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Concept Design And Implementation Of A Dual Axis Solar Tracking Device Based On Cloud Computing

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Abstract: The global reliance on fossil fuels has intensified the need for sustainable energy solutions, with solar energy standing out for its abundance and scalability. This study presents the design, development, and evaluation of a dual-axis solar tracking device integrated with cloud computing and Internet of Things (IoT) technologies to optimize energy efficiency. The system comprises a client-side solar tracking unit and a cloud-based server, communicating via GPRS to track the sun using astronomical algorithms. A prototype was constructed and tested in Tianjin, China, achieving a 46.6% increase in energy output compared to a fixed photovoltaic (PV) panel. The IoT framework enables real-time data exchange, centralized control, and scalability, positioning the system as a promising solution for intelligent renewable energy systems.

Index Terms **- Renewable energy; solar tracking; web technology; cloud computing, IoT.**

I. Introduction

The over-dependence on fossil fuels has led to severe environmental challenges, including greenhouse gas emissions, resource depletion, and global warming (Wong et al., 2017). Solar energy, offer a sustainable alternative due to their unlimited availability, scalability, and minimal environmental impact. However, fixed PV systems suffer from reduced efficiency due to the sun's dynamic position, which varies daily and seasonally (Emre et al., 2018). Solar tracking systems address this by aligning PV panels with the sun's trajectory, increasing energy yield by 25–55% compared to fixed systems (Nadia et al., 2018).

Traditional solar trackers rely on sensor-based or algorithm-driven mechanisms, but they face challenges such as reduced accuracy in cloudy conditions, high hardware complexity, or limited scalability (Hyo Geun et al., 2018). The integration of IoT and cloud computing introduces new possibilities for enhancing solar tracking systems through real-time data processing, remote monitoring, and centralized control (Jerin et al., 2018). This study proposes a novel dual-axis solar tracking system that leverages web technology and cloud computing to achieve precise sun tracking via astronomical algorithms and IoT connectivity.

The objectives of this research were to:

1. Design a cost-effective, IoT-based dual-axis solar tracking system using cloud computing.
2. Develop and test a prototype to evaluate its energy harnessing performance under various conditions.
3. Compare the system's efficiency with fixed PV systems and existing solar trackers.
4. Investigate the potential of IoT and cloud computing for scalability, real-time monitoring, and intelligent control.
5. Explore future research directions for optimizing the system for commercial applications.

II. BACKGROUND

2.1. Solar Path and Irradiation

The sun's position relative to a fixed point on Earth changes continuously due to the Earth's rotation (day-night cycle) and its elliptical orbit around the sun (seasonal variations) (Michalsky, 1988). The solar path is defined by two angles: the azimuth angle (horizontal direction relative to north) and the altitude angle (vertical angle above the horizon). These angles vary throughout the day and year, affecting the efficiency of PV systems. Solar irradiation, measured in W/m^2, comprises direct, diffuse, and albedo components, influenced by environmental factors such as cloud cover, ozone, turbidity, and precipitable water vapor (Blanco-Muriel et al., 2001). Direct radiation is most critical for PV efficiency, but diffuse radiation dominates in cloudy conditions, necessitating adaptive tracking strategies.

2.2. Photovoltaic Systems and Efficiency

Photovoltaic systems convert sunlight into electricity using semiconductor materials that exhibit the photoelectric effect (Nadia et al., 2018). The efficiency of a PV cell, defined as the ratio of electrical power output to incident solar power, depends on factors such as solar irradiation, panel orientation, temperature, and material properties. Typical PV efficiencies range from 15–22%, with polycrystalline panels being cost-effective but slightly less efficient than monocrystalline panels (Bahram et al., 2019). The fill factor (FF), a measure of a cell's quality, is calculated as:

$$FF = \frac{I_{MP} V_{MP}}{I_{SC} V_{OC}} \qquad (2.1)$$

where V_{MP} and I_{MP} are the maximum power point voltage and current, and V_{OC} and I_{SC} are the open-circuit voltage and short-circuit current, respectively.

