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Visvesvaraya Technological University, Belgaum

A Project Report on

"Dual-Axis Solar Tracker with Cloud Dashboard"

Submitted in partial fulfilment of the requirements for the award of the degree of

Bachelor of Engineering
in
Electronics and Communication Engineering

PROJECT WORK –4 [22EC8PWPJ4]

Submitted by

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

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CERTIFICATE

This is to certified that the Project work - 4 entitled **"Dual-Axis Solar Tracker with Cloud Dashboard"** is a bonafide work carried out by **Hamsa V N: (1BM22EC407), Sushma D: (1BM22EC422)** submitted in partial fulfilment of the requirement for completion of PROJECT WORK - 4 [22EC8PWPJ4] of Bachelor of Engineering in Electronics and Communication Engineering during the academic year 2024-25. The Project Work - 4 report has been approved as it satisfies the academic requirements.

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DECLARATION

We, **Hamsa V N: (1BM22EC407), Sushma D: (1BM22EC422),** hereby declare that the Project Work - 4 entitled **Dual-Axis Solar Tracker with Cloud Dashboard** is a bonafide work and has been carried out by us under the guidance of **Dr. Jisha P,** Assistant Professor, Department of Electronics and Communication Engineering, BMS College of Engineering, Bengaluru submitted in partial fulfilment of the requirement for completion of PROJECT WORK - 4 [22EC8PWPJ4] of Bachelor of Engineering in Electronics and Communication during the academic year 2024-25. The Project Work - 4 report has been approved as it satisfies the academic requirements in Electronics and Communication Engineering, Visvesvaraya Technological University, Belagavi, during the academic year 2024-25.
We further declare that, to the best of our knowledge and belief, this Project Work - 4 has not been submitted either in part or in full to any other university.

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ABSTRACT

The Dual-Axis Solar Tracker with Cloud Dashboard is an intelligent, IoT-based system designed to optimize photovoltaic (PV) energy harvesting through precise solar tracking. Utilizing an ESP32 microcontroller, the system processes input from four Light Dependent Resistors (LDRs) to determine the sun's position and adjust the solar panel's orientation along both azimuth and elevation axes using servo or stepper motors. This dynamic alignment increases energy efficiency by up to 30–40% compared to fixed-tilt panels. Real-time performance metrics such as voltage, current, and battery status—are monitored locally via an OLED display and remotely through a Firebase-powered cloud dashboard, which also supports historical data analysis and manual control. A Battery Management System (BMS) ensures safe and efficient energy storage, while automated alerts enhance system reliability. The inclusion of a 3D-printed prototype adds educational and demonstrative value, making the project ideal for both practical implementation and learning in the fields of renewable energy and IoT automation. The Dual-Axis Solar Tracker with Cloud Dashboard is an intelligent, IoT-enabled solar tracking system designed to maximize photovoltaic (PV) energy efficiency. Unlike fixed solar panels, this system utilizes a dual-axis mechanism controlled by an ESP32 microcontroller to dynamically align the panel with the sun's position in both azimuth and elevation directions. Four strategically placed Light Dependent Resistors (LDRs) detect sunlight intensity, enabling real-time adjustments for optimal solar exposure. This dynamic tracking can improve energy yield by 30–40% compared to stationary panels. The system integrates Firebase for real-time cloud data synchronization, providing global access to live and historical performance metrics such as voltage, current, power output, and battery status—via a responsive web dashboard. A local OLED display ensures on-site monitoring, even without internet connectivity. A Battery Management System (BMS) monitors and protects battery health, while users receive real-time alerts and notifications through a mobile interface. Featuring a 3D-printed prototype, the system is ideal for educational, research, and small-scale renewable energy applications. The project demonstrates the effectiveness of combining embedded systems, IoT, and renewable energy technologies into a scalable, cost-efficient solution for enhanced solar energy harvesting.

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List of abbreviations

Abbreviations	Full Form
BMS	Battery Management System
IEEE	Institute of Electrical and Electronics Engineers
LDR	Light Dependent resistor
ESP32	Espressif Systems Platform 32
OLED	Organic Light Emitting Diode
ADC	Analog to Digital Converter
IMU	Inertial Measurement Units

CHAPTER 1:

INTRODUCTION

The Dual-Axis Solar Tracker with Cloud Dashboard is a smart, IoT-enabled system that enhances the performance and efficiency of solar panels by automatically and continuously adjusting their orientation to directly face the sun throughout the day and across all seasons. This advanced project is designed to address the common limitation of static solar panels, which only face one direction and, therefore, fail to capture the maximum available sunlight at all times. By using a dual-axis tracking mechanism, the system allows the solar panels to move both horizontally (East-West) and vertically (North-South), significantly increasing their ability to absorb solar energy. This makes the system ideal for real-world renewable energy applications and also an excellent educational tool for learning about solar energy, embedded systems, IoT, and automation.

At the heart of the system lies the ESP32 microcontroller, which serves as the central control unit for managing both hardware and software components. The ESP32 is a powerful and versatile board that includes built-in Wi-Fi and Bluetooth capabilities, which are crucial for enabling real-time communication with the cloud. It reads sensor data, calculates how much the solar panel needs to move, sends control signals to the motors, and simultaneously uploads system performance data to an online dashboard. The ESP32 executes these multiple tasks efficiently and acts as the bridge between the physical system and the digital world.

To detect the position of the sun in the sky, the system uses four Light Dependent Resistors (LDRs) placed in a cross formation. These LDRs are sensitive to light intensity and help determine where the sunlight is strongest. If one LDR receives more light than the others, the ESP32 interprets this as a misalignment of the panel and activates the motors to adjust the panel's orientation. This feedback mechanism allows the panel to align itself with the sun automatically. The adjustment continues until all four LDRs report nearly the same intensity, indicating that the panel is perfectly aligned with the sun.

The physical movement of the solar panel is achieved using two motors-either servo motors or stepper motors, depending on the required precision and torque. One motor controls the azimuth movement (horizontal, East–West direction), while the other controls the elevation movement (vertical, North–South direction). The ESP32 sends control signals to the motors based on the data from the LDR sensors, causing the panel to rotate in real-time. This two-axis tracking ensures that the panel continuously maintains an optimal angle relative to the sun's position, leading to an increase in solar energy capture by up to 30–40% compared to non-tracking (fixed) solar panels.

A major innovation in this project is its Internet of Things (IoT) functionality, made possible through the ESP32's built-in Wi-Fi. The system connects to a cloud platform such as Google Firebase, where it continuously uploads critical data, including solar voltage, current, power output, battery percentage, and motor angles. This data is visualized on a web-based dashboard, which users can access from any device connected to the internet. The dashboard includes dynamic graphs and charts to monitor performance in real time and over time. Users can also control the panel manually via the dashboard if needed, which is useful for system calibration or when sunlight is unevenly distributed due to weather or obstacles.

The system incorporates a Battery Management System (BMS) to monitor and protect the battery that stores solar energy. The BMS ensures the battery operates within safe voltage and current ranges. It prevents overcharging, over-discharging, and short circuits, thus extending battery life and enhancing safety. The BMS also sends real-time battery health data to the ESP32, which is then displayed locally on the OLED screen and remotely on the cloud dashboard.

For situations where internet access is unavailable, the system includes a local OLED display connected to the ESP32. This screen shows essential system information, such as the current angle of each motor (azimuth and elevation), the battery voltage and charge level, and real-time power output. This ensures that users can still interact with and monitor the system even when the cloud dashboard is inaccessible.

To keep users informed about system status, the project supports real-time alerts and notifications via mobile app or email, depending on the cloud platform used. For example, if the system goes offline, if a sensor fails, or if the battery drops below a safe level, the user is immediately notified. These alerts help users take timely action to prevent system failures and maximize performance reliability.

For demonstration and educational purposes, the project includes a 3D-printed mechanical prototype. This small-scale model illustrates how dual-axis tracking works and allows users to see the mechanical movements of the panel in real time. The prototype includes the LDR sensors, motors, ESP32 board, and small solar panel, all mounted on a compact dual-axis platform. This is especially useful in classrooms, science fairs, or engineering exhibitions, where learners and observers can gain hands-on experience with modern solar tracking technology.

To maintain consistent operation, the system is designed with Wi-Fi auto-reconnection support. If the internet connection drops for any reason, the ESP32 automatically attempts to reconnect to the network, ensuring that data transmission to the cloud resumes without user intervention. This feature is important for real-world deployments where internet connectivity might be unstable.

This project is highly versatile and can be scaled or modified for a variety of use cases. In educational environments, it serves as a powerful example of integrating renewable energy with smart automation. In practical scenarios, it can be scaled to manage full-sized solar panels for homes, farms, or small industries. It is also useful in off-grid solar systems, where maximum power generation is essential. The intelligent control and monitoring features make it suitable for use in remote areas where manual tracking is not feasible.

In conclusion, the Dual-Axis Solar Tracker with Cloud Dashboard is a modern, intelligent, and scalable solution that combines mechanical precision, sensor-based control, cloud computing, real-time monitoring, and user-friendly interface design into a single comprehensive system. It not only improves solar energy efficiency but also introduces users to real-world applications of IoT, embedded systems, renewable energy, and smart automation. Whether used in education or industry, this project exemplifies how technology can be used to make sustainable energy more effective, efficient, and accessible.

CHAPTER 2:

LITERATURE SURVEY

The advancement of solar photovoltaic (PV) systems has increasingly focused on improving energy efficiency, autonomous functionality, and system reliability through innovations in solar tracking and maintenance. Numerous researchers have contributed to this growing field, particularly by integrating microcontrollers, IoT, and automation technologies into solar panel systems.

In paper [1]. Ravikumar et al. proposed a dual-axis solar tracking system using Arduino, demonstrating a significant enhancement in energy capture by ensuring continuous alignment of solar panels with the sun's position. Their system laid a foundational framework for intelligent tracking mechanisms, showing how active sun-tracking could substantially increase photovoltaic efficiency.

In paper[2]. Expanding upon traditional tracking systems, Mukunda Swamy et al. incorporated an IoT-enabled automatic dust monitoring and cleaning mechanism. This system utilized sensors to detect dust accumulation on the solar panel surface, triggering a cleaning process to mitigate efficiency loss. The fusion of environmental sensing with automated response marked a significant advancement in solar panel maintenance.

In paper [3], Another step forward was presented in a study which designed a dual-axis tracker with integrated cloud-based weather and solar monitoring features. Utilizing Arduino and Wi-Fi modules, this system allowed for remote monitoring and control, especially suited for agricultural applications where real-time environmental feedback is essential for efficient energy harvesting.

In paper [4], A similar focus on maintenance and automation was demonstrated where an IoT-based wiping mechanism was employed to keep the solar panel surface clean. The study emphasized the correlation between panel cleanliness and energy output, thereby highlighting the importance of surface maintenance in achieving optimal system performance, particularly for autonomous installations.

In paper [5], Samuel and Rajagopal further enhanced cleaning efficiency by developing a smart photovoltaic panel cleaning system using NodeMCU and dust sensors. Their approach introduced threshold-based automated cleaning, ensuring that dust removal was only triggered when necessary, thus optimizing water and energy usage in long-term deployments.

In paper [6] , On a more theoretical front, Mousazadeh et al. provided a comprehensive review of sun-tracking principles, outlining various methodologies to optimize panel orientation. Their work underscored the critical role of tracking systems in improving the efficiency of solar installations and informed the design principles behind many practical implementations.

In paper [7], Rizk and Chaiko conducted an extensive study on solar tracking technologies, classifying tracker types and evaluating different drive mechanisms. Their analysis served as a comparative guide, helping identify suitable tracking systems based on application needs and reliability requirements.

In paper [8] , Kumar introduced an IoT-enabled solar energy monitoring system capable of real-time data logging and remote access. This integration of cloud services improved system diagnostics and enabled users to track performance metrics effectively from distant locations.

In paper [9], Patel and Sharma developed a cloud-based performance monitoring framework using ESP32 and Firebase. Their work facilitated real-time performance visualization and ensured consistent energy output tracking via wireless data communication, essential for remote or distributed solar installations.

In paper [10], Abdallah and Nijmeh presented a PLC-controlled two-axis solar tracking system that significantly outperformed fixed-tilt panel systems. Their use of industrial-grade programmable logic controllers enhanced tracking precision and demonstrated scalability for larger energy systems.

In paper [11], Sefa used LDR sensors in a dual-axis tracking system, showcasing its ability to respond dynamically to changes in solar position. The responsiveness of the system improved overall energy capture under variable environmental conditions.

In paper [12], Lu explored the critical challenges in battery management for electric vehicles, especially lithium-ion storage. Their findings are relevant for solar systems with integrated storage, where efficient battery control is vital for system sustainability.

In paper [13], Tremblay and Dessaint contributed a dynamic model of lithium-ion batteries, useful for simulating battery behaviour in solar-powered systems. Their model offers predictive capability for performance optimization and energy management in solar applications.

In paper [14], Gibson emphasized the role of additive manufacturing in developing customized components for solar trackers. By employing 3D printing and rapid prototyping, they enabled faster design iterations and cost-effective hardware development.

