking System that dynamically adjusts the position of solar panels based on real-time sunlight intensity detection and time-based solar irradiance models. The system is built using Raspberry Pi pico, which processes sunlight data from BH1750 light sensors and adjusts the panel's orientation using servo motors to maximize energy absorption. Additionally, the system incorporates time-based solar irradiance models to optimize panel movement when real-time data is unavailable. Weather parameters such as temperature, humidity, and atmospheric pressure are also monitored using IoT-enabled sensors. The collected data is transmitted to a cloud platform for remote monitoring and analysis. By integrating real-time light intensity detection with predictive solar models, the system enhances energy harvesting efficiency, outperforming static and single-axis tracking systems. This smart, autonomous, and IoT-driven solar tracking solution is ideal for renewable energy applications in both residential and industrial environments.

Keywords: IoT-based Solar Tracking, Raspberry Pi Pico, Solar Panel Orientation Optimization, Solar Irradiance Modeling, Remote Monitoring and Cloud Analytics, Smart Solar Energy System

I. INTRODUCTION

The growing global energy demand and the environmental consequences of fossil fuel consumption have accelerated the shift toward renewable energy sources, with solar energy emerging as a leading alternative due to its abundance, sustainability, and low environmental impact. Conventional fixed solar panels, however, are limited in efficiency because they cannot adapt to the sun's changing position throughout the day and across seasons. To address this limitation, solar tracking systems have been developed to dynamically align solar panels with the sun's movement, thereby maximizing solar irradiance capture. Among these, dual-axis solar trackers offer superior performance by adjusting both azimuth and elevation angles, ensuring optimal panel orientation at all times.

Recent advancements in Internet of Things (IoT) technologies, low-cost microcontrollers, and sensor networks have enabled the development of intelligent solar tracking systems. By integrating real-time sunlight detection with predictive solar irradiance models, IoT-enabled trackers can optimize energy harvesting while providing remote monitoring, data-driven decision-making, and adaptive control. This project focuses on designing an affordable, IoT-based dual-axis solar tracking system using a Raspberry Pi Pico, BH1750 light sensors, and servo motors. Additionally, the system monitors environmental parameters such as temperature, humidity, and atmospheric pressure, with all data transmitted to a cloud platform for analysis. By combining real-time sensing and predictive modeling, the proposed system aims to significantly enhance solar energy efficiency, outperforming conventional static and single-axis tracking solutions in both residential and industrial applications.

II. Literature Review and Related Works

Solar energy is one of the most abundant renewable resources, but its efficiency depends heavily on panel orientation, environmental conditions, and shading. Conventional fixed photovoltaic (PV) systems cannot track the sun, limiting energy conversion throughout the

day and seasons. To address this, solar tracking systems have been developed, classified as single-axis and dual-axis trackers. Single-axis trackers follow the sun in either east–west or north–south directions, providing modest efficiency improvements, while dual-axis trackers adjust both azimuth and elevation angles, achieving up to 30–40% higher energy harvesting than fixed systems. Researchers have implemented sensor-based tracking using light-dependent resistors (LDRs) or BH1750 sensors for real-time sunlight detection, as well as time-based predictive algorithms that calculate the sun’s position using geographical coordinates, date, and time. Comparative studies indicate that systems combining real-time sensing with predictive models outperform traditional trackers, ensuring consistent energy capture under variable weather conditions. Integration of IoT further enhances these systems, enabling remote monitoring, data analytics, fault detection, and adaptive control, improving both operational efficiency and scalability.

Existing solar tracking systems, however, face several limitations. Many rely solely on LDR sensors or microcontroller-based control for unidirectional or single-axis panel movement, which restricts maximum power generation under changing solar angles. Fixed panels, even with Maximum Power Point Tracking (MPPT), only achieve peak output during specific hours, typically around midday, and cannot adapt to early morning, late afternoon, or cloudy conditions. Moreover, while IoT integration has been explored, comprehensive systems combining real-time light sensing, predictive solar models, and environmental monitoring remain limited. The proposed project addresses these gaps by developing an IoT-enabled dual-axis solar tracking system using BH1750 sensors, time-based irradiance models, and weather monitoring to optimize panel orientation continuously, thereby enhancing energy efficiency, adaptability, and scalability across various environmental conditions and applications.

