iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** IV **Month of publication:** April 2025

DOI: https://doi.org/10.22214/ijraset.2025.68525

Dual-Axis Solar Panel Tracking System

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Abstract: The Dual-Axis Solar Panel Tracking System is an advanced solution designed to enhance solar energy efficiency by dynamically adjusting the panel's position to follow the sun's movement throughout the day. Unlike fixed solar panels, which have limited energy absorption due to their stationary nature, this system optimizes solar power generation by enabling both horizontal and vertical adjustments. The system continuously monitors sunlight direction and adjusts the solar panel accordingly, ensuring maximum exposure for higher energy conversion rates. In addition to tracking sunlight, it also monitors environmental parameters such as temperature and humidity, displaying real-time data for analysis and system optimization. The collected solar energy is stored and utilized for practical applications, demonstrating the system's effectiveness in renewable energy management. By integrating smart automation and energy storage capabilities, this system not only increases power generation efficiency but also contributes to the advancement of sustainable energy solutions. Its ability to function autonomously with minimal manual intervention makes it a promising technology for solar power applications in residential, industrial, and remote areas.
Keywords: Node MCU ESP8266, Arduino IDE, Microcontroller, Servomotor, LDR, LCD, DHT11 Sensor, Power Supply, Dual-axis, Rotation, Real-time display, Automation, Testing, Programming, Thing Speak Integration, Firmware.

I. INTRODUCTION

Solar energy is one of the most abundant and sustainable sources of renewable energy, offering a clean and cost-effective solution to meet global energy demands. However, conventional fixed solar panels have limitations in capturing maximum sunlight throughout the day due to their static positioning. To address this challenge, a dual-axis solar panel tracking system has been developed to optimize energy absorption by automatically adjusting the panel's orientation based on the sun's movement. By tracking sunlight in both horizontal and vertical directions, this system ensures that the solar panel receives maximum solar radiation at all times, thereby significantly improving energy efficiency. Additionally, the integration of automated control and environmental monitoring features enhances the system's adaptability and functionality. As renewable energy becomes increasingly vital for sustainable development, this solar tracking system offers a promising solution for maximizing solar power generation while reducing dependence on conventional energy sources. The Dual-Axis Solar Panel Tracking System is an intelligent and innovative solution aimed at enhancing the efficiency of solar energy generation. Unlike conventional fixed panels, this system actively tracks the sun's movement in both horizontal and vertical axes, ensuring optimal sunlight exposure throughout the day. This dynamic alignment significantly improves energy absorption and overall power output. The system is powered by a NodeMCU microcontroller, which processes data from four LDR sensors to determine the sun's position and control servo motors for precise panel adjustments. Additionally, it incorporates a temperature and humidity sensor to monitor environmental conditions, which are displayed in real time on an LCD screen for better performance analysis. By integrating automation, sensor technology, and energy storage, this system presents a reliable, scalable, and eco-friendly solution for residential, industrial, and remote solar applications. It not only boosts power generation but also supports the global move toward renewable and sustainable energy sources**.**

II. LITERATURE REVIEW

A. Related Work

1) Dual-Axis Solar Tracking System for Enhanced Photovoltaic Efficiency: This study presents a dual-axis solar tracking system designed to optimize photovoltaic energy harvesting by continuously aligning the solar panel with the sun's position. The system utilizes sensors to determine the optimal tilt and rotation angles, improving energy conversion efficiency compared to fixed panels. Experimental results demonstrate that the proposed system increases power output by 30% under varying weather conditions. The implementation of real-time monitoring further enhances performance analysis, making it a viable solution for sustainable energy applications.