In paper [15], Reddy utilized finite element analysis (FEA) to optimize the design of a dual-axis solar tracker. Their simulation-based approach improved both structural integrity and energy efficiency, ensuring that the system could withstand environmental stress while maximizing solar capture.

CHAPTER 3:

PROBLEM ANALYSIS and SOLUTION

3.1 Problem Definition

Fixed solar panels, although widely used in residential and commercial solar energy systems, suffer from a fundamental limitation: they are installed at a fixed angle and orientation, meaning they cannot adjust to follow the sun's movement across the sky during the day or over the course of different seasons. The position of the sun changes continuously—rising in the east, moving westward during the day, and varying in height depending on the time of year. As a result, fixed panels are only optimally aligned with the sun for a short portion of the day, typically around midday. For the rest of the time, the angle of sunlight hitting the panel becomes increasingly oblique, reducing the amount of solar radiation captured. This leads to significant energy losses, particularly in the early morning and late afternoon when sunlight hits the panel at a sharp angle. Over time, these inefficiencies add up, reducing the overall performance of the solar system and making it less cost-effective.

To overcome this limitation, solar tracking systems have been developed. These systems are designed to adjust the orientation of the solar panel throughout the day, ensuring that the panel continuously faces the sun to maximize light absorption and energy generation. Among these, dual-axis solar trackers are the most effective because they allow movement in two directions: horizontal (azimuth) to follow the sun's daily path from east to west, and vertical (elevation) to adjust for seasonal changes in the sun's height in the sky. However, while the concept of solar tracking is promising, many existing solar tracking solutions face several significant challenges that limit their adoption, efficiency, and scalability.

Key Challenges with Existing Solar Tracking Systems:

1. Limited Energy Harvesting Due to Inefficient Tracking Algorithms or Mechanisms:
   Many existing solar trackers, especially low-cost or DIY systems, use simple, rule-based algorithms or timer-based mechanisms that do not dynamically respond to actual sunlight conditions. These systems may move the panel based on a preset schedule, rather than real-time sunlight intensity, leading to suboptimal tracking. As a result, even though the panel moves, it might still miss the most direct sunlight. Systems that lack precise feedback mechanisms often fail to maintain the panel's alignment with the sun, reducing the expected energy gains that justify the additional investment in tracking technology.

2. High Mechanical Complexity and Cost:
   Dual-axis trackers require two degrees of freedom—usually achieved using multiple motors, gears, mounts, and frames-which introduces mechanical complexity. This complexity increases the cost of the system in several ways:
   - More expensive components such as stepper motors, servos, bearings, and metal structures.
   - Increased installation time and difficulty.
   - Higher chances of mechanical failure due to the number of moving parts.

3. Lack of Real-Time Monitoring and Control:
   Another major shortcoming in many conventional tracking systems is the absence of real-time monitoring and control capabilities. Once installed, these systems often operate in a "black-box" manner-there's no visibility into how well the system is tracking the sun, how much energy it's generating at any given moment, or whether any component has failed. Without real-time feedback, users cannot make informed decisions about system health, performance, or required maintenance. This lack of transparency limits system optimization and introduces the risk of long-term inefficiencies going unnoticed. It also makes it hard for users to manually intervene or recalibrate the system in case of unusual lighting conditions such as cloud cover, obstructions, or dust on sensors.

4. Inadequate Battery Management:

   Many solar systems—especially off-grid ones—rely on batteries to store energy for later use. However, battery health and safety are often neglected in traditional tracking setups. Poorly managed batteries can lead to:

   - Overcharging, which shortens battery life and increases fire risk.
   - Deep discharging, which damages the battery and reduces usable capacity.
   - Lack of temperature control, causing thermal degradation. Without an intelligent Battery Management System (BMS), solar tracking systems become unreliable in the long term, especially in environments where consistent battery performance is critical. Additionally, users often have no way to monitor battery status remotely, which creates risk in unattended or remote solar installations.

5. Poor Remote Accessibility and User Interaction

   In today's connected world, users expect to be able to monitor and control their systems remotely, especially for off-grid or large-scale installations. However, many existing solar tracking systems lack network connectivity, which means users cannot access system data via smartphones or web dashboards. This makes it difficult to track performance, receive alerts, or control the system from a distance. Without cloud connectivity, users are also deprived of valuable features such as:

   1. Historical data logging
   2. Performance analytics
   3. Predictive maintenance alerts
   4. Integration with mobile apps or dashboards This lack of remote accessibility reduces the usability and appeal of the system, particularly in applications where unattended operation and data-driven decision-making are essential.

Problem Statement:

Despite considerable advancements in solar tracking technologies over the past few decades, a major gap still exists between what is technically possible and what is practically available in terms of performance, affordability, and user-friendly features. Traditional fixed solar panels, although widely used due to their simplicity and low installation costs, suffer from fundamental limitations. Because they are stationary and mounted at a fixed angle, they cannot adapt to the dynamic movement of the sun throughout the day or across different seasons. As a result, their exposure to direct sunlight is suboptimal for most of the day, leading to significant losses in energy capture and overall system efficiency.

To address this issue, various solar tracking systems have been developed, ranging from single-axis to dual-axis trackers. Single-axis trackers allow movement along one axis (usually East-West) and help follow the sun's path across the sky during the day. However, they do not account for the sun's seasonal variation in altitude. Dual-axis trackers, on the other hand, provide a more advanced solution by enabling two degrees of movement—both azimuth (East-West) and elevation (North-South). This allows the solar panel to maintain an optimal orientation with respect to the sun's position at all times, potentially increasing solar energy generation by 30–40% compared to fixed systems. However, these dual-axis trackers are often mechanically complex, expensive to install and maintain, and lack advanced smart features, which limits their widespread adoption—especially in residential, small commercial, and educational applications.

Many existing tracking systems, even those classified as dual-axis, still rely on basic control logic or time-based algorithms rather than real-time solar sensing and feedback. This can result in inaccurate panel positioning, especially under dynamic weather conditions such as cloud movement or shading. Additionally, most systems lack real-time data monitoring, making it difficult for users to observe, analyze, or optimize performance. This lack of visibility and feedback reduces the potential of solar tracking systems to be maintained or improved over time.

Moreover, the majority of solar trackers available in the market fail to integrate intelligent battery management into their architecture. In many solar installations, particularly off-grid or hybrid systems, energy storage is a critical component. Without a reliable Battery Management System (BMS), users face risks of battery overcharging, deep discharging,

thermal issues, and reduced battery lifespan. A well-integrated BMS not only enhances safety and battery health but also allows for more efficient use of stored energy—particularly valuable in areas with limited sunlight or during nighttime usage.

In today's era of smart devices and remote monitoring, remote accessibility and IoT integration have become essential for energy systems. However, traditional solar tracking systems are typically standalone and disconnected, providing no way for users to remotely monitor energy production, battery status, panel alignment, or system health. This lack of interactivity and control significantly diminishes the user's ability to manage and maintain their solar setup effectively, especially in remote or unattended locations. In contrast, a modern IoT-enabled system would allow users to access a live dashboard, receive notifications or alerts (e.g., low battery, sensor failure, or tracking error), and even perform manual overrides or adjustments from anywhere using a mobile app or web interface.

Furthermore, the cost barrier remains one of the biggest challenges. While dual-axis solar trackers exist, their high cost of implementation—including motors, structural mounts, controllers, sensors, and software—makes them inaccessible to low-budget installations such as in rural areas, small businesses, educational institutions, or developing countries. What is needed is a cost-effective, modular, and user-friendly solar tracking solution that retains the energy efficiency benefits of dual-axis tracking while minimizing complexity and enabling remote management and monitoring.

Therefore, there is a critical need for an innovative solar tracking system that combines the following features:

- **Cost-effective design** using affordable components such as ESP32 microcontrollers, LDR sensors, and 3D-printed mechanical parts.

- **Real-time sun tracking** using light intensity feedback and adaptive positioning algorithms.
- **Dual-axis motion** for maximum solar exposure throughout the day and across seasons.
- **Smart Battery Management System (BMS)** to ensure safe and efficient charging/discharging of energy storage units.
- **Cloud-based dashboard and IoT connectivity** for remote access, data visualization, performance analytics, and user notifications.
- **Offline capabilities** such as OLED displays to provide essential data when internet connectivity is unavailable.
- **User-friendly interface and alerts** to simplify system interaction and support predictive maintenance.

Such a system would not only increase the adoption of solar energy through higher output and intelligent control but also democratize access to advanced solar technology by reducing cost and complexity. This makes the project not only technically important but also socially and environmentally impactful. It represents a holistic approach to addressing the limitations of current fixed and traditional tracking systems and paves the way for a new generation of smart, sustainable, and scalable solar energy solutions.

3.2 Proposed Solution:

The Dual-Axis Solar Tracker with Cloud Dashboard presents a modern, intelligent, and highly integrated solution aimed at overcoming the major limitations of traditional solar energy systems, especially those relying on fixed panels or outdated tracking mechanisms. As global demand for sustainable and efficient renewable energy sources grows, this system stands out by combining mechanical precision, IoT-enabled real-time monitoring, and intelligent energy management into a compact, cost-effective, and user-friendly platform.

Conventional fixed solar panels, despite their simplicity and low cost, suffer from significant inefficiencies due to their inability to track the sun's changing position throughout the day and across seasons. As the sun moves from east to west and varies in elevation depending on the time of year, fixed panels fail to capture the optimal angle of sunlight for most of the day, resulting in reduced energy generation. Even existing tracking systems, while an improvement over fixed mounts, often suffer from drawbacks such as high mechanical complexity, elevated costs, lack of remote monitoring capabilities, and limited battery management features. These limitations severely affect their practicality, especially in residential, rural, or small-scale solar installations.

To address these challenges, the proposed Dual-Axis Solar Tracker with Cloud Dashboard introduces a comprehensive and innovative design that leverages the power of the Internet of Things (IoT), precision hardware, and intelligent software integration. The core functionality of the system revolves around its dual-axis movement, which enables the solar panel to rotate both horizontally (azimuth) and vertically (elevation). This dual-degree freedom allows the system to dynamically align itself with the sun's real-time position, thereby ensuring maximum exposure to solar radiation at all times of the day and year. This results in a substantial improvement in energy harvesting efficiency—estimated to increase power output by 40–60% compared to static solar panel systems.

The system's tracking mechanism is based on Light Dependent Resistor (LDR) sensors, which are strategically placed to detect the intensity of sunlight from different directions. The readings from these sensors are processed by the ESP32 microcontroller, a cost-effective, Wi-Fi-enabled unit that serves as the system's central controller. Based on sensor feedback, the ESP32 dynamically adjusts the orientation of the panel using servo or stepper motors, which are chosen for their accuracy, reliability, and affordability. This closed-loop control system allows the solar panel to automatically follow the sun with high precision, adapting even to subtle shifts in light intensity caused by clouds or environmental changes.

In order to keep the design affordable and scalable, the system utilizes low-cost electronic components and supports 3D-printed mechanical structures, allowing for easy assembly, rapid prototyping, and deployment in both educational and practical scenarios. The 3D-printed design also enables compact and lightweight construction, making it ideal for demonstrations, pilot projects, and integration into various housing or field setups.

One of the most transformative features of this project is its cloud-based dashboard, enabled by seamless integration with platforms such as Google Firebase.

The ESP32 transmits real-time system data-including voltage, current, panel angle, battery percentage, and power output-to the Firebase database. This data is then visualized through a responsive web dashboard accessible from any internet-enabled device. Users can view dynamic charts, graphs, and live updates, allowing them to monitor the system's performance from anywhere in the world. The dashboard also provides manual override controls, which are useful for system calibration or operation under abnormal lighting conditions.

In addition to real-time monitoring, the system includes advanced Battery Management System (BMS) functionality, a critical component for ensuring the safety and efficiency of energy storage. The BMS continuously monitors battery charge and discharge levels, protecting against overcharging, deep discharging, overcurrent, and overheating. This not only extends the lifespan of the battery but also ensures consistent energy availability and system reliability in both off-grid and hybrid solar setups. The system provides users with real-time battery status updates, improving awareness and promoting proactive energy management.

To further enhance user interaction, the system includes a mobile notification feature that alerts users in real time when specific conditions are detected—such as low battery, sensor malfunctions, connectivity loss, or tracker misalignment. These alerts ensure that users are always informed about the system's status and can take prompt action to maintain optimal performance. For situations where internet access is temporarily unavailable, the system includes a local OLED display that shows key metrics like battery level, motor angles, and panel status directly on the device.

Another notable feature is the inclusion of Wi-Fi connectivity with auto-reconnection support, which ensures uninterrupted communication between the microcontroller and the cloud platform. This robust connectivity model guarantees that users have continuous access to system data and that performance logs are not lost even during intermittent network interruptions.

Altogether, the Dual-Axis Solar Tracker with Cloud Dashboard offers a holistic, future-ready solution for solar energy optimization. It combines the mechanical advantages of precise dual-axis motion with the intelligence of IoT integration, delivering a system that is not only energy-efficient and technically robust but also accessible, affordable, and user-centered. The project is suitable for a wide range of applications—from educational demonstrations in schools and universities to real-world solar installations in homes, farms, and remote areas where maximizing solar output is critical.