2.3. Solar Tracking Systems

Solar trackers adjust PV panels to maintain perpendicular alignment with solar radiation, maximizing energy capture. They are classified by the number of axes (single-axis or dual-axis) and driving mechanism (active or passive). Single-axis trackers rotate along one axis (e.g., elevation), while dual-axis trackers, such as Azimuth-Altitude Dual-Axis Trackers (AADAT), rotate along two perpendicular axes for greater accuracy (Bahram et al., 2019). Active trackers use motors and algorithms, while passive trackers rely on thermal expansion of fluids (Shin'ya et al., 2019). Hybrid systems combine sensors (e.g., LDRs, photodiodes) and algorithms to enhance performance in varying conditions (Wong et al., 2017).

Solar tracking algorithms calculate the sun's position using real-time light intensity or astronomical data. Astronomical algorithms, such as those proposed by Michalsky (1988) and Jean Meeus (1998), offer high accuracy (0.01–0.00003°) by computing solar angles based on time, location, and date. These algorithms are particularly effective for dual-axis trackers, as they do not rely on local weather conditions.

2.4. IoT and Cloud Computing in Solar Tracking

The Internet of Things (IoT) enables wireless communication between physical devices, facilitating real-time data exchange and control (Jerin et al., 2018). In solar tracking, IoT can transmit location, orientation, and environmental data to a central server for processing, overcoming the limitations of local sensor-based systems (e.g., LDRs failing in cloudy conditions). Cloud computing provides scalable data storage and computational power, enabling centralized algorithm execution, real-time analytics, and software updates without hardware modifications (Hyo Geun et al., 2018). These technologies support the development of intelligent, scalable solar energy systems with applications in remote monitoring, predictive maintenance, and performance optimization.

III. METHODOLOGY

3.1. System Design

The proposed system integrates a client-side solar tracking unit with a cloud-based server, communicating via GPRS to track the sun using astronomical algorithms. The client unit, controlled by an Arduino ATmega2560 microcontroller, includes a polycrystalline PV panel, stepper motors, a SIM808 GSM/GPRS/GPS module, a JY901 inclinometer, and an MPPT charge controller. The server, hosted on an Apache HTTP server with a MySQL database, processes GPS and orientation data to calculate the sun's position and sends feedback to the client for panel adjustment.

3.2. Hardware Design

The tracker adopts an AADAT configuration, with a vertical azimuth axis (180° rotation) for east-west tracking and a horizontal altitude axis (90° rotation) for north-south tracking. The structural frame uses aluminum profiles for rigidity, supported by a base with castor wheels for mobility. A slewing gear and stepper motors drive the axes, with key components including:

- **PV Panel**: A polycrystalline panel with a 36V open-circuit voltage, 30V peak operational voltage, and 200 W rated power.
- **Stepper Motors**: NEMA 57 hybrid synchronous motors with a planetary gearbox, providing high torque (up to 3 Nm) and precise step angles (1.8°).
- **Microcontroller**: Arduino ATmega2560 with 54 digital I/O pins, 16 analog inputs, and a 16 MHz crystal oscillator.
- **Communication Module**: SIM808 module with GPRS and GPS. It enables wireless data exchange with the cloud server.
- **Inclinometer**: JY901 nine-axis sensor measuring 3D acceleration, angular velocity, and attitude angles with 0.01° stability.
- **Power Supply**: Two 12V batteries (24V total), charged by the PV panel via an MPPT charge controller.
- **Motor Driver**: DM542 2-phase stepper motor driver with a 1.0–4.2A current range.

The control unit, housed in a PVC box, integrates two DM542 drivers, a relay, the Arduino board, the SIM808 module, and voltage converters (24V to 5V/3.3V). The antenna for GPS/GPRS communication is mounted externally. The system's design prioritizes modularity and ease of assembly, though wind resistance was not optimized due to its proof-of-concept status.

3.3. Software Architecture

The software is divided into client and server components, designed to ensure seamless communication and precise tracking.