III. Solar Energy and Sunlight Characteristics

Solar energy reaching the Earth arrives in two forms: direct beam and diffuse sunlight. The direct beam carries approximately 90% of total solar energy, while the remaining 10% is diffuse light scattered by the atmosphere, which becomes more prominent during cloudy or winter conditions. Maximum energy collection occurs when panels directly face the sun, making direct beam absorption crucial. On cloudy days, the ratio of direct to diffuse light can drop to 60:40, reducing power generation significantly. To address this, solar trackers have been developed that adjust panel orientation based on sunlight intensity, location, and weather conditions, including reflective systems such as heliostats, which use mirrors or lenses to concentrate sunlight onto panels or absorber plates.

3.1 Solar Tracking Systems and MPPT

Heliostat-based trackers operate by reflecting sunlight onto copper plates positioned at optimal angles, transferring absorbed energy either to batteries or the grid. These systems can achieve $\pm 5^\circ$ angular accuracy, capturing nearly 100% of diffuse light and 99.6% of direct beam energy, making them suitable for concentrating PV applications. In contrast, conventional fixed solar panels often rely on Maximum Power Point Tracking (MPPT) to optimize output at a fixed orientation. While MPPT can enhance efficiency by up to 60%, it does not adapt to changing sunlight intensity or direction. Fixed panels oriented toward a single direction may lose up to 75% of available energy during morning or evening hours, highlighting the need for panel movement to track the sun from east to west throughout the day.



Fig1. Reflective mirror based solar trackers (Image source: Wikipedia)



Fig2: Fixed solar panels that are placed with MPPT protocol



Fig3: Single axis solar panels tilt source: Mahindra sustain

3.2 Single-Axis and Dual-Axis Trackers

Single-axis trackers allow movement in only one direction, typically east to west, improving energy capture compared to fixed panels but still susceptible to seasonal variations in the sun's path. Seasonal changes in solar altitude can lead to additional energy losses—up to 40% at high-latitude vertical trackers during summer or 33% at horizontal trackers in

winter. Dual-axis trackers address these losses by adjusting both azimuth and elevation angles, compensating for daily and seasonal variations. Although the improvement over single-axis trackers is relatively modest (around 4% in total annual energy gain), dual-axis systems offer flexibility for diverse applications and locations. Proper angular alignment is critical, as misalignment even by a few degrees can lead to significant power loss, as shown in Table 1, emphasizing the importance of precise tracking mechanisms for optimal energy harvesting.

Table1: Angle of variation and % of power loss

Direct power lost (%) due to misalignment (angle i) where $\text{Lost} = 1 - \cos(i)$				
i	Lost	i	hours	Lost
0°	0%	15°	1	3.4%
1°	0.015%	30°	2	13.4%
3°	0.14%	45°	3	30%
8°	1%	60°	4	>50%
23.4°	8.3%	75°	5	>75%

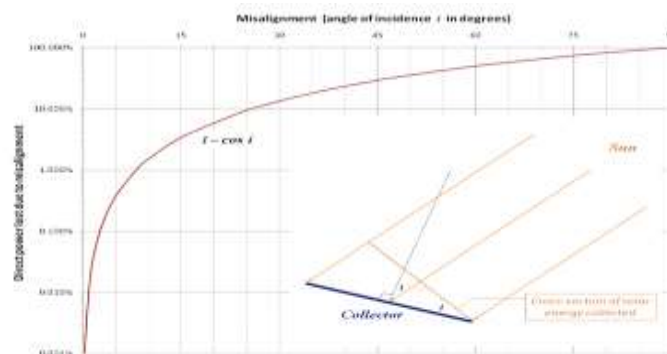


Fig4: Direct power lost due to Misalignment of angle

IV. SYSTEM DESIGN AND IMPLEMENTATION

The proposed IoT-based dual-axis solar tracking system consists of both hardware and software components that work together to optimize solar energy absorption. The system works with a Raspberry Pi microcontroller, which processes real-time sunlight intensity data and controls the movement of solar panels accordingly. The integration of IoT ensures remote monitoring and control capabilities.

The proposed IoT-based dual-axis solar tracking system is designed to maximize solar energy absorption by intelligently adjusting the orientation of photovoltaic panels. The system integrates both hardware and software components, which function in coordination to achieve real-time solar tracking, environmental monitoring, and remote data accessibility.

At the core of the system lies the Raspberry Pi Pico microcontroller, which acts as the main processing and decision-making unit. It continuously processes real-time sunlight intensity data obtained from BH1750 digital light sensors. Based on this information, the controller calculates the optimal azimuth and elevation angles for the solar panels and

transmits Pulse Width Modulation (PWM) signals to servo motors, ensuring precise mechanical alignment with the Sun's position.