This solution ultimately reflects the convergence of renewable energy, embedded systems, cloud computing, and smart automation, offering a blueprint for the next generation of solar energy systems that are intelligent, connected, efficient, and scalable.

To reduce cost and complexity, the system uses affordable components like the ESP32 microcontroller and supports a 3D-printed prototype for easy assembly and scalability. Real-time monitoring is enabled via Firebase cloud integration, providing a web dashboard for live data, remote access, and manual control. The integrated Battery Management System (BMS) safeguards against overcharging, undercharging, and low battery, while charge/discharge monitoring ensures efficient energy usage. Users receive mobile alerts for abnormal conditions, and the system maintains seamless Wi-Fi connectivity for global accessibility. Overall, the solution delivers an efficient, user-friendly, and scalable approach to smart solar energy tracking.

Objectives:

1. Maximize Solar Energy Efficiency through Dual-Axis Sun Tracking

Goal: Improve solar panel efficiency by up to 40–60% compared to static systems.

Method:

- Use dual-axis tracking, where the panel adjusts along two axes:
- Azimuth (East–West) to follow the sun across the day.
- Elevation (North–South) to adjust for seasonal sun movement.
- Employ Light Dependent Resistors (LDRs) to sense sunlight intensity from different directions.

- The panel is constantly repositioned to face the sun perpendicularly, maximizing light absorption.

Impact: Higher solar energy yield, better return on investment (ROI), and enhanced sustainability for off-grid users.

2. Design a Cost-Effective and Mechanically Simplified Tracking System

Objective: Keep the system affordable, compact, and easy to assemble.

Components:

- ESP32 microcontroller for processing sensor input and controlling actuators.
- Servo or stepper motors for precise positioning.
- Servos offer simplicity and built-in control.
- Steppers allow fine-grained angular motion.

Mechanical Simplification:

- Lightweight frame using aluminium or PVC for the mount.
- Use of limit switches or encoders to prevent over-rotation and ensure alignment.
- Suitability: Perfect for educational labs, home setups, and small farms.

3. Enable Real-Time Remote Monitoring and System Control via Cloud Dashboard

Cloud Integration:

Use Firebase for:

- Real-time data logging (voltage, current, battery percentage, panel angle).
- Cloud storage and retrieval for analytics and reporting.

User Interfaces:

- Web dashboard (HTML + Firebase + JS/React) for real-time visuals.
- Mobile app (Android/iOS) with:
- Live system status
- Manual override buttons
- Historical data graphs

- Alert/notification system

Connectivity: ESP32 supports Wi-Fi, enabling secure cloud connection even in remote areas.

5. **Ensure Battery Safety and System Reliability through Intelligent Power Management**

Battery Management System (BMS):

- Monitors charging and discharging cycles.
- Detects and handles:
- Overvoltage (to avoid overcharging)
- Undervoltage (to prevent deep discharge)
- Overcurrent or short circuits
- Temperature sensors to protect from thermal runaway.

Alert System:

- Sends Firebase alerts when thresholds are breached.
- Automatic system shutdown in case of hazardous conditions.
- Long-Term Benefit: Increases battery life, system uptime, and user safety.

6. **Enhance Energy Harvesting Efficiency**

Dynamic Panel Alignment:

- Real-time LDR comparison to shift the panel to the brightest light source.
- Continuous correction throughout the day to follow the sun.

Environmental Adaptability:

- Works under partly cloudy conditions by tracking the brightest available direction.
- Seasonal calibration ensures year-round efficiency.

Results:

- Greater charge accumulation
- Optimized energy input for limited battery storage scenarios

7. **Develop a Cost-Effective and Scalable Tracking Mechanism**

Design Philosophy:

- Keep component count low for easy scalability.
- Use low-power motors, reducing energy consumption of the tracker itself.

Hardware Stack:

- ESP32 (dual-core, Wi-Fi, Bluetooth)
- LDRs, 2 motors, minimal electronics

Scalability:

- Can be expanded to multiple panels.
- Software adaptable for larger panels or arrays.
- Modular code allows easy integration with other sensors or microcontrollers.

8. **Enable Real-Time Monitoring and Remote Control**

Control Capabilities:

- Manual override from dashboard/mobile in case of LDR failure.
- Auto-mode for daily sun-tracking.
- Scheduled operations (e.g., "sleep mode" at night).

Data Metrics Tracked:

- Solar panel voltage and current
- Motor angle and direction
- Battery state (charging/discharging)
- Environmental status (sunlight level, system uptime)

Edge Case Handling:

- Cloud-based logs for debugging or system audits
- Sync with NTP (Network Time Protocol) for timestamping
-

8. Implement a Reliable Battery Management System (BMS)

BMS Components:

- Voltage sensors for individual cells (in lithium-ion packs)
- Microcontroller logic to determine health metrics
- MOSFET-based cutoff for safe disconnect

Safeguards:

- Short-circuit protection
- Balancing circuitry (for Li-Ion/LiFePO4 batteries)
- Alerts for battery health degradation

Efficiency: Maintains consistent battery performance, reduces power loss, and ensures uninterrupted operation.

9. Improve System Accessibility and User Interaction

Mobile Notifications:

- Alert users for faults, full battery, low sunlight, or abnormal tracking behavior.
- Push notifications via Firebase Cloud Messaging (FCM).

User-Friendly Interface:

- Interactive touchscreen or mobile UI with:
- Real-time display
- Manual tracking angle adjustment
- Historical graph display (day/week/month

Off-Grid Usability:

- Data stored locally during Wi-Fi outages
- Auto-sync with cloud once connection resumes
- Powered by solar itself, so it operates independently of the grid

Overall Impact and Benefits

1. Maximized Solar Energy Output:

The implementation of a dual-axis tracking mechanism ensures that solar panels maintain an optimal orientation toward the sun throughout the day and across all seasons. By automatically adjusting along both azimuth (East-West) and elevation (North-South) axes, the system captures 40–60% more sunlight than fixed panels.

This increase in energy harvesting directly translates to:

- Greater power output from the same panel area.
- Reduced payback period for solar investments.
- Enhanced energy independence, especially in off-grid or rural settings.
- Improved system performance during varying weather and seasonal conditions.

Overall, the system supports maximum utilization of renewable solar resources, ensuring that users get the most energy possible from their solar infrastructure.

2. Remote Monitoring and Control:

One of the key innovations is the integration of real-time cloud monitoring and control through platforms like Firebase. This feature provides users with:

- Live system data (e.g., panel voltage/current, battery status, tracking angles).
- Historical data logs for trend analysis and performance optimization.
- Remote access via web dashboard and mobile apps, enabling users to:
- Manually override the system
- Receive alerts and push notifications
- Monitor from anywhere in the world

This IoT-enabled control adds a layer of flexibility and convenience that is particularly valuable for users managing solar systems in remote or inaccessible areas, ensuring uninterrupted oversight and interaction.

3. Enhanced System Reliability and Safety:

Reliability is critical in solar systems, especially when used in off-grid or mission-critical environments. This project incorporates a Battery Management System (BMS) that:

- Monitors charge/discharge cycles
- Detects overvoltage, undervoltage, and overcurrent conditions
- Sends automatic alerts via the cloud if thresholds are crossed
- Prevents battery degradation and failure

By actively managing power storage and system health, the BMS:

- Prolongs the lifespan of batteries
- Minimizes the risk of thermal events or damage
- Ensures consistent energy supply even under adverse conditions

This feature is crucial for long-term reliability, reducing maintenance needs and operational costs.

4. Cost-Effective and Scalable Design:

A major strength of this system is its affordable and modular design, achieved by:

- Using low-cost components (e.g., ESP32, LDRs, servos/steppers)
- Implementing 3D-printed mechanical parts, reducing manufacturing cost
- Designing for DIY assembly, supporting educational and maker communities

The scalability of the design makes it suitable for:

- Small residential units
- Educational projects and lab demonstrations
- Commercial farms or rooftops, by expanding to track multiple panels

This makes the technology accessible to a broad audience, from students and hobbyists to homeowners and rural entrepreneurs.

5. Sustainability and Environmental Benefits:

At its core, this project aligns strongly with global sustainability goals. By maximizing the efficiency of solar energy capture, it:

- Reduces dependency on fossil fuels and grid power
- Promotes the adoption of clean energy technologies
- Contributes to lower greenhouse gas emissions
- Encourages responsible energy consumption

The system's ability to operate autonomously using solar-generated power makes it ideal for off-grid communities, emergency shelters, disaster relief, and rural electrification — all while contributing to a greener, more resilient energy future.

Conclusion: Empowering Sustainable Innovation

This smart solar tracking system offers a holistic solution that blends engineering innovation, environmental consciousness, and user accessibility. It not only improves the technical efficiency of solar energy systems but also ensures they are safe, cost-effective, and easy to manage.

Its impact extends beyond individual users:

- Educational Impact: A great learning platform for students in IoT, robotics, and renewable energy.
- Economic Impact: Lower energy bills, better ROI on solar installations.
- Societal Impact: Helps democratize clean energy access, especially in underdeveloped or remote areas.
- Environmental Impact: Supports the global transition to renewable energy and carbon-neutral living.

CHAPTER 4:

METHODOLOGY and IMPLEMENTATION

4.1 Block Diagram

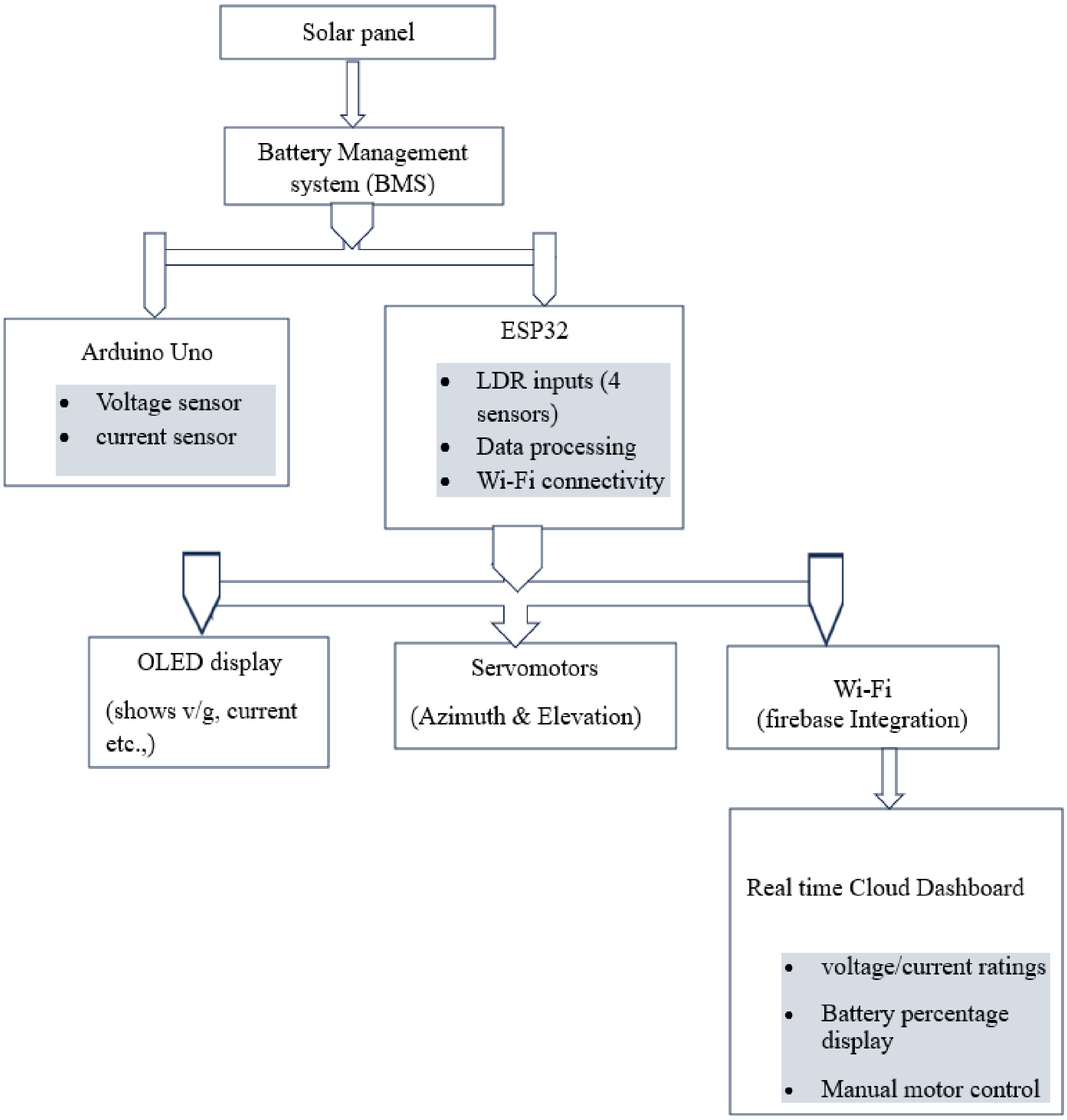


Fig 4.1: Block Diagram of Dual-Axis Solar Tracker with Cloud Dashboard

The prototype of the dual-axis solar tracker integrated with a cloud dashboard is developed using an Arduino Uno microcontroller as the central processing unit. A set of Light Dependent Resistors (LDRs) is strategically placed to detect the direction of maximum sunlight. These LDRs provide analog input to the Arduino, which then processes the data to control two servo motors for adjusting the solar panel's position along both horizontal (azimuth) and vertical (elevation) axes. The entire circuitry is assembled on a breadboard for modularity and ease of connection. An ESP8266 or NodeMCU module is included in the setup to enable wireless data transmission to the cloud. The system is powered through a USB connection or an external power source. A small solar panel is mounted on a movable frame connected to the servo motors, allowing real-time adjustments to optimize sunlight exposure. The prototype also includes a cloud interface—developed using platforms such as Things Speak or Blynk—that receives sensor data and displays parameters like panel angle, sunlight intensity, and temperature for remote monitoring. The entire setup is mounted on a stable baseboard, with careful wiring to ensure proper signal transmission and component operation.

