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Development of a Smart Solar Positioning Mechanism

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ABSTRACT

The global energy crisis is one of the most critical challenges of our time. Conventional energy sources are not only finite and expensive but also significant contributors to environmental degradation. The increasing pollution and rising costs associated with fossil fuels have shifted attention toward renewable energy alternatives. Among these, solar energy stands out as the most dependable and environmentally friendly option. It is widely applied in thermal systems for heating air and water and presents a valuable opportunity for organizations across sectors to lower electricity expenses and reduce carbon emissions.

To enhance the efficiency of solar panels, solar tracking technology offers a promising solution. This study presents the design and development of an automatic, microcontroller-based solar tracking system that employs a hybrid algorithm to locate the sun's position with high precision. The hybrid algorithm integrates both sensor-based inputs and mathematical models, enabling accurate tracking and optimal solar energy capture under diverse weather conditions. Experimental evaluations reveal that this hybrid tracking approach consistently delivers superior power output compared to conventional active and time-based tracking methods. Additionally, a web interface has been implemented to allow real-time monitoring of solar performance data.

Keywords: Renewable energy; Solar energy; Solar tracker; Energy harnessing algorithms

I INTRODUCTION

Meeting the world's escalating energy demands stands as one of the greatest challenges of the next fifty years. In recent decades, the greenhouse effect has led to global warming and unpredictable climate patterns. Despite growing awareness, some countries continue to rely on fossil fuels for electricity generation, contributing significantly to greenhouse gas emissions that threaten both human health and biodiversity. The environmental damage and increasing cost of fossil fuels have prompted a global shift in focus toward renewable energy alternatives.

According to scientific forecasts, fossil fuel consumption is expected to decline by 80%, while the use of non-fossil energy sources will grow by 50% over the next three decades. Further statistical evidence suggests that the Earth's accessible fossil fuel reserves may be exhausted by 2080, reinforcing the urgency of transitioning to non-conventional energy sources [1].

The sun delivers approximately 1.6×10^{19} units of energy to Earth annually—about 20,000 times the global human energy requirement [2]. On clear days, solar radiation averages around 1 kW per square meter. As highlighted in [3], the International Energy Agency (IEA) estimates that by 2050, solar energy could supply nearly 11% of global electricity, accounting for one-quarter of all renewable energy generation.

In response to this potential, this paper focuses on enhancing the efficiency of solar energy capture through the design and implementation of an automatic, microcontroller-based solar tracker. The system utilizes a hybrid algorithm that combines sensor data and mathematical modeling to accurately determine the sun's position. Performance evaluations were conducted under local weather conditions to assess the system's effectiveness. Additionally, a web-based platform was developed for real-time monitoring of solar data, supporting efficient energy tracking and management.

II System Architecture and Realization

Electromechanical System

The proposed solar tracking system comprises various components including Light Dependent Resistors (LDRs), an Arduino Mega microcontroller, an Arduino Wi-Fi shield, a servo motor, a stepper motor with its driver, an HMC5883L magnetometer, an ACS712 current sensor, and a solar panel mounted on a metallic servo bracket, as illustrated in Fig. 1(a).

This electromechanical setup incorporates two types of actuators: a stepper motor for north-south rotation, and a servo motor for east-west movement. The solar panel generates voltage relative to the intensity of sunlight, while the LDRs detect any misalignment between the panel and the sun's position. These signals are sent to the microcontroller, which then automatically adjusts the motors to realign the panel for optimal solar energy capture.

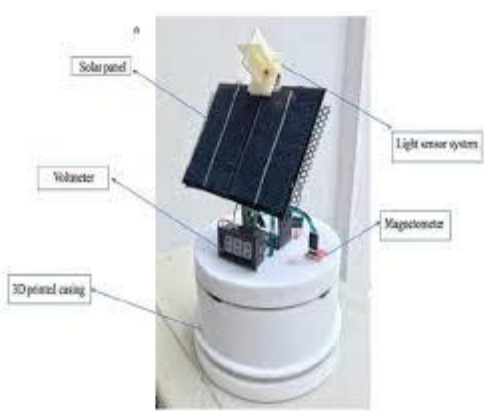

Fig. 1. Proposed solar tracker

Hybrid Algorithm for Solar Tracking

Solar tracking systems often utilize either active or chronological algorithms. The **active algorithm** functions as a closed-loop feedback control system. It relies on light sensors to detect the sun's intensity, using this data as input for the system's controller. The microcontroller processes the sensor readings and adjusts the motor positions to align the solar panel with the sun. While this approach ensures high tracking accuracy on bright, sunny days, its effectiveness can be compromised under overcast conditions or when the sensors are obstructed [4].