To enhance reliability, the system also integrates time-based solar irradiance models. These predictive models allow the tracker to estimate the Sun's trajectory even during cloudy conditions, low-light scenarios, or sensor malfunctions, thereby ensuring uninterrupted operation.

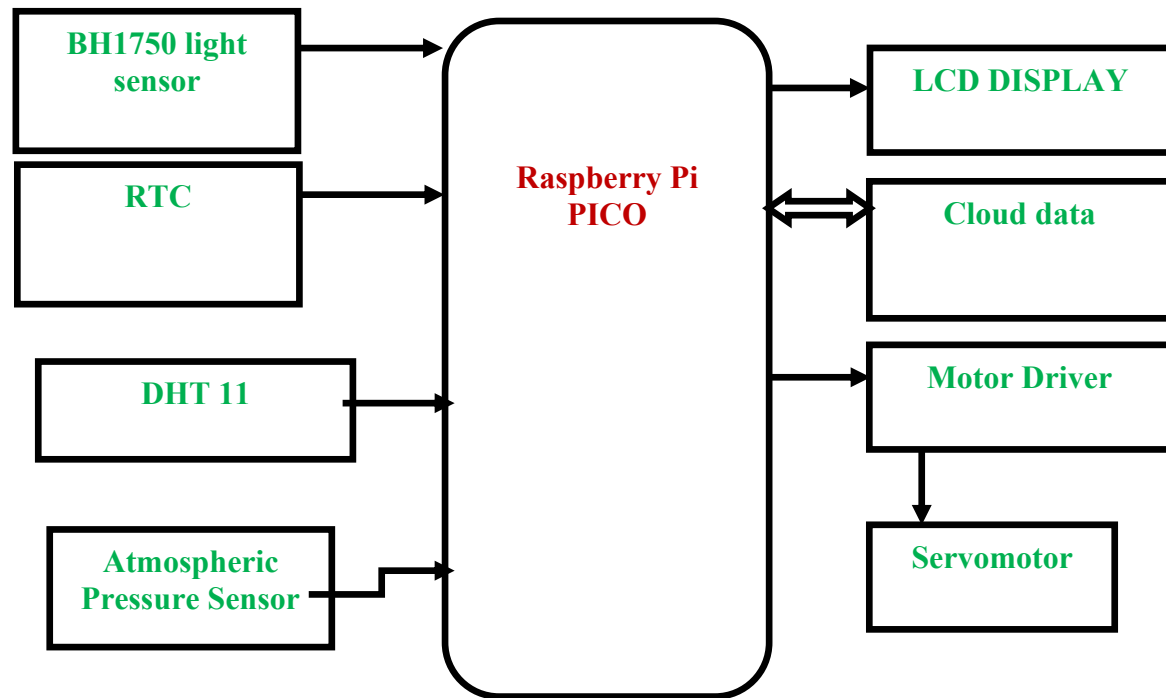


Fig 5 Block Diagram of Proposed System

In addition to sunlight tracking, the system incorporates IoT-enabled environmental sensors that measure parameters such as temperature, humidity, and atmospheric pressure. These values are crucial for analyzing the effect of weather conditions on solar panel efficiency and for ensuring long-term system sustainability.

The collected data is transmitted via an IoT platform ThingSpeak, enabling remote monitoring, visualization, and control through web dashboards or mobile applications. Users can observe real-time performance, receive notifications, and analyze historical trends to evaluate system efficiency.

By combining sensor-based real-time detection with predictive solar models and IoT-driven monitoring, the proposed system offers significant improvements in energy harvesting compared to static or single-axis trackers. It provides a scalable, cost-effective, and autonomous solution suitable for both residential and industrial renewable energy applications.

The proposed IoT-based dual-axis solar tracking system is designed to maximize solar energy harvesting by intelligently aligning the solar panels with the Sun's position throughout the day. The system combines real-time sunlight detection, predictive solar modeling, and IoT-enabled environmental monitoring, providing both high efficiency and remote accessibility.

4.1 Methodology for System Design

The step by step implementation and execution of the implemented work is depicted below.

Step1: Initialize the hardware as per requirement and program the microcontroller as per our needs to get the input parameters from various sources and process as per output requirements.

Step2: Initialize Wi-Fi for the purpose of IoT establishment and date and time using RTC for accurate timings.