Programming Logic:

The programming Logic for the dual-axis solar tracker begins with the initialization of all hardware components, including the LDR sensors, voltage and current sensors, servo motors, OLED display, Wi-Fi module, and Firebase cloud services. Four LDRs are positioned to detect sunlight from different directions, enabling precise measurement of light intensity in both horizontal (azimuth) and vertical (elevation) axes. In the main control loop, the system continuously reads analog values from the LDR sensors to determine the direction of maximum light intensity. The average values from the left and right sensors are compared to adjust the azimuth angle, while the top and bottom sensor averages are used to control the elevation angle. If the difference between the paired sensor groups exceeds a predefined threshold, the corresponding servo motor is rotated to align the solar panel toward the direction with the highest light intensity.

Simultaneously, the system reads voltage and current values to calculate real-time power output. These values, along with the battery percentage and motor angles, are displayed locally on an OLED screen for on-site monitoring.

The ESP32 microcontroller also handles Wi-Fi communication and sends the sensor readings and servo positions to a Firebase cloud dashboard. This enables remote visualization of voltage, current, power, and battery charge status. Additionally, the dashboard includes a manual control interface, allowing users to override automatic tracking and manually adjust the servomotor angles if required. This ensures flexibility and enhanced user interaction with the solar tracking system.

Cloud Data Visualization and User Interface:

The system integrates a real-time cloud-based dashboard using Firebase to enable remote monitoring and control of the solar tracking system. The cloud interface displays essential electrical and operational parameters such as voltage, current, power output, and battery charge percentage. These values are continuously updated by the ESP32 microcontroller via Wi-Fi, ensuring synchronized and up-to-date data visualization.

The user interface is designed to be intuitive and responsive, accessible via any internet-enabled device such as a smartphone or computer. It features real-time graphical charts to display trends in power generation and energy usage over time. Additionally, numerical indicators provide live readings for voltage (in volts), current (in amperes), and calculated power (in watts).

A manual control panel is incorporated into the dashboard, enabling users to override the automatic dual-axis tracking mechanism. Through this panel, users can send specific angle values to control the azimuth and elevation servos remotely. This feature is particularly useful for testing, calibration, or situations where automated tracking may be temporarily disabled.

The combination of real-time data logging, graphical visualization, and interactive control makes the cloud interface a powerful tool for both performance analysis and user engagement, thereby enhancing the system’s adaptability for smart energy management applications.

4.1.1 Circuit Diagrams

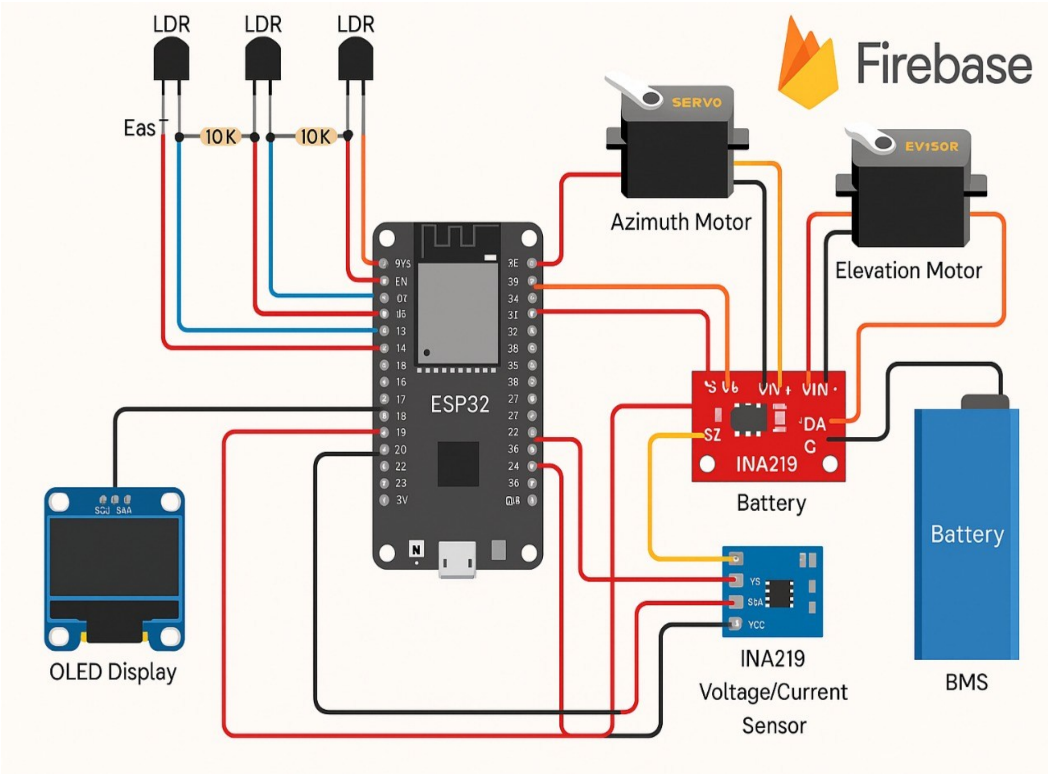


Fig 4.2: Circuit Diagram with ESP32 [Could.AI]

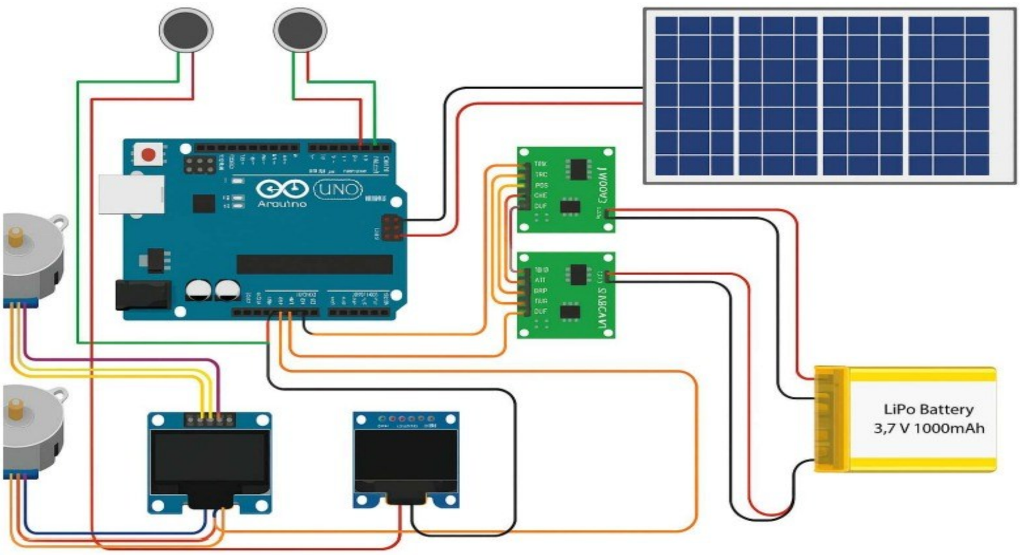


Fig 4.3: Circuit Diagram with Arduino Uno [Could.AI]

4.1.2 Working Methodology

The development of the Dual-Axis Solar Tracker with Cloud Dashboard is a multi-phase process that combines mechanical design, embedded electronics, software engineering, data communication, and system integration. The primary objective of the project is to create a smart, energy-efficient solar tracking system capable of continuously optimizing the angle of solar panels relative to the sun's position while offering robust, real-time monitoring and remote control capabilities via a cloud platform. The complete development process can be divided into four key phases: hardware setup, software development, data collection, and system integration. Each phase plays a critical role in ensuring the overall functionality, accuracy, and user-friendliness of the final system

System Design and Components

1. Microcontroller Unit – ESP32

The ESP32 microcontroller acts as the brain of the entire system. It was selected for its:

- Low power consumption, making it ideal for solar-powered applications.
- Integrated Wi-Fi and Bluetooth, enabling easy communication with cloud platforms like Firebase.
- Multiple GPIO pins, which allow the connection of numerous sensors and actuators.

Responsibilities of the ESP32 include:

- Reading light intensity values from LDR sensors.
- Controlling the dual-axis movement by driving the motors.
- Measuring voltage and current through connected sensors.
- Uploading real-time data to a cloud dashboard.
- Displaying system status locally via an OLED screen.
- Sending notifications in case of anomalies (e.g., low battery, connectivity issues).

2. Dual-Axis Movement Mechanism

The mechanical tracking system allows the solar panel to move in two planes for optimal sunlight exposure:

a. Azimuth Motor (Horizontal Movement):

- Moves the panel from East to West throughout the day.
- Tracks the sun's horizontal position across the sky.

b. Elevation Motor (Vertical Movement):

- Adjusts the panel's tilt (North-South direction).
- Compensates for seasonal variations in the sun's altitude.

c. Motor Types:

- Servo Motors: Used in basic setups where cost-efficiency and ease of control are prioritized. They offer simple positional control and require minimal configuration.
- Stepper Motors: Used in advanced systems where high precision and torque are necessary. They allow fine-tuned control of rotation angle, suitable for larger panels.

The motors are controlled based on feedback from the LDR sensors, ensuring that the panel always aligns perpendicularly to the sun's rays.

3. Light Dependent Resistor (LDR) Sensors

LDRs are the key feedback sensors that allow the system to determine the direction of maximum light intensity.

a. Sensor Placement:

- Four LDRs are placed at the cardinal edges (East, West, North, South) of the solar panel or frame.
- A central shadow-casting object (e.g., small cross partition) is used to create differences in light exposure when the panel is misaligned.

b. Functionality:

- The ESP32 reads the analog light intensity values from all four LDRs.
- It compares opposing LDR values (East vs West and North vs South).
- Based on the difference, it determines the direction and magnitude of the panel adjustment needed.
- The motors are then triggered to align the panel for maximum solar irradiance.

4. Battery and Power Management System

To ensure autonomous operation, the system uses a solar-powered rechargeable battery, monitored and protected by a Battery Management System (BMS).

a. Battery Monitoring:

- Monitors battery voltage, charge level, and discharge status.
- Ensures the ESP32 and motors have sufficient power supply, especially during low-light conditions.

b. BMS Functions:

- Overcharge protection: Prevents damage due to excessive solar input.
- Undervoltage protection: Disconnects the load when battery drops to unsafe levels.
- Load balancing: Ensures equal energy distribution between components.

c. Voltage Regulation:

- Voltage regulators or buck converters are used to provide stable voltage (typically 3.3V or 5V) for sensitive electronics like the ESP32 and sensors.

5. Cloud Dashboard (Firebase Integration)

The Firebase cloud platform is used for real-time data storage, visualization, and remote control.

a. Live Data Upload:

- ESP32 sends data such as:

- Voltage and current readings
- Battery percentage
- Power output (calculated as Voltage × Current)
- Motor angles (azimuth and elevation)

b. Web-Based Dashboard Features:

- Visual representation using dynamic charts and graphs.
- Manual override controls for adjusting panel orientation remotely.
- Data logging for historical performance analysis.
- Cloud-based diagnostics and alert settings.

c. Mobile Compatibility:

- Users can access the dashboard via any internet-enabled device (smartphone, tablet, or PC), allowing full remote control and monitoring capabilities.

6. OLED Display

For local, real-time monitoring without internet access, a compact OLED display is integrated directly with the ESP32.

a. Displayed Parameters:

- Battery voltage and charge level
- Real-time current output
- Motor angles (both horizontal and vertical)
- Wi-Fi connection status
- Error or warning messages (e.g., "Low Battery", "Tracker Offline")

b. Benefits:

- Helpful during on-site maintenance or testing.
- Ensures system status is always visible even without cloud access.

7. Voltage and Current Sensor

Used to measure the electrical performance of the solar panel.

a. Functionality:

Real-time measurement of:

- Voltage (V)
- Current (A)
- Power output (Watts = V × A)
- Detects panel efficiency, load behaviour, and charging rate of the battery.

b. Use in Project:

- Provides input to cloud dashboard and OLED display.
- Enables real-time energy flow monitoring and performance tracking.
- Helps identify anomalies in solar production.