2) IoT-Enabled Dual-Axis Solar Tracking for Smart Energy Systems: The increasing demand for renewable energy has led to the development of smart solar tracking systems. This project introduces an IoT-based dual-axis solar tracker that adjusts the solar panel's orientation dynamically using real-time data. The system incorporates environmental sensors and a wireless communication module to transmit data for monitoring and optimization. The results indicate significant improvements in power output, demonstrating the potential of IoT integration in solar energy systems.
3) Design and Implementation of an Autonomous Dual-Axis Solar Tracker: Fixed solar panels often suffer from reduced efficiency due to their inability to adapt to changing sunlight positions. This project proposes an autonomous dual-axis solar tracker that continuously adjusts the panel's tilt and rotation to maximize energy absorption. The system is controlled by a microcontroller and employs light sensors to detect the sun's position. Experimental validation shows a 25% increase in power output compared to traditional solar panel setups.
4) Smart Dual-Axis Solar Tracking System Using Artificial Intelligence: This research introduces an AI-driven dual-axis solar tracking system that optimizes energy absorption using machine learning algorithms. The system learns from historical sunlight patterns and adjusts the solar panel's position accordingly, reducing energy losses due to environmental changes. The proposed system demonstrates a 35% efficiency improvement over static panels and enables predictive tracking for enhanced solar energy management.
5) FPGA-Based Dual-Axis Solar Tracking System for Renewable Energy Optimization: This study presents a field-programmable gate array (FPGA)-based solar tracking system designed for real-time energy optimization. The system employs advanced digital control techniques to enhance precision and response time in solar tracking. Performance evaluations indicate a significant increase in energy efficiency, making it a viable solution for large-scale solar energy applications.

B. Problem Statement

1) Traditional solar panels are fixed in position and do not adjust to the sun's movement, leading to suboptimal energy absorption.
2) Fixed solar systems lose efficiency during different times of the day and across seasons due to improper panel alignment.
3) Lack of automation in conventional systems increases the need for manual intervention, making them impractical for remote or unattended installations.
4) Existing systems often do not include real-time environmental monitoring (e.g., temperature and humidity), which limits performance analysis and optimization.
5) Inefficient energy storage mechanisms prevent effective use of harvested solar power, especially during non-sunny hours.
6) There is a growing need for smart, self-adjusting solar systems that improve energy generation efficiency while being cost-effective and low maintenance.
7) The absence of IoT integration in many current systems limits remote monitoring and data-driven decision-making for energy management.

III. EXISTING SYSTEM

Dual-axis solar tracking systems are designed to follow the sun's path in both azimuth (horizontal) and altitude (vertical) directions to maximize energy harvest throughout the day and across seasons. Several existing methods have been developed for implementing such systems, categorized mainly into mechanical designs**,** tracking control algorithms**,** and sensing technologies.

A. Mechanical Designs

- Rotary Actuators and Motors**:** Most dual-axis trackers use stepper or servo motors for precision movement. Mechanical linkages are designed to support movement along two axes.
- Gear and Chain Mechanisms: For durability and high load handling, some systems utilize gearboxes or chain drives, especially in large-scale solar farms.

B. Control Strategies

- Open-loop Control Systems: These use predefined astronomical equations (e.g., Solar Position Algorithm - SPA) to calculate sun position based on time, date, and location. No feedback is used.

  Advantages: High accuracy in clear weather, no sensor needed.

  Disadvantages: Not adaptive to weather changes or local shading.

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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- Closed-loop Control Systems: These rely on real-time feedback from sensors (typically LDRs or photodiodes) to adjust panel orientation.
  Advantages: Simple implementation, responsive to real-time sun position.
  Disadvantages: Susceptible to inaccuracies in cloudy or diffused lighting conditions.
- Hybrid Control Systems: Combine open-loop and closed-loop systems to benefit from both precision and adaptability.
  Example: Sun tracking is guided primarily by astronomical algorithms, but minor real-time corrections are made via sensor feedback.

C. Sensing Technologies

- Light-Dependent Resistors (LDRs): Commonly used in simple closed-loop systems due to low cost and ease of use.
- Photodiodes and Phototransistors: Offer faster and more linear response than LDRs.

D. Energy Consumption Optimization

- Some systems implement power-aware tracking, where the panel does not continuously move but adjusts position only when significant power gain is expected, reducing motor usage.

E. IoT and Smart Tracking

- Integration of IoT and wireless communication allows remote monitoring, control, and data logging.
- AI and machine learning algorithms are emerging for predictive tracking and fault detection.