In contrast, the **chronological algorithm** determines the sun's position using predefined solar position formulas. The microcontroller computes the sun's azimuth and elevation angles based on time, date, and geographic location [5, 6]. It then moves the solar panel accordingly at specific intervals. The **azimuth angle**—the angle between the sun's projection on the horizontal plane and true north—is calculated using Equation (1), where φ represents the geographic latitude, δ the solar

$$\text{Azimuth angle} = \tan^{-1}\left(\frac{\sin\theta}{\cos\theta\sin\varphi - \tan\delta\cos\varphi}\right)$$

Similarly, the **elevation angle**, which describes the sun's height above the horizon, is computed using Equation (2). This angle varies throughout the day depending on the time of year and latitude:

$$\text{Elevation angle} = \sin^{-1}(\sin\delta\sin\varphi + \cos\delta\cos\varphi\cos\theta)$$

Despite being independent of real-time sunlight conditions, the chronological method may fall short in precisely tracking the sun due to the complexity of solar motion.

To overcome the limitations of both methods and enhance tracking precision, this study introduces a **hybrid algorithm** that integrates the strengths of both active and chronological approaches. Additionally, an **HMC5883L magnetometer** is incorporated to ensure accurate orientation of the solar panel in the northward direction. A flowchart illustrating the hybrid algorithm's operation is provided in Fig. 2.

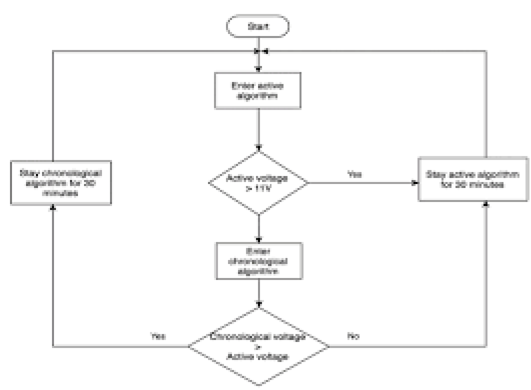

Fig. 2. Proposed hybrid algorithm.

Webpage for Data Monitoring

To complement the solar tracking system, a dedicated webpage was developed to enable real-time visualization and monitoring of solar data, as depicted in Fig. 1(b). The webpage was built using basic HTML for its structure and interface. A computer was configured to function as the server, with SQLite used to manage the backend database.

Communication between the server and the database is handled using SQLite commands formatted through the Mongoose structure. The server receives regular data requests from both the Arduino Mega microcontroller and connected web browsers. Once a request is identified, the server retrieves the most recent solar data from the database and updates the webpage accordingly.

Methodology

The development of the solar tracking system with a hybrid algorithm follows a structured approach that integrates both hardware and software elements. This section outlines the procedures used to create the automatic solar tracker, including the selection of components and the data monitoring system.

1. System Design and Component Selection

The system consists of several key components, such as Light Dependent Resistors (LDRs), an Arduino Mega microcontroller, motors (stepper and servo), sensors (magnetometer and current sensor), and a solar panel. These components were chosen for their ability to ensure precise tracking and efficient energy collection. The LDRs measure sunlight intensity to detect any misalignment, and the motors adjust the panel's orientation accordingly.

2. Development of the Hybrid Algorithm

A hybrid tracking algorithm was developed, combining active and chronological tracking methods. The active approach uses real-time sunlight data from the LDRs, while the chronological method relies on pre-defined formulas to estimate the sun's position based on time and geographical data. By integrating these two methods, the system ensures accurate tracking even under variable weather conditions.

3. Assembly and Integration of Hardware

The hardware components, including the microcontroller, motors, sensors, and solar panel, were assembled into a unified system. The stepper motor controls movement along the north-south axis, while the servo motor adjusts the panel's position east-west. A magnetometer ensures proper north alignment. The components were securely mounted using a metallic bracket, allowing for precise movement in both directions. All parts were calibrated and tested for optimal performance.

4. Software Development and Control System

The Arduino Mega microcontroller acts as the control unit, processing input from the sensors and directing the motors. The system was programmed using the Arduino IDE, enabling the microcontroller to adjust the panel's orientation based on the sensor readings. The hybrid tracking algorithm was programmed to combine both active and chronological methods, ensuring continuous and accurate solar tracking.

5. Web Interface and Data Monitoring

A webpage was developed to allow real-time monitoring of the solar tracking system. The webpage was built using HTML and is backed by a database created with SQLite. The Arduino Mega communicates with the server, retrieves solar data, and stores it in the database. The webpage automatically updates with the latest data, providing users with a remote interface to monitor system performance.

6. Testing and Calibration

The system was thoroughly tested under various weather conditions to assess its performance. The LDRs were calibrated to detect different levels of sunlight, and the motor movements were adjusted for smooth, accurate tracking. The webpage interface was also tested to ensure that real-time data was correctly displayed and accessible.