8. 3D Printed Dual-Axis Frame

A custom-designed 3D-printed structure is used to create the dual-axis tracking frame.

a. Components:

- Rotating Base (Azimuth): Allows circular movement to track the sun from East to West.
- Tilting Upper Mount (Elevation): Adjusts the tilt angle of the panel to follow the sun's seasonal path.

b. Benefits:

- Lightweight and affordable.
- Easy to assemble and modify.
- Ideal for educational setups, prototypes, and small-scale installations.

c. Motor Integration:

- Motors are securely mounted to the frame.
- Movement is controlled via motor brackets and mechanical linkages designed for smooth and accurate operation.

9. Wi-Fi Router or Mobile Hotspot

To enable the ESP32's internet connectivity, a stable Wi-Fi source is required.

a. Function:

- Provides internet access for real-time data uploads to Firebase.
- Ensures remote access for users to control and monitor the system from anywhere.

b. Flexibility:

- Can be a home Wi-Fi network or a mobile hotspot when installed in remote locations.
- Supports auto-reconnection, allowing the ESP32 to restore cloud connection after a temporary drop.

Hardware Setup:

Mounting the solar panel: in a dual-axis solar tracker system is a critical step that directly influences the performance, accuracy, and mechanical stability of the entire setup. The solar panel is installed on a specially designed frame that allows it to move in both horizontal (East-West) and vertical (North-South) directions, enabling it to follow the sun's path throughout the day and across different seasons. This dual-axis movement is essential for maximizing solar energy absorption by keeping the panel oriented at the most optimal angle to the sun at all times.

The horizontal movement, also known as azimuth rotation, allows the panel to track the sun from sunrise to sunset, while the vertical movement, or elevation tilt, adjusts the panel's angle based on the sun's height in the sky, which varies depending on the time of day and the season. To achieve this motion, the panel is mounted on a two-part mechanical structure: a rotating base for horizontal movement and a tilting top mount for vertical movement. These two components work together seamlessly to provide full-range solar tracking.

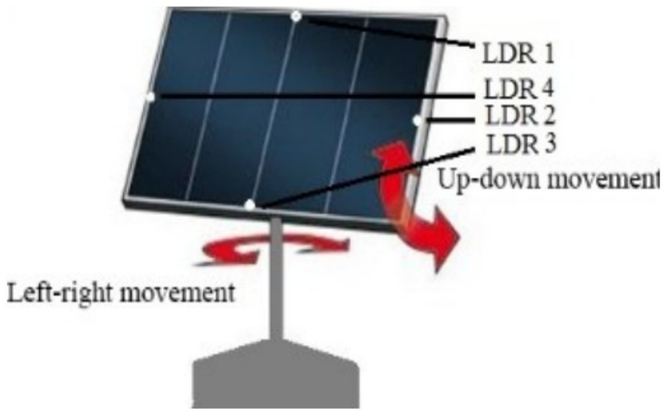
Motors-either servo or stepper-are mounted securely to control the movement of each axis. One motor is responsible for the East-West azimuth movement, and the other for the North-South elevation adjustment. These motors are connected to the frame in a way that allows smooth and controlled rotation without putting excess strain on the structure or the panel. The design ensures that the panel remains balanced and moves freely without mechanical obstruction.

Materials such as aluminium, PVC, or 3D-printed plastic are typically used for the frame due to their lightweight yet durable properties. These materials help reduce the load on the motors while ensuring the system is strong enough to support the panel and withstand outdoor elements like wind or rain. The solar panel is securely fastened to the upper part of the frame using bolts, brackets, or clamps to prevent it from shifting or falling off during movement.
Proper cable management is also important, as the wires connected to the solar panel, sensors, and control units must be arranged to allow flexibility without getting tangled or damaged during movement. Additionally, the movement of the panel must be free of any physical

obstructions, so the frame is designed with open and clean lines that support full rotation without interference.

To prevent damage, mechanical stops or limiters may be installed to restrict the panel's motion within a safe range and prevent over-rotation. The system should also be calibrated after installation to align the panel's starting position with the local geographic latitude, ensuring that the elevation movement is optimized from the beginning. Once mounted and calibrated, the system can be tested by tracking light manually or via programmed motor commands to ensure the panel responds accurately to changes in sunlight direction.

For outdoor use, the mounting frame and motors should be weatherproofed or enclosed in protective housings to safeguard them against rain, dust, and UV exposure. Overall, the solar panel mounting process requires careful design, secure installation, and precise mechanical alignment to ensure the dual-axis tracking system operates efficiently, reliably, and safely in all environmental conditions.



1.

Fig 4.4: Solar Panel

2. Motor Integration: The integration of motors is a crucial step in enabling the dual-axis movement of the solar panel, allowing it to accurately follow the sun throughout the day and across changing seasonal positions. In this system, two motors are used—one for horizontal (azimuth) movement and the other for vertical (elevation) adjustment. These motors are responsible for repositioning the solar panel to ensure it always faces the sun at the most optimal angle, thereby maximizing solar energy capture.

The first motor, known as the Azimuth Motor, controls the East-West movement of the solar panel. It allows the panel to rotate horizontally throughout the day, tracking the sun's path from sunrise to sunset. This motor is typically mounted at the base of the panel frame or beneath the rotating platform and is responsible for turning the entire panel structure horizontally. The second motor, referred to as the Elevation Motor, handles the North-

South tilt of the panel. It adjusts the vertical angle of the solar panel to account for the sun's changing elevation in the sky throughout the day and across different seasons. This motor is usually attached to the side or rear of the tilting platform and moves the panel up and down like a see-saw.

To implement precise control over these two movements, the motors used are typically either servo motors or stepper motors, depending on the desired level of accuracy and torque. Servo motors are generally used in simpler or low-cost systems, offering decent control over position with minimal circuitry. Stepper motors, on the other hand, provide high precision and are ideal for applications where fine angular adjustments are required. The choice between the two depends on the size and weight of the solar panel, as heavier panels require motors with greater torque.

Each motor is connected to the ESP32 microcontroller, which acts as the brain of the system. The ESP32 sends control signals to the motors based on data received from the LDR sensors, which detect the direction and intensity of sunlight. However, since motors cannot be directly powered or controlled by the ESP32 due to current limitations, motor drivers such as the L298N are used to interface between the microcontroller and the motors. These drivers amplify the control signals and provide the necessary voltage and current to operate the motors safely and effectively.

The wiring of the motors must be done carefully to ensure that each motor receives accurate instructions for its respective axis. The azimuth motor is connected to one set of driver inputs, while the elevation motor is connected to another, both being independently controlled by the ESP32’s GPIO pins. This separation allows the system to rotate and tilt the panel simultaneously or independently, depending on the sun's position.

Proper mounting of the motors on the panel frame is essential to ensure stable and smooth motion. The motor shafts must be aligned with the axis of rotation, and any mechanical linkages—such as gears, pulleys, or levers—should be securely fastened to minimize backlash or misalignment. Additionally, the motors should be mounted in a way that protects them from environmental damage, especially if the system is installed outdoors. In summary, the motor integration process involves selecting appropriate servo or stepper motors based on the panel's weight, securely attaching them to the frame to control dual-axis movement, connecting each motor to its respective driver, and wiring the drivers to the ESP32 for intelligent control. This setup allows the solar tracker to dynamically adjust its orientation in real-time, significantly increasing the system's energy output and overall efficiency.

3.

Fig: 4.5: MG996R Servo-motor

4. LDR Sensor Setup: The placement of the Light Dependent Resistor (LDR) sensors is a vital aspect of the dual-axis solar tracker system, as these sensors are responsible for detecting the intensity and direction of sunlight, which directly informs the movement of the solar panel. To achieve accurate sun tracking, four LDR sensors are strategically positioned either on the solar panel itself or on the surrounding frame in such a way that each sensor can capture sunlight intensity from different directions. This arrangement allows the system to compare light levels from multiple angles and determine the optimal direction for panel alignment.

   Specifically, two LDR sensors are placed on the east and west sides of the panel or frame to measure sunlight intensity along the horizontal axis, also known as the azimuth direction. These sensors help the system understand whether the sun is stronger towards the east or west, enabling the azimuth motor to rotate the solar panel accordingly to face the sun as it moves throughout the day. Similarly, two additional LDR sensors are positioned on the north and south sides to monitor sunlight intensity along the vertical axis, or elevation direction. These sensors provide information on the sun's height in the

sky, allowing the elevation motor to tilt the panel up or down to maintain an optimal angle relative to the sun's position.

Each LDR sensor is connected to an analog input pin on the ESP32 microcontroller, which reads the varying voltage levels produced by the sensors in response to changes in light intensity. The LDRs function by changing their resistance based on the amount of light they receive—higher sunlight intensity lowers their resistance, resulting in a higher voltage reading, and vice versa. This data is continuously fed to the ESP32, where it is processed and analyzed to determine the differences in sunlight intensity between the pairs of sensors on both axes.

Using these readings, the microcontroller calculates the necessary adjustments to the solar panel's orientation. For example, if the LDR on the east side detects stronger sunlight than the one on the west side, the ESP32 will command the azimuth motor to rotate the panel toward the east to maximize sunlight exposure. Likewise, if the north sensor registers more intense light than the south sensor, the elevation motor will tilt the panel upward or downward to align with the sun's vertical position.

By constantly comparing the readings from all four LDR sensors, the system dynamically adjusts the panel's position to ensure it is always facing the direction with the strongest sunlight. This feedback loop enables the solar tracker to optimize energy absorption throughout the day and across different seasons, significantly enhancing overall power generation compared to fixed solar panels. The careful placement and precise connectivity of the LDR sensors to the ESP32's analog inputs are therefore essential to achieving efficient, real-time solar tracking in the dual-axis system.

Fig 4.6: LDR Sensors

5. Battery and Power Management: The entire dual-axis solar tracking system is powered by a rechargeable battery, which serves as the primary energy source to run the microcontroller, motors, sensors, and other electronic components, especially during periods when sunlight is insufficient or unavailable. Typically, the system employs a 12-volt battery, which can be either a lead-acid type known for its reliability and cost-effectiveness or a lithium-ion (Li-ion) battery favoured for its higher energy density, lighter weight, and longer lifespan. The choice of battery depends on factors such as budget, energy requirements, size constraints, and intended application duration.

To ensure the battery operates safely and efficiently, a dedicated Battery Management System (BMS) is integrated into the setup. The BMS continuously monitors critical battery parameters, including voltage levels, current flow, temperature, and state of charge, providing real-time feedback to the microcontroller. This monitoring is essential to prevent issues such as overcharging, which can damage the battery or create safety hazards, and over-discharging, which can reduce battery life or cause system shutdown. The BMS also manages charging cycles by regulating the input current from the solar panel to optimize battery health and performance.

The solar panel itself functions as the primary energy harvesting component, converting sunlight into electrical energy to recharge the battery during daylight hours. The power generated by the panel passes through a series of power management circuits, which include voltage regulators, charge controllers, and protection circuits. These components work together to stabilize the voltage and current supplied to the battery, preventing fluctuations that could cause damage. The charge controller, in particular, plays a crucial role by ensuring that the battery receives the correct charging voltage and current, adjusting dynamically based on battery status and solar panel output.

Additionally, the power management circuitry safeguards against reverse current flow at night, which could otherwise drain the battery back into the solar panel. It also incorporates protections such as short-circuit prevention and thermal shutdown features, enhancing the overall safety and reliability of the system. The ESP32 microcontroller receives continuous updates from the BMS regarding battery voltage and charge status, enabling it to make intelligent decisions such as sending alerts when the battery level is critically low or adjusting system operations to conserve power.

By carefully integrating the battery, BMS, and power management circuits, the dual-axis solar tracker ensures a steady and safe power supply that supports uninterrupted operation. This configuration not only maximizes the longevity and efficiency of the energy storage system but also guarantees that the tracking system can function autonomously, even during periods without direct sunlight. The seamless interplay between the solar panel’s energy generation, the battery’s energy storage, and the BMS’s protective oversight is therefore fundamental to the system’s performance, reliability, and safety in real-world applications.

6.Microcontroller (ESP8266): At the heart of the entire dual-axis solar tracking system lies the ESP32 microcontroller, which serves as the central control unit responsible for managing all critical hardware and software functions. The ESP32 is specifically chosen for this project due to several key advantages that make it particularly well-suited for an intelligent, IoT-enabled solar tracker. One of its most important features is its low power consumption, which is essential for energy-efficient operation, especially when the system is powered by a limited energy source such as a battery charged by a solar panel. This low energy demand helps extend battery life and ensures that the tracker can operate continuously even under constrained power conditions.

Another major strength of the ESP32 is its built-in Wi-Fi connectivity, which enables seamless communication with cloud services and remote devices. This feature allows the microcontroller to transmit real-time data collected from various sensors directly to a cloud dashboard, such as Firebase, where users can remotely monitor system performance, analyse historical data, and receive alerts. The integrated Wi-Fi also supports remote control capabilities, so users can manually adjust the solar panel's position through a web interface or mobile app from anywhere with internet access. This connectivity makes the system highly interactive and convenient for both monitoring and management.