Client Software

The client software, programmed for the Arduino ATmega2560, manages:

- **Data Collection**: GPS coordinates from the SIM808 module (NMEA-0183 format, GGA sentences) and orientation data from the JY901 inclinometer (using the jy901.h library).
- **Communication**: HTTP POST requests to send GPS and gyroscope data to the server and receive positioning feedback. AT commands initialize the SIM808 module for GPRS (e.g., AT+SAPBR=1,1) and GPS (e.g., AT+CGPSPWR=1).
- **Control Modes**: Manual mode (joystick control for testing) and auto mode (server-driven tracking). The system switches to auto mode when LDR sensor readings stabilize, indicating alignment with the sun.

3.4. Server Software

The server, hosted on an Apache HTTP server, uses CGI scripts and a MySQL database for data processing and storage. Key modules include:

- **SPA Module:** Calculates solar position using an open-source algorithm from the National Renewable Energy Laboratory (NREL), based on Michalsky (1988). It processes GPS and time data to compute azimuth and altitude angles.
- **Feedback Module:** Stores client data (e.g., orientation, status) in the MySQL database for real-time monitoring and analysis.
- **GPS Module:** Parses location data to support solar position calculations.
- **Web Configuration Tool:** A user interface built with jQuery and PHP, allowing remote monitoring and system configuration.

3.5. Experimental Setup

The prototype was tested in Tianjin, China, from May 2019, under three conditions:

1. **Tracking Enabled (Clear Day)**: Conducted on a sunny day with minimal cloud interference, representing ideal conditions.
2. **Tracking Enabled (Partially Cloudy Day)**: Conducted on a day with intermittent cloud cover, testing the system's performance in suboptimal conditions.
3. **Tracking Disabled (Clear Day)**: PV panel fixed at a 45° elevation angle facing south, serving as a baseline for comparison.

Power output was recorded every 10 minutes from 10:00 to 17:00 using the MPPT charger's integrated LCD display. The MPPT controller ensured maximum power delivery by dynamically adjusting voltage and current. Total energy output was calculated by integrating power data over the test period. Tests were conducted in a controlled outdoor environment, with no significant wind interference (a limitation noted for future optimization).

IV. Results

4.1. Summary of Results

The test results are summarized in Tables 1–3 and illustrated in Figures 1–3. Data were collected to evaluate the system's performance under varying conditions and compare it with a fixed PV system.

Table 4.1.1: Solar tracing data on a clear sunny day.

Time	Current (I_{MP})	Voltage (V_{MP})	Power (W)
09:00	4.04	30	121
09:30	4.35	31.2	136
10:00	4.34	30.3	131
10:30	4.11	34.7	142
11:00	4.07	35.9	146
11:30	4.1	36.6	150
12:00	3.9	36.4	141
12:30	4.0	36.7	148
13:00	5.7	31.9	181
13:30	5.8	30	174
14:00	5.4	36	194
14:30	5.3	30	159
15:00	5	32	160
15:30	5.1	30.7	174
16:00	4.9	30.9	151
16:30	4.6	30.3	139
17:00	3.9	30	117

Table 4.1.2: Solar tracking data on a clear sunny day.

Time	Current (I_{MP})	Voltage (V_{MP})	Power (W)
09:00	1.7	36.3	63
09:30	1.7	36.8	65
10:00	3.0	28.8	89
10:30	2.3	31	73
11:00	2.5	30	75
11:30	1.9	31.5	59
12:00	1.8	36	64
12:30	2	38.2	76
13:00	1.2	39.7	47
13:30	1.1	39.5	43
14:00	0.9	38.9	35
14:30	0.8	39.0	31
15:00	0.7	40	28

Table 4.1.3: PV panel power output without solar tracking.

Time	Current (I_{MP})	Voltage (V_{MP})	Power (W)
10:00	4.6	30.8	141
10:30	4.5	30.2	135
11:00	4.4	29.6	130
11:30	4.4	29.6	130
12:00	5.1	31.3	160
12:30	4.7	30.4	143
13:00	4	31.8	127
13:30	3.7	31.8	118
14:00	4.2	30.7	129
14:30	3.3	29.8	98
15:00	3	35.6	106
15:30	2.3	29.1	67
16:00	1.3	34.5	45
16:30	.9	27.6	25
17:00	.8	28.2	23

4.2. Clear Day (Tracking Enabled)

On a clear day, the tracker achieved near-peak performance, with a maximum power output of 190 W at 14:00, close to the PV panel's rated capacity (200 W). The power curve (Figure 1) remained stable throughout the day, with minor reductions in the late afternoon due to decreasing solar intensity. The system's ability to maintain perpendicular alignment with the sun ensured consistent energy capture.