Step3: Update time values on LCD display on every consecutive time and send time, date and position values to the server using IoT.

Step3: Server used to calculate azimuth angle and altitude of the sun on that day and time for that position and transfer the same values to the device that is placed at solar panels.

Step 4: Tilt the solar panels according to the angles provided by the server using actuators that are placed for both north to south and east to west.

Step5: Calculate wind speed, direction regularly and made an arrangement to rotate the panels according to speed and direction to avoid damage.

Step6: Tilt the solar panels to east before sunrise every day.

4.2 Solar Position Algorithm

As there is much advancement in technology position calculation of the solar panel will be made easy. Even though we have technology there is always smaller uncertainty in solar position with an error calculation of ± 0.01 which will be very less in comparison with gain that we are getting in terms of power. Many people were already done the work for calculations. Those calculations will be useful over the years up to 2050. For calculating solar position we use pyranometers.

The angle between the center of the sun and zenith is named as zenith angle. The elevation angle is the altitude of the sun. It is the angle between the center of the sun and the horizontal axis.

Since these two angles are opposite to each other. They can both be calculated with the same formula, using results from spherical trigonometry [11].

Solar angles mainly depend on the location (latitude and longitude) and time. Thus, we were calculating the solar angles. The hour angle (h) is defined as the longitude of the sun, which is calculated as:

$$h = -(t - 12) / 12$$

where t is the fractional GMT time (e.g., for hh:mm:ss then $t = hh + mm/60. + ss/3600.$)

Solar zenith angle (θ_s) is calculated as:

$$\cos\theta_s = \sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos h$$

θ_s solar zenith angle

α = solar elevation angle or

solar altitude angle $\alpha = 90^\circ - \theta_s$

h is hour angle with

GMT + 5:30(Indian Time)

δ is the current declination of the sun

ϕ latitude

4.3 Hardware Implementation

Implementation of this work divided into 2 units. One is the weather monitoring system and the second one is a solar tracking system. The weather monitoring system will be placed as a single unit for the entire plant over a single location. Because of environment, temperature, and humidity is the same at the location for all panels. Solar trackers were placed for individually at each and every individual unit in the plant. Weather monitoring system mainly connected with pico microcontroller. Here in this, we were used hardware components like wind sensor to calculate wind speed and direction, DHT11 temperature sensor to calculate the temperature and humidity in the air. These sensors are used for solar tracking purpose. DS1307 RTC was used to store the time and

date values in the controller. The Calculated data will be printed on LCD regularly. Solar plants are located in various places we are unable to collect the data from those positions every time. In this aspect, we were designed system which could send the information to server using ESP8266 wifi module in access point mode connectivity to the controller. Here am using a free server thingspeak to update the values. It will work on the API keys for reading and write operations individually.

Hardware was configured with raspberry pi pico. RTC DS1307 which used to update time and date that was taken by using RTC to get accurate. If any change in time then it will be updated to original and display date and time on LCD. The same can be passed to the server using Wi-Fi.

Based on date and time values the server will calculate the azimuth and elevation angles of the sun. According to azimuth and elevation angles the solar panels moves into the angles measured. Here we were used servo motors as shown in figure mentioned below. We were used relays to operate the servo motors in both clockwise and anticlockwise direction as per the requirement.



Figure 6: panel used for movement



Figure 7: Actuator used for tilting the solar panel from north to south. RTC



Figure 8. model display of Values on LCD for both azimuth and elevation angles with date and time.



Fig9. Model Dual axis solar panel on single pole.

V. Results:

Experimental Analysis was done with respect to theoretical and practical positional variation. Considered 24V solar panel and measured voltage values at various intervals of time and date at fixed position of solar panel in south facing.

Sl.No	Date	Time	Voltage
1	11 th August	12:20PM	14.30
2	11 th August	13:45PM	2.59

Considered 24V solar panel and measured voltage values at various intervals of time and date with variable position of solar panel from east to west.

Sl.No	Date	Time	Voltage
1	11 th August	12:20PM	14.30
2	11 th August	13:45PM	2.59

Conclusion

Development of IoT-based dual-axis solar tracking system dynamically adjusts solar panel orientation to maximize energy absorption. The integration of real-time sunlight intensity detection and predictive solar irradiance models significantly improved efficiency compared to static and single-axis systems. Additionally, the inclusion of weather monitoring sensors provided valuable insights into environmental conditions affecting solar panel performance.

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