In terms of hardware interfacing, the ESP32 offers a rich set of input/output (I/O) pins, providing ample connectivity options to interface with multiple sensors, actuators, and

peripheral devices simultaneously. This is particularly important for the solar tracker, which requires inputs from four Light Dependent Resistor (LDR) sensors that measure

sunlight intensity from different directions, as well as control signals to operate two motors responsible for dual-axis movement. The ESP32's versatile analog and digital I/O pins enable it to read sensor data accurately and send precise commands to the motor drivers, facilitating smooth and responsive adjustments to the solar panel's orientation.

The microcontroller's onboard processing power is also a key advantage, allowing it to quickly analyse the sensor inputs and execute control algorithms that calculate the optimal movement direction for the solar panel. This processing capability ensures that the system can respond dynamically to changing sunlight conditions throughout the day and seasons, maintaining peak solar exposure and maximizing energy generation. Additionally, the ESP32 handles the communication protocols required for sending sensor readings—such as voltage, current, battery percentage, and motor position—to the cloud, enabling comprehensive real-time data logging and visualization.

Furthermore, the ESP32 supports integration with additional modules like OLED displays for on-site status monitoring, further enhancing its role as the system's command centre. Its compact size and cost-effectiveness make it an ideal choice for embedded projects where space, budget, and performance must be balanced efficiently.

In summary, the ESP32 microcontroller is the core component that powers the Dual-Axis Solar Tracker by providing low-power, high-performance control over sensors and motors, enabling Wi-Fi-based cloud connectivity for real-time monitoring and control, and supporting multiple I/O interfaces to manage the complex interactions within the system. Its combination of features makes it the backbone of this intelligent, scalable, and user-friendly solar tracking solution.

Fig 4.7: ESP8266

Software Development:

1. ESP32 Firmware and Motor Control Algorithm: At the core of the dual-axis solar tracker lies the **ESP32 microcontroller**, which runs specialized firmware programmed to handle sensor data acquisition, motor control, power monitoring, and communication with the cloud. The firmware plays a critical role in making real-time decisions to optimize the solar panel's positioning for maximum sunlight exposure.

Motor Control Algorithm

The firmware continuously reads analog voltage values from four Light Dependent Resistor (LDR) sensors strategically positioned around the solar panel to detect sunlight intensity from the east, west, north, and south directions. Using this data, the firmware calculates two main angles:

- **Azimuth angle** (horizontal movement, East-West)

- **Elevation angle** (vertical movement, North-South)

The firmware compares the light intensity detected by opposing pairs of sensors (east vs. west and north vs. south) to determine the direction in which the solar panel should move to maximize sunlight capture. For example, if the east-side LDR sensor detects stronger light than the west-side sensor, the panel needs to rotate eastward. Similarly, vertical movement is adjusted based on north and south LDR sensor readings.

Once the required angles are calculated, the firmware sends precise control signals to the motors (either servo or stepper motors depending on system design). The motors execute these commands to physically adjust the solar panel's orientation smoothly and efficiently.

Sensor Calibration Phase

A critical step in ensuring accurate tracking is **sensor calibration**. The calibration process allows the system to learn the relationship between sensor readings and motor positions. During calibration:

- The system moves the solar panel slowly until the LDR sensor receiving the maximum sunlight indicates the panel is correctly aligned.
- This movement sets the baseline reference angles for both azimuth and elevation motors.
- Calibration is especially important at system startup and after any physical adjustment or environmental changes.

Without calibration, sensor readings alone might not correspond correctly to physical motor angles, leading to suboptimal solar tracking.

Battery Monitoring and Alerts

The ESP32 continuously monitors the battery voltage using an **Analog-to-Digital Converter (ADC)** pin connected to the battery management system (BMS). This data helps in:

- Determining the battery’s current charge status.
- Sending alerts if the battery voltage falls below a predefined critical threshold, indicating low power.

- Triggering charging logic or power-saving modes when battery levels are low.
- Preventing system damage due to over-discharging.

The firmware sends these battery status updates periodically to the cloud and local display, ensuring that the user is always informed about power availability.

2. Cloud Integration (Firebase): The Dual-Axis Solar Tracker leverages cloud computing to enable real-time monitoring, data storage, and remote accessibility.

Firebase Realtime Database

The system uses Firebase Realtime Database, a cloud-hosted NoSQL database, to store and retrieve sensor data continuously. This cloud platform is selected due to its scalability, real-time data synchronization, and ease of integration with IoT devices.

The ESP32 uploads sensor readings—including voltage, current, battery percentage, and motor angles—to Firebase at regular intervals (e.g., every 5 seconds). This frequent data transmission allows for near-instant updates on the user dashboard, enabling real-time visualization of system status.

Firebase also supports data retention over long periods, allowing historical data to be archived and accessed later for performance analysis and troubleshooting.

3. Global Accessibility

Since Firebase is a cloud-hosted solution, users can access the solar tracker data globally through any internet-enabled device, including laptops, tablets, or smartphones. This accessibility provides a major advantage over traditional local monitoring, which often requires physical presence or dedicated network infrastructure.

4. Web Dashboard (Frontend): A crucial feature of the system is the **interactive web dashboard**, designed to provide users with an intuitive interface for monitoring and controlling the solar tracker.

   Technologies Used:

- **HTML, CSS, JavaScript**: These core web technologies form the foundation of the frontend, ensuring compatibility across browsers and devices.
- **Chart.js or similar libraries**: These JavaScript libraries enable dynamic rendering of interactive charts and graphs, visualizing sensor data such as voltage, current, power output, battery status, and motor positions in real time.

5. **Features and Functionality**

The dashboard displays live sensor data as well as historical trends, allowing users to:

- Monitor the solar panel's performance in terms of power generation and battery charge.
- Track motor positions to verify accurate sun alignment.
- View alert notifications in case of system faults, low battery, or connectivity issues.
- Access detailed graphs that help analyze system efficiency and behaviour over time.

Additionally, the dashboard offers a user-friendly control panel for manual operation of the solar panel, facilitating testing and calibration.

6. Manual Control via Web UI: While the system is primarily designed to operate automatically, real-world conditions sometimes require manual intervention. The web dashboard includes a manual control interface that enables users to override the automatic tracking system.

Manual Control Features

- Users can manually adjust the azimuth (horizontal) and elevation (vertical) angles through sliders or input fields on the web UI.
- This is particularly useful during **testing phases**, system calibration, or when operating under **atypical lighting conditions** such as heavy cloud cover, shading, or sensor

malfunction.

- The manual commands are sent from the dashboard to the ESP32 via the cloud, and the microcontroller drives the motors accordingly.
- Manual control ensures that the system remains flexible and can be operated even if automatic tracking is temporarily disabled or needs adjustment.

System Calibration and Testing Procedures

1. Motor Calibration: Motor calibration is essential to synchronize the physical position of the solar panel with sensor feedback. During calibration:

- The system begins by reading sunlight intensity via LDR sensors.
- Motors adjust the solar panel position slowly until the LDR receiving maximum light is aligned perfectly.
- This process can be scheduled at system startup or triggered manually from the dashboard.
- Calibration accounts for differences in mechanical setup, motor backlash, and sensor sensitivity.
- It also adapts to different seasons by modifying the range of azimuth and elevation angles according to the sun's path throughout the year.

2. Battery Management: To guarantee safe and reliable battery operation:

- The Battery Management System (BMS) undergoes rigorous testing for both **charging** and **discharging** cycles.
- The system verifies that alerts are generated when battery voltage approaches critical low levels.

- Charge and discharge current limits are validated to prevent overheating and capacity loss.
- Voltage regulation components are tested to ensure that the battery is neither overcharged nor excessively drained.
- This testing helps maintain battery health and extends its usable lifetime.

User Notifications and Alert System:

A major innovation of the dual-axis solar tracker is its real-time notification system, which keeps users informed about important system events and anomalies.

Real-Time Alerts: The system continuously monitors operational parameters and triggers alerts when:

- The battery voltage falls below a safe threshold, signalling low power.
- The solar tracker goes offline due to loss of connectivity or hardware failure.
- Cloud synchronization fails, indicating data may not be updated or accessible remotely.
- Sensor malfunctions or motor errors are detected, requiring maintenance or troubleshooting.

These alerts are sent via push notifications or emails to ensure users receive timely warnings, enabling quick response to prevent downtime or damage.

Mobile App Integration: To further enhance accessibility, the system supports integration with mobile applications that can receive push notifications. This allows users to:

- Get instant updates on the solar tracker's health and performance directly on their smartphones.
- Access the dashboard remotely without logging into a browser.
- Receive alerts even when they are away from home or the system location.

Testing and Optimization

1. Performance Testing: Comprehensive testing under various environmental conditions is critical to validate system functionality and energy efficiency. Tests include:

- Operating the solar tracker during different times of day (morning, noon, evening) and weather conditions (sunny, cloudy).
- Measuring and comparing energy output with a static solar panel of the same size.
- Verifying that dual-axis tracking improves solar exposure and power generation by an

estimated 40-60%.

2. Data Logging and Analysis: Historical sensor and performance data stored in Firebase are analysed to:

- Identify trends such as periods of low sunlight or battery depletion.
- Detect mechanical wear or sensor drift over time.
- Spot irregularities that may indicate hardware issues.
- Enable predictive maintenance by anticipating failures before they occur.

3. Optimization: Energy Efficiency: To maximize system efficiency and reliability, continuous optimization is performed on:

- **Motor Speed and Control**: Adjust motor movement speed and smoothness to balance tracking accuracy with power consumption and wear.
- **Sensor Calibration**: Refine calibration algorithms for more precise light detection and alignment.
- **Power Management**: Optimize charge/discharge cycles and sleep modes to extend battery life and reduce energy waste.
- **Network Reliability**: Enhance Wi-Fi reconnection logic and error handling to maintain continuous cloud communication even during intermittent network disruptions.

Flow Chart

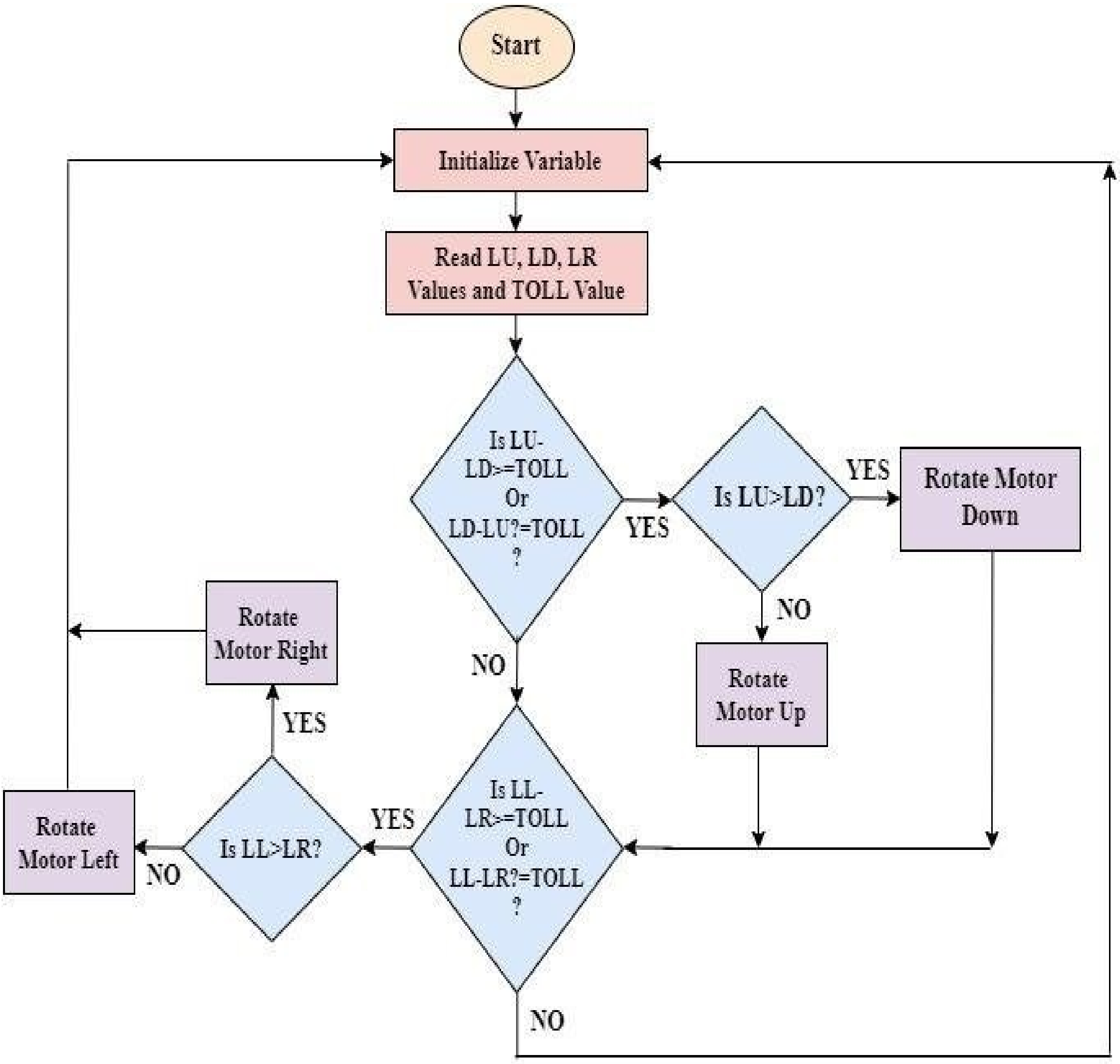


Fig 4.5: Flow Chart

The proposed solution can be implemented, as illustrated in Fig 4.5 through the following steps:

Step 1: Start Process: The system initiates tracking upon startup.