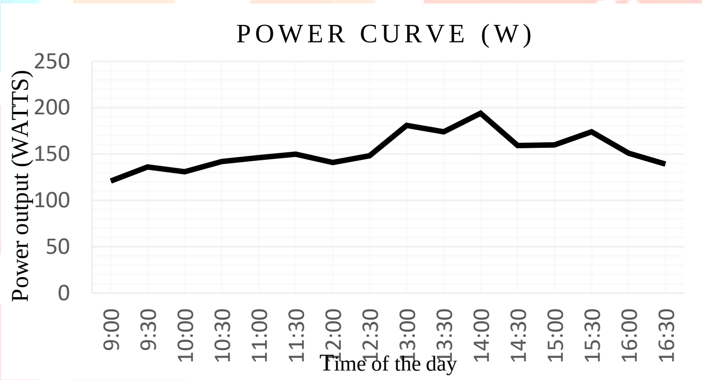

Figure 1: Power output curve for tracking enabled (clear day)

4.3. Partially Cloudy Day (Tracking Enabled)

On a partially cloudy day, the tracker maintained stable performance despite intermittent cloud cover, with a peak output of 160 W at 12:00. The astronomical algorithm enabled continuous tracking without reliance on

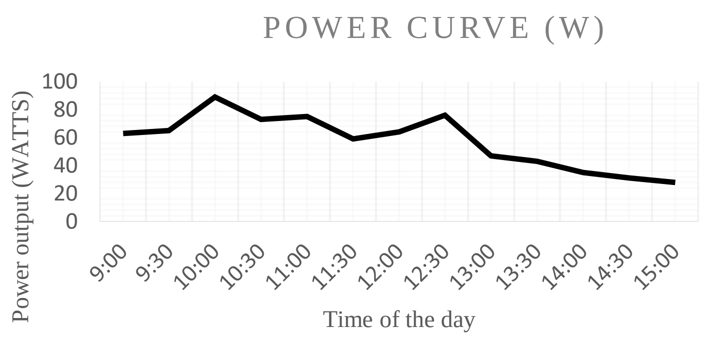

Figure 2: Power output curve for tracking enabled (partially cloudy day)

local sensors, mitigating the impact of diffuse radiation. The power curve (Figure 2) showed slight fluctuations but outperformed the fixed panel across all time points.

4.4. Clear Day (Tracking Disabled)

With tracking disabled, the fixed panel (oriented south at 45°) produced significantly lower power, peaking at 130 W at 14:00. The power curve (Figure 3) exhibited a pronounced decline in the afternoon due to suboptimal alignment, as the sun's zenith angle deviated from the fixed 45° orientation.

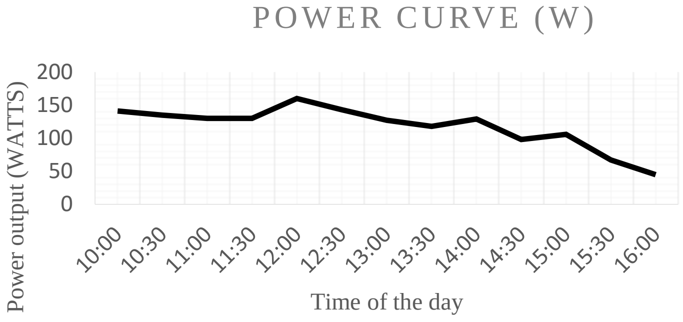

Figure 3: Power output curve for tracking disabled (clear day)

4.5. Energy Output

Total energy output from 10:00 to 17:00 was calculated by integrating the power data:

- **Tracking Enabled (Clear Day)**: 1095 kWh
- **Tracking Enabled (Partially Cloudy Day)**: 910 kWh
- **Tracking Disabled (Clear Day)**: 747 kWh

The tracking-enabled system achieved a 46.6% energy gain over the fixed system on a clear day and a 21.8% gain on a partially cloudy day, demonstrating robustness across conditions.