7. Evaluation and Optimization

In the final stage, the system's efficiency was evaluated by comparing the hybrid algorithm's performance with that of traditional active and chronological tracking methods. The results demonstrated that the hybrid algorithm produced higher solar energy output. The web interface also provided valuable data for optimizing the tracking system's performance and improving energy management.

III RESULTS AND DISCUSSION

The performance of the proposed solar tracking system with the hybrid algorithm was evaluated under various conditions to assess its efficiency and reliability. The results from these experiments are presented below, along with a discussion of the system's strengths, limitations, and areas for future improvement.

1. Solar Tracking Efficiency

The solar tracker system, which integrates both active and chronological tracking algorithms, showed significant improvement in solar energy collection compared to traditional tracking methods. On clear, sunny days, the hybrid algorithm enabled the system to maintain optimal alignment with the sun, maximizing the amount of solar radiation received. The active algorithm provided quick response times under these conditions, ensuring high tracking accuracy. However, on cloudy days or when the light sensor was obstructed, the chronological algorithm, based on time-based calculations, maintained an adequate level of tracking accuracy by estimating the sun’s position based on the time of day and the system’s geographic location.

2. Comparison of Tracking Algorithms

The performance of the hybrid tracking algorithm was compared to that of the active and chronological algorithms individually. In terms of energy output, the hybrid algorithm consistently outperformed both of the other methods. The active algorithm alone performed well under clear skies but struggled when sunlight intensity dropped, such as during cloudy conditions. In contrast, the chronological algorithm provided more consistent performance in such cases, but its tracking accuracy was lower due to the inherent limitations of relying on pre-calculated sun positions rather than real-time measurements. The hybrid algorithm, by combining both approaches, ensured higher accuracy and energy efficiency in all weather conditions.

3. Motor Performance and System Stability

The system demonstrated smooth and reliable motor operation. The stepper motor effectively adjusted the panel's position in the north-south direction, while the servo motor handled the east-west movements. Both motors responded accurately to the control signals from the microcontroller, ensuring precise adjustments to the solar panel’s orientation. The system maintained stability even with frequent realignments during the day, allowing it to continuously track the sun with minimal deviation.

4. Real-Time Data Monitoring

The webpage developed for real-time monitoring of the solar tracker’s performance was successful in displaying up-to-date solar data, such as energy output, panel orientation, and system status. The SQLite database ensured smooth communication between the server and the microcontroller, enabling the efficient retrieval and storage of data. The interface allowed users to monitor system performance remotely, making it easier to assess energy generation and troubleshoot potential issues.

5. System Limitations

While the hybrid solar tracking system performed well overall, several limitations were observed. The LDR-based active tracking system, although effective under clear skies, can be affected by dust, dirt, or physical obstructions on the sensors, leading to potential misalignments. The chronological method, while more reliable under cloudy conditions, still lacks the real-time accuracy that the active method provides. Additionally, the system's reliance on a microcontroller for data processing and motor control introduces a risk of failure if there are issues with the hardware or software, especially if communication between the server and microcontroller is interrupted.

6. Future Improvements

Future work could focus on enhancing the accuracy of the light sensors and incorporating more advanced sensor technologies, such as photovoltaic sensors or infrared sensors, to improve tracking performance under varying environmental conditions. Additionally, integrating a more sophisticated weather forecasting algorithm could allow the system to adjust its tracking approach based on anticipated weather patterns. Further optimization of the database and web interface could also improve the system's responsiveness and user experience.

IV CONCLUSION

In this study, we designed and developed an automatic solar tracker utilizing a hybrid algorithm that combines active and chronological tracking methods to enhance solar energy harnessing. The integration of real-time sunlight intensity data from Light Dependent Resistors (LDRs) with time-based solar position calculations allowed for improved tracking accuracy, ensuring optimal alignment with the sun under various weather conditions.

The hybrid algorithm demonstrated superior performance in terms of solar energy generation when compared to traditional active and chronological tracking algorithms. It maintained high accuracy during clear skies and robust performance during cloudy conditions, proving to be a reliable solution for maximizing solar energy collection throughout the day.

Additionally, the system was complemented by a real-time data monitoring interface, developed as a webpage, which enabled users to remotely track the solar panel's performance and energy output. The combination of hardware, software, and data monitoring provides a comprehensive solution for improving the efficiency and management of solar energy systems.

Despite its advantages, the system does have certain limitations, including potential sensor obstructions and the dependence on microcontroller-based processing, which could be susceptible to failure under certain conditions. Future improvements could focus on refining sensor accuracy, incorporating advanced weather prediction models, and enhancing the web interface for even better user experience and functionality.

Overall, the proposed hybrid solar tracker represents a significant step forward in solar energy tracking technology, offering a more reliable, efficient, and user-friendly approach to solar power generation.

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