IV. PROPOSED SYSTEMS

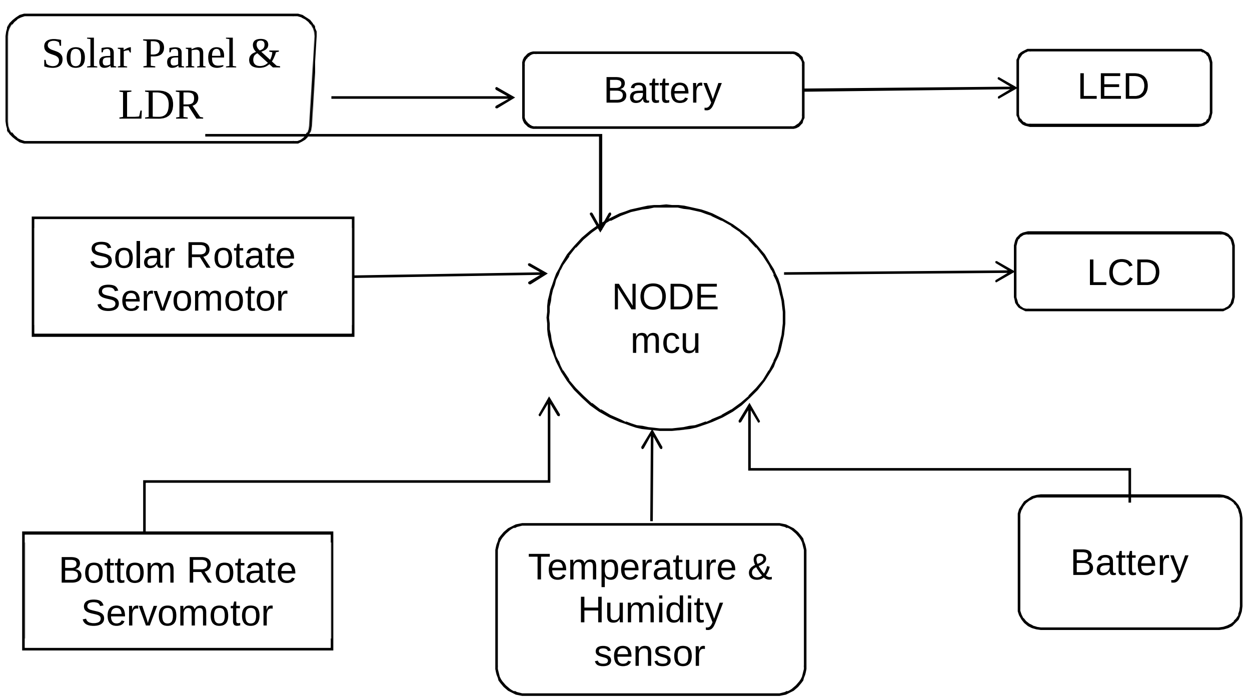

Fig.4.1. Block Diagram for Proposed Systems

The proposed Dual-Axis Solar Panel Tracking System is designed to enhance the efficiency of solar energy harvesting by automatically adjusting the panel's orientation based on the sun's movement. This system uses NodeMCU as the central microcontroller to process real-time data and control the movement of the solar panel. Four Light Dependent Resistors (LDRs) are strategically placed to detect the sun's position and send signals to the controller, which then adjusts the panel's alignment accordingly.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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The system employs two servo motors—one for 360-degree rotation at the base and another for tilt adjustment—to ensure maximum exposure to sunlight throughout the day. A temperature and humidity sensor continuously monitors environmental conditions, and the data, including solar power output, is displayed on an LCD screen.

The power supply consists of two 3V batteries, where one powers all components, and the other stores solar energy, which is later used to power a test LED light.

This automated system improves energy conversion efficiency, reduces manual intervention, and contributes to the advancement of smart renewable energy solutions.