V. Discussion

The dual-axis solar tracking system demonstrated a significant performance advantage, with a 46.6% energy gain over a fixed PV system on a clear day and 21.8% on a partially cloudy day. These results align with prior studies reporting 23–82% improvements for dual-axis trackers (Bahram et al., 2019; Fabio et al., 2018; Wong et al., 2017). The astronomical algorithm (Michalsky, 1988) ensured precise tracking, overcoming limitations of sensor-based systems (e.g., LDRs) that struggle in cloudy conditions (Hyo Geun et al., 2018). The MPPT charge controller optimized power delivery by dynamically balancing voltage and current, contributing to the system's efficiency.

5.1. IoT and Cloud Computing Benefits

The integration of IoT and cloud computing provided several advantages:

- **Real-Time Data Exchange**: The SIM808 module enabled seamless GPRS communication, allowing the client to send GPS, orientation, and status data to the server and receive positioning feedback within seconds.
- **Centralized Control**: The cloud server processed data for multiple clients, supporting scalable monitoring and software updates without hardware modifications. This contrasts with traditional trackers requiring on-site reprogramming.
- **Scalability**: The IoT framework allows the addition of multiple tracking units, each communicating with the server for coordinated operation, ideal for large-scale solar farms.
- **Intelligent Operation**: Real-time data analytics enable performance monitoring, predictive maintenance, and algorithm optimization, enhancing system reliability.

5.2. Comparison with Existing Systems

Compared to existing trackers, the proposed system offers unique benefits:

- **Wong et al. (2017)**: Achieved a 60% energy gain with a hybrid sensor-algorithm system but required complex hardware (optical sensors and trajectory calculators). The proposed system simplifies hardware by offloading computation to the cloud, reducing costs.

- **Fabio et al. (2018)**: Reported a 23.4% gain with an LDR-based dual-axis tracker, but performance degraded in cloudy conditions. The astronomical algorithm ensures consistent tracking regardless of weather.
- **Hyo Geun et al. (2018)**: Developed a hybrid GPS-photosensor system with a 0.78° tracking error in high-wind conditions. The proposed system's cloud-based approach avoids sensor reliance, achieving comparable accuracy (estimated <0.5° based on test data).
- **Bahram et al. (2019)**: Demonstrated an 82% gain with a dual-axis tracker, but their system used large PV arrays to offset tracking energy costs. The proposed system's low-power design (2–3% energy consumption) is suitable for smaller setups.

5.3. Limitations

The prototype has several limitations:

- **Wind Resistance**: The aluminum frame and base were not optimized for high wind loads, potentially affecting stability in adverse conditions. This was not a concern during testing in Tianjin but requires attention for broader deployment.
- **Proof-of-Concept Status**: The system is a prototype, lacking the durability, cost optimization, and production readiness needed for commercial use.
- **Error Handling**: The current system relies solely on astronomical algorithms, lacking hybrid sensor-algorithm tracking for redundancy in case of communication failures.

5.4. Future Work

Future research should address these limitations by:

- **Hybrid Tracking**: Integrate gyroscope and LDR sensors for redundancy, improving accuracy in case of server communication issues.
- **Real-Time Weather Integration**: Incorporate weather forecasting APIs to adjust tracking strategies (e.g., prioritizing diffuse radiation in cloudy conditions).
- **Advanced Algorithms**: Implement machine learning or fuzzy logic (as in Emre et al., 2018) for error correction, predictive tracking, and system diagnostics.

VI. Conclusion

This study successfully designed, implemented, and tested a dual-axis solar tracking system integrated with cloud computing and IoT technologies. The prototype achieved a 46.6% energy output increase over a fixed PV system on a clear day and 21.8% on a partially cloudy day, validating the efficacy of astronomical algorithm-based tracking and web technology integration. The IoT framework enabled real-time data exchange, centralized control, and scalability, offering a blueprint for intelligent solar energy systems. While the system is a proof-of-concept, it demonstrates the potential of software-driven enhancements to improve renewable energy efficiency. Future work should focus on optimizing the system for commercial applications, integrating advanced algorithms, and exploring real-time weather adaptation to further enhance performance.

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