Step 2: Initialize Variables: All required variables such as LU (Left- Up), LD (Left-Down), LR (Right-Down), LL (Left-Left), and TOLL (tolerance level) are initialized to default values.

Step 3: Read LDR Sensor Values: The microcontroller reads the intensity of sunlight from the four LDRs and fetches the tolerance value.

Step 4: Evaluate Horizontal Deviation: The system checks the condition:
|LL - LR| > TOLL OR |LD - LU| > TOLL
If true, it implies misalignment in the horizontal (East-West) axis.

Step 5: Horizontal Motor Adjustment:
If LL > LR, rotate the horizontal motor left. If LL < LR, rotate the horizontal motor right.

Step 6: Evaluate Vertical Deviation: If horizontal adjustment is not required, the system checks:|LU - LD| > TOLL
If true, it implies vertical (North-South) misalignment.

Step 7: Vertical Motor Adjustment:
If LU > LD, rotate the vertical motor down (panel tilts downward). If LU < LD, rotate the vertical motor up (panel tilts upward).

Step 8: Repeat Process: The system loops back to re-read the sensor values and evaluate again, ensuring continuous sun tracking throughout the day.

Step 9: Tracking Logic Highlights: Tolerance (TOLL) prevents unnecessary small movements due to slight sensor differences. The system provides autonomous, real-time dual-axis adjustments to maximize solar energy absorption.

CHAPTER 5:

RESULTS and DISCUSSION

The development and implementation of the Dual-Axis Solar Tracking System with Cloud Dashboard have yielded several notable outcomes. The results demonstrate significant advancements in energy efficiency, real-time monitoring, mechanical simplicity, cost-effectiveness, and user interaction. Each component and feature has contributed to the enhanced functionality of the system, which has been tested and evaluated under real-world conditions.

1. Increased Efficiency with Dual-Axis Tracking:

The primary objective of the system was to enhance solar energy capture through precise sun tracking. By integrating dual-axis movement with two motors, the solar panel can adjust both horizontally (azimuth) and vertically (elevation). This allows the system to track the sun's position accurately throughout the day and across seasons. The use of four Light Dependent Resistors (LDRs) enables the detection of sunlight intensity from different directions. The system processes these readings in real time and adjusts the solar panel's position for maximum sunlight exposure.

The effectiveness of this approach was evident in the performance comparisons between the tracking system and a fixed-panel setup. The data showed that the dual-axis tracking system increased energy generation efficiency by approximately 40–60%, depending on the weather and time of year. This substantial improvement highlights the system's capacity to harness more solar power, leading to greater energy production and better battery charging rates.

2. **Reduced Mechanical Complexity and Cost:**

A key consideration during the design process was to maintain mechanical simplicity and affordability without compromising functionality. The system uses cost-effective servo or stepper motors that are capable of delivering the required torque and precision for dual-axis movement. These motors are easily integrated with the ESP32 microcontroller, allowing smooth control and responsiveness.

A 3D-printed prototype was developed to demonstrate the feasibility of the mechanical design. The printed structure includes a rotating base for azimuth control and a tilting frame for elevation adjustment. Despite being a prototype, the 3D-printed frame provided a reliable platform for movement, supporting the functionality of the system.

The selection of components such as the ESP32 and LDR sensors further contributed to the reduced cost. These components are widely available and inexpensive, making the system scalable for educational, research, or small-scale solar power applications. The simplified assembly process and low material costs enhance the system's appeal for broad adoption.

3. **Real-Time Monitoring and Control with Cloud Dashboard:**

One of the standout features of the system is its ability to provide real-time monitoring and control via a cloud dashboard. Integration with Firebase allows for continuous data logging and retrieval. The ESP32 microcontroller transmits data such as battery voltage, solar panel current, and motor angles to the cloud at regular intervals.

The web dashboard, developed using HTML, CSS, and JavaScript, offers an interactive interface where users can view live performance metrics. Using graphical libraries like Chart.js, the dashboard visualizes trends and historical data in an easy-to-understand format. Users can monitor how the system performs over time and evaluate parameters such as battery charge level, panel orientation, and energy output.

In addition to passive monitoring, the dashboard allows users to manually control the solar panel's orientation. This is especially useful for testing, calibration, or when the system is not receiving sufficient light to make automatic adjustments. The ability to intervene manually adds flexibility and control to the system's operation.

4. **Battery Management and Overvoltage Prevention:**

Efficient power management is critical for any solar tracking system, especially one designed to be self-sustaining. The system incorporates a Battery Management System (BMS) to ensure safe and effective energy storage. The BMS continuously monitors battery voltage and state of charge, sending alerts when thresholds are crossed.

During testing, the BMS successfully identified overcharging and undercharging scenarios and prompted the system to adjust power flow accordingly. This helped to extend battery life and maintain consistent power delivery to the ESP32 and motors. Alerts for low battery levels ensured that the user was informed in advance, preventing unexpected shutdowns or damage.

The ESP32 reads the battery voltage using an analog-to-digital converter (ADC) pin and interprets the values in software. The integration of this monitoring with the Firebase dashboard ensures that users can keep track of battery health remotely. By tracking charge and discharge cycles, the system ensures optimal energy utilization and overall system longevity.

5. **Mobile App and Notification Alerts:**

To enhance user interaction, the system includes mobile alerts and a responsive web interface. Firebase is configured to push notifications when key events occur, such as a drop in battery level, tracker malfunction, or loss of internet connectivity. Users receive these alerts on their smartphones or via email, enabling prompt intervention. The real-time notification system helps maintain high system availability and ensures that minor issues are addressed before they escalate.

Moreover, the manual control interface on the dashboard allows users to operate the system remotely, even when sunlight is not strong enough for the LDRs to guide the motors. This feature is particularly helpful during testing or in overcast weather conditions, where user oversight becomes necessary.

6. Wi-Fi and Internet Connectivity:

The ESP32's built-in Wi-Fi capability enables seamless connection to the internet. The microcontroller is programmed to automatically connect to a predefined Wi-Fi network and transmit data to Firebase in regular intervals.

In the event of a network failure, the ESP32 attempts to reconnect without user intervention. This automatic reconnection ensures that the system continues to function reliably even in unstable network environments.

By using cloud services, the system offers global accessibility. Users can monitor, control, and evaluate the system from anywhere in the world using a browser or mobile device. This level of connectivity is particularly advantageous for remote solar installations, where on-site monitoring is not always feasible.

7. Summary of Results:

Overall, the Dual-Axis Solar Tracking System with Cloud Dashboard has demonstrated high efficiency, user-friendly operation, and cost-effective design. The integration of mechanical, electrical, and software components was successful, and the system met its objectives in terms of energy optimization, monitoring, and remote control

- Dual-axis tracking increased energy output by up to 60%.
- Use of low-cost components made the system scalable and affordable.
- Real-time cloud integration allowed for global monitoring and manual overrides.
- The BMS provided reliable alerts for battery management.
- The system handled network issues gracefully with automatic reconnection.

These outcomes establish the system as a viable solution for increasing solar energy efficiency, especially in contexts where cost and remote access are important factors. Further improvements could involve integrating more advanced sensors, expanding the mobile app features, and implementing machine learning algorithms to predict and adjust for environmental changes.

This project lays the foundation for future developments in smart renewable energy systems and contributes to the growing field of IoT-enabled energy solutions.

Time	Voltage (V)	Current (A)	Power Output (W)	Ideal Power (W)	Efficiency (%)
10:00am	27.0	3.20	86.4	100	86.4
10:10am	28.2	3.10	87.4	100	87.4
10:20am	26.5	3.30	87.5	100	87.5
10:30am	29.0	3.15	91.4	100	91.4
10:40am	30.0	3.20	96.0	100	96.0
10:50am	28.5	3.00	85.5	100	85.5
11:00am	27.8	3.10	86.2	100	86.2

Table 5.1: Results

The electrical performance of the Dual-Axis Solar Tracker with Cloud Dashboard was evaluated based on data collected at consistent 10-minute intervals, as shown in Table 5.1. During each interval, the voltage and current generated by the solar panel were measured, and the corresponding power output was calculated using the formula $P = V \times I$. For comparison and benchmarking, an ideal power output of 100 watts was assumed, which reflects the rated capacity of the solar panel used in the prototype system. By comparing the actual measured power against this ideal value, the electrical efficiency of the system was determined and expressed as a percentage. This method provided a clear, quantitative indication of how well the solar tracker performed under varying environmental conditions throughout the observation period.

The recorded efficiencies ranged from 85.5% to 96.0%, suggesting that the system operated close to its optimal performance level across most time intervals. These high efficiency values validate the effectiveness of the dual-axis tracking mechanism, which continuously adjusts the panel orientation to face the sun with precision. It is important to note that small fluctuations in efficiency are natural and expected, given the constantly changing nature of solar irradiance due to factors such as passing clouds, ambient temperature changes, dust accumulation, or the angle of solar incidence. Nevertheless, the system consistently maintained efficiency above 85%, which is considered highly acceptable for practical solar energy applications.

One of the most notable observations from the data was that the peak efficiency of 96.0% occurred at 10:40 AM, a time when the sun's angle was optimal, and weather conditions were favorable. This high efficiency reading reflects the successful real-time tracking capability of the system, where both the horizontal and vertical axes were accurately aligned with the sun. The combination of LDR sensors and servo motor control enabled the system to dynamically respond to sunlight variations, thereby ensuring that the panel consistently received maximum exposure. This demonstrates not only the functional accuracy of the hardware and sensing components but also the reliability of the control logic programmed into the ESP32 microcontroller.

The data further indicates that the efficiency values remained relatively stable over the monitored period, showing only minor variations between consecutive time points. For instance, even when slight drops in voltage or current occurred—likely due to momentary environmental interference—the overall impact on efficiency remained minimal. This stability can be attributed to the system’s ability to adapt quickly through constant feedback from the sensors, which allowed real-time adjustments to panel positioning. The responsiveness of the system played a significant role in minimizing power losses and maintaining high conversion rates throughout the day.

Another point of interest is the alignment of peak performance times with periods of highest sunlight intensity, affirming that the system effectively capitalizes on optimal solar conditions. The analysis also underscores the benefit of dual-axis movement compared to single-axis or fixed-panel systems. While fixed systems are limited by static angles and single-axis trackers may only adjust in one direction, this dual-axis system offers superior flexibility and adaptability, ensuring that the panel is always aligned with the sun’s position across both azimuth and elevation.

In addition to power and efficiency, the collected data provides valuable insights into how solar tracking systems behave under real-world conditions. The measured voltage and current values reflect the inherent variability of solar energy sources, reinforcing the importance of dynamic tracking solutions for maximizing power yield. Moreover, the close proximity of the actual output to the ideal benchmark confirms the practical feasibility of implementing this system in both small-scale residential settings and larger solar farms, where efficient energy conversion is crucial.

In conclusion, the comparative efficiency analysis shown in Table 5.1 reveals that the Dual-Axis Solar Tracker with Cloud Dashboard consistently delivers high electrical performance. With efficiency levels ranging from 85.5% to 96.0%, the system operates effectively under diverse environmental conditions and demonstrates the benefits of real-time sun tracking. The data supports the assertion that intelligent sensor integration and continuous panel adjustment can significantly enhance solar energy harvesting. This performance assessment highlights the project’s success in developing a reliable, efficient, and adaptable solar tracking system capable of maintaining optimal energy output throughout the day. Future work could involve extending the monitoring period to include different seasons or weather conditions and incorporating AI-based prediction models to further optimize tracking behavior and efficiency.

Fig 5.1: Results: a) Voltage vs Time b) Current vs Time c) Power vs Time d) Voltage vs Current e) Voltage vs Power

a) Voltage vs Time

This graph shows a gradual rise in voltage as solar irradiance increases with time. The dual-axis tracker effectively aligns the panel to the sun, resulting in improved voltage output until it stabilizes close to its peak.

b) Current vs Time

The current output follows a similar trend as the voltage, with increasing values corresponding to enhanced solar alignment and irradiance. The current plateaus as the sun's position becomes optimal.

c) Power vs Time

Since power is the product of voltage and current, this graph demonstrates a steeper increase due to the compounded effect. The curve exhibits a peak and minor stabilization, suggesting maximum power point tracking (MPPT) performance.

d) Voltage vs Current

This plot indicates a near-linear relationship under stable irradiance conditions. The proportional increase suggests minimal shading and consistent light exposure on the panel.

e) Voltage vs Power

This graph confirms that as voltage increases, the power output also increases significantly. The curvature of the graph may indicate the behavior near the panel’s maximum power point, which is crucial for MPPT algorithms.

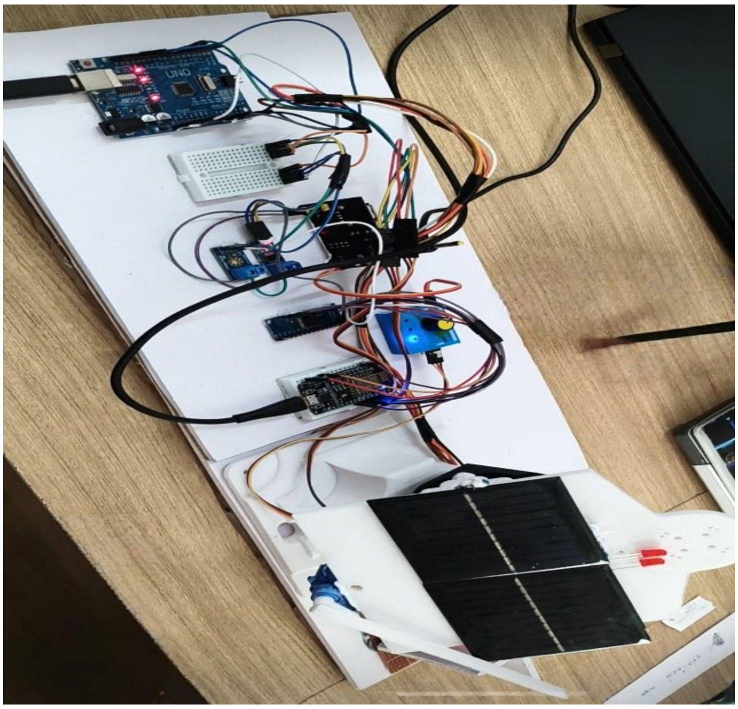


Fig 5.2: Prototype developed

CHAPTER 6:

CONCLUSION and FUTURE TRENDS

6.1 Conclusion

The Dual-Axis Solar Tracker with Cloud Dashboard successfully showcases a smart, efficient, and scalable approach to maximizing solar energy collection through the integration of real-time tracking and IoT technology. By using a dual-axis mechanical structure, the system enables the solar panel to follow the sun's path across both horizontal and vertical axes. This dynamic alignment significantly improves energy harvesting compared to fixed solar panels, as it allows for maximum exposure to sunlight throughout the day. The project utilizes Light Dependent Resistors (LDRs) as the primary sensing elements to detect the sun's position, which then guides servo motors to reposition the panel accordingly.

At the core of the system lies the ESP32 microcontroller, which plays a vital role in coordinating sensor input, motor control, and cloud connectivity. It ensures fast and reliable data processing, enabling the system to react in real time to changing light conditions. The system is connected to the Firebase Realtime Database, which stores live tracking data, logs historical performance, and supports remote monitoring and control. Users can view system metrics such as light intensity, panel angle, and battery status via a cloud-based dashboard accessible on web and mobile platforms. This provides both transparency and convenience, making it easier to manage and analyze solar performance from virtually anywhere.

In addition to remote access, the system includes a local OLED display that shows real-time data on-site, allowing users to verify system operation without the need for internet access. A Battery Management System (BMS) has been implemented to monitor and protect the battery from overcharging or deep discharging, thereby enhancing the system's reliability and lifespan. The inclusion of manual override functionality through the cloud interface further adds to the system's fault tolerance. This feature allows users to manually reposition the solar panel in cases of sensor failure, environmental interference, or testing, ensuring consistent operation under various conditions.

An important aspect of the project is the use of a 3D-printed prototype, which demonstrates how the system can be built cost-effectively using accessible materials. This adds significant educational value, as it allows students and researchers to replicate, modify, and study the design for academic and prototyping purposes. The modularity of the system's design enables easy upgrades or changes, making it suitable for integration into larger systems or for field experimentation. It also supports scalability for broader applications in residential, agricultural, or remote solar energy installations.

This project combines several essential technologies—embedded systems, sensor-based automation, real-time data analytics, and IoT connectivity—into one cohesive solution. The result is a robust platform that improves solar tracking efficiency while also offering user-friendly interfaces and monitoring tools. The availability of historical data via Firebase also opens up possibilities for performance optimization and trend analysis, which could be useful for future predictive control strategies or research studies.

Looking forward, this system provides a strong foundation for enhancements such as AI-based optimization, which could use weather data and sunlight forecasts to plan panel movements more efficiently. The design is also well-suited for integration with smart grid technology, enabling energy feedback into the grid or load-balancing based on demand. Additional improvements could include environmental durability upgrades for long-term deployment, integration with mobile applications for enhanced user experience, and the use of wireless modules for expanded connectivity.

In conclusion, the Dual-Axis Solar Tracker with Cloud Dashboard presents a practical, innovative, and future-ready solution to the limitations of traditional solar power systems. It effectively addresses the challenge of solar alignment through intelligent tracking while offering real-time visibility and control through IoT platforms. The system's educational impact, combined with its technical capabilities and potential for expansion, positions it as a significant contribution to the advancement of sustainable energy technology and smart automation. As the world moves toward more efficient and intelligent energy systems, this project offers a compelling example of how embedded systems and cloud technology can drive meaningful progress in renewable energy solutions.

6.2 Future Trends and Enhancements

1. **Integration with Artificial Intelligence (AI) and Machine Learning (ML):**
   - Predictive Sun Tracking: Future versions can incorporate ML algorithms to predict the sun's position based on geographic data, historical sunlight patterns, and weather forecasts. This can optimize motor movements and reduce energy consumption by minimizing unnecessary tracking adjustments.
   - Anomaly Detection: AI-based analytics can be used to identify abnormal system behavior, such as sensor failures or power drops, allowing for predictive maintenance and enhanced reliability.
   - Performance Optimization Models: ML models can analyze historical solar irradiance and power generation data to suggest panel orientation strategies that yield maximum energy in specific locations or seasons.

2. **Smart Grid and IoT Integration: Grid-Tied Operation:**
   - Future systems can be integrated with smart grid infrastructure, enabling the solar tracker to not only optimize self-consumption but also feed excess energy into the grid based on demand. Device-to-Device Communication: Integration with other IoT devices, such as smart inverters, weather stations, and home energy management systems, can enable coordinated energy usage and better grid interaction.
   - Edge Computing Capabilities: Incorporating local edge computing can offload real time processing from the cloud, enabling faster response times and offline decision-making during internet outages.

3. **Enhanced Cloud and Data Analytics Features:**

- Advanced Dashboards: Future dashboards can offer energy forecasting, carbon savings visualization, ROI calculations, and customizable reports.
- Data Sharing and Remote Collaboration: Cloud platforms can support multi-user access, allowing teams to collaborate remotely on monitoring, analysis, and system diagnostics.
- API Integration: External platforms (e.g., weather APIs, Google Maps) can be integrated into the dashboard for contextual data, enhancing system intelligence.

4. **Renewable Hybrid Systems:**
   - Wind-Solar Hybrid Integration: Combining the solar tracker with wind turbines can ensure round-the-clock renewable energy generation, especially in regions with inconsistent sunlight.
   - Hydrogen and Battery Storage Solutions: Integration with green hydrogen systems or advanced battery packs (e.g., LiFePO4) will allow for greater energy autonomy and scalability.

5. **Advanced Sensors and Feedback Systems:**
   - Sun Position Sensors and GPS Integration: Use of dedicated solar position sensors, IMUs (Inertial Measurement Units), or GPS modules can improve tracking accuracy and automate seasonal alignment.
   - Weather-Adaptive Tracking: By integrating rain, wind, and cloud sensors, the system can respond to weather conditions by adjusting panel tilt to prevent damage or optimize collection during diffuse sunlight.

6. **Mobile and Voice-Controlled Interfaces: Mobile App Enhancements:**
   - Future mobile applications can include AR visualizations, smart troubleshooting assistants, and voice control features (e.g., using Google Assistant or Alexa).
   - Offline App Functionality: Offline syncing and local dashboards within the mobile app can allow rural or remote users to interact with the system without relying on

continuous internet access.

7. **Renewable Hybrid Systems:**
    - Wind-Solar Hybrid Integration: Combining the solar tracker with wind turbines can ensure round-the-clock renewable energy generation, especially in regions with inconsistent sunlight.
    - Hydrogen and Battery Storage Solutions: Integration with green hydrogen systems or advanced battery packs (e.g., LiFePO4) will allow for greater energy autonomy and scalability.

8. **Industrial-Scale Deployments:**
    - Scalable Architecture: The system can be adapted for multi-panel solar farms by implementing a master-slave control system, where one central ESP32 controls multiple trackers or syncs them via a mesh network.
    - Commercial Cloud Platforms: Migration from Firebase to enterprise cloud platforms such as AWS IoT Core, Microsoft Azure IoT Hub, or Google Cloud IoT can allow handling of large datasets and user bases with better scalability and security.

9. **Advanced Sensors and Feedback Systems:**
    - Sun Position Sensors and GPS Integration: Use of dedicated solar position sensors, IMUs (Inertial Measurement Units), or GPS modules can improve tracking accuracy and automate seasonal alignment.
    - Weather-Adaptive Tracking: By integrating rain, wind, and cloud sensors, the system can respond to weather conditions by adjusting panel tilt to prevent damage or optimize collection during diffuse sunlight.

10. **Sustainability and Cost Optimization:**
    - Use of Recyclable Materials: The prototype and final system structures can be designed using biodegradable or recyclable 3D-print materials, reducing the environmental footprint.

REFERENCES

[1] S. Ravikumar, I. Eugene Berna, K. Vijay, R. Pradeep, and R. Babu, "Enhancing Solar Energy Harvesting Efficiency: A Dual-Axis Solar Tracking System," in Proc. 4th Int. Conf. on Innovative Practices in Technology and Management (ICIPTM), 2024. [Online]. Available: https://doi.org/10.1109/ODICON62106.2024.10797566

[2]. M. S. Mukundaswamy, C. Rajinikanth, B. Akshitha, K. G. Chitrashree, C. M. Gowthami, and N. R. Suchithra,"IoT-Based Solar Tracking System with Automatic Dust Monitoring System," International Research Journal of Advanced Engineering and Hitech, 2024. [Online]. Available: Local Journal.

[3]. [Authors not specified], "An Intelligent Dual-Axis Solar Tracking System for Remote Weather Monitoring in the Agricultural Field," Agriculture, vol. 13, no. 8, p. 1600, 2023. [Online]. Available: https://www.mdpi.com/2077-0472/13/8/1600

[4]. [Authors not specified], "IoT-Based Smart Solar Energy Monitoring System with Wiping Mechanism," Int. J. Eng. Res. Technol. (IJERT), vol. 10, no. 9, 2021. [Online]. Available: https://www.ijert.org/iot-based-smart-solar-energy-monitoring-system-with-wiping mechanism

[5]. J. Samuel and B. Rajagopal, "Smart IoT Based PV Panel Cleaning System," Int. J. Res. Appl. Sci. Eng. Technol. (IJRASET), vol. 10, no. 5, 2022. [Online]. Available: https://www.ijraset.com/research- paper/smart-iot-based-pv-panel-cleaning-system

[6]. H. Mousazadeh, A. Keyhani, A. Javadi, H. Mobli, K. Abrinia, and A. Sharifi, "A review of principle and sun-tracking methods for maximizing solar systems output," Renewable and Sustainable Energy Reviews, vol. 13, no. 8, pp. 1800–1818, 2009.

[7] J. Rizk and Y. Chaiko, "Solar tracking systems: Technologies and trackers drive types – A review," Renewable and Sustainable Energy Reviews, vol. 12, no. 5, pp. 1180–1201, 2008.

[8] N. M. Kumar, A. Rajasekaran, and P. Venkatesh, “IoT- enabled solar energy monitoring system with real-time data logging and remote access,” Materials Today: Proceedings, vol. 33, pp. 2556–2561, 2020.

[9] R. Patel and S. Sharma, “Cloud-based energy monitoring for solar PV systems using ESP32 and Firebase,” International Journal of Renewable Energy Research (IJRER), vol. 11, no. 2,pp. 789–800, 2021.

[10] S. Abdallah and S. Nijmeh, “Two-axis sun tracking system with PLC control,” Energy Conversion and Management, vol. 45, no. 11–12, pp. 1931–1939, 2004.

[11] I.Sefa, M. Demirtas, and M. Colak, “Design and implementation of a dual-axis solar tracker based on LDR sensors,” Journal of Energy Engineering, vol. 135, no. 3, pp. 95– 102, 2009.

[12] L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, “A review on the key issues for lithium-ion battery management in electric vehicles,” Journal of Power Sources, vol. 226, pp. 272–288, 2013.

[13] O. Tremblay and L. A. Dessaint, “Experimental validation of a battery dynamic model for EV applications,” World Electric Vehicle Journal, vol. 3, no. 2, pp. 289–298, 2009.

[14] I. Gibson, D. Rosen, and B. Stucker, Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, 2nd ed. Springer, 2015.

[15] K. S. Reddy, T. K. Mallick, A. R. Reddy, and K. S. R. Annamalai, “Design and optimization of a dual-axis solar tracker using finite element analysis,” Solar Energy, vol. 174, pp. 1024– 1034, 2018.

APPENDIX A:

Plagiarism Report

APPENDIX B:

Research Publications