- Feasibility Study: The Dual-Axis Solar Panel Tracking System is evaluated for feasibility across multiple dimensions, including technical, economic, operational, and environmental aspects to determine its practicality and efficiency in real-world applications.
- Technical Feasibility: The proposed system utilizes readily available and cost-effective components, including NodeMCU, LDR sensors, servo motors, and a temperature and humidity sensor, making implementation straightforward. The system's microcontroller is capable of handling real-time data processing, ensuring precise solar tracking. The integration of LCD display and solar energy storage enhances the system's usability. Given the reliability of existing technologies and ease of implementation, the technical feasibility of this project is high.
- Economic Feasibility: The project is designed to be a low-cost and energy-efficient solution for optimizing solar power generation. Compared to conventional fixed solar panels, the addition of an automated tracking system improves power output by a significant margin, leading to a better return on investment over time. The use of low-power servo motors and microcontrollers ensures minimal operational costs. Given the rising global interest in renewable energy, this system offers an economically viable solution for residential and industrial solar applications.
- Operational Feasibility: The system is designed to operate autonomously with minimal human intervention. The NodeMCU microcontroller automates the tracking process, while sensors ensure real-time adjustment of the solar panel. Additionally, the system requires low maintenance, making it feasible for long-term use in various locations, including urban and remote areas. The LCD display provides useful real-time data, ensuring users can monitor performance efficiently.
- Environmental Feasibility: Solar energy is a clean and renewable energy source, and the proposed system further enhances its efficiency. By maximizing solar energy absorption, the system reduces dependence on non-renewable energy sources, thereby minimizing carbon emissions. Additionally, since the components used are energy-efficient and environmentally friendly, the overall environmental impact of this system is minimal.

A. Hardware & Software Specification

1) Hardware

- Solar Panel – Converts sunlight into electrical energy.
- NodeMCU (ESP8266) – Acts as the microcontroller, processing sensor data and controlling servo motors.
- Light Dependent Resistors (LDR) (x4) – Detects the sun's position and provides input to adjust panel orientation.
- Servo Motors (x2) – Controls the movement of the solar panel One for 360-degree base rotation Another for tilting the panel in the sun's direction.
- Temperature & Humidity Sensor (DHT11/DHT22) – Measures environmental conditions and displays values on the LCD.
- LCD Display (16x2 or 20x4) – Shows real-time solar power output, temperature, and humidity values.
- Battery (3V x2) – One pair powers all components. The second stores solar energy for testing with an LED light.
- LED Light – Used to test solar energy storage efficiency.
- Power Supply Module – Regulates voltage to the microcontroller and other components

2) Software

- Arduino IDE.
- Thing view.

B. System Design

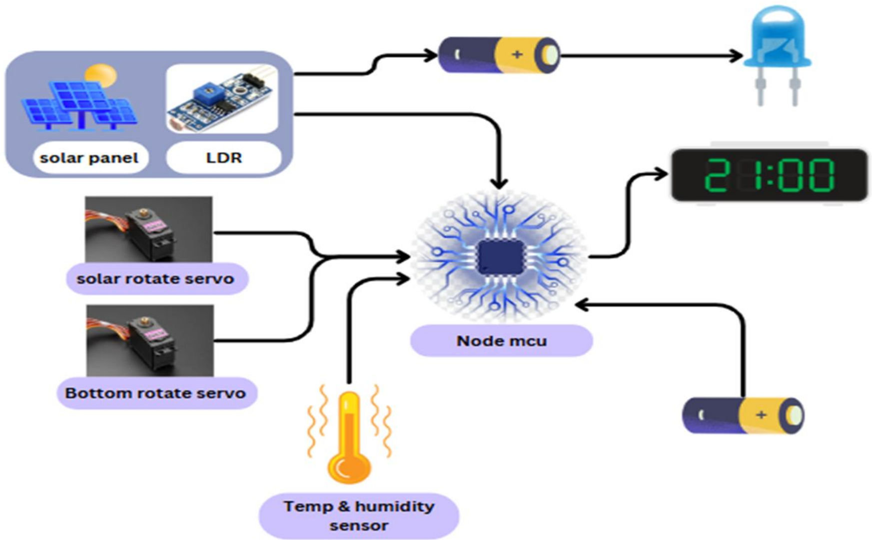

Fig.4.2. Architecture Diagram for Proposed System

1) Key Features and Functionalities

The proposed system includes the following key features:

a) Dual Axis Movement:
- Tracks the sun in both azimuth (horizontal) and altitude (vertical) directions.
- Maximizes solar panel exposure throughout the day.

b) Real-Time Sun Tracking:
- Uses light-dependent resistors (LDRs) or sensors to detect sunlight intensity.
- Continuously adjusts panel orientation for optimal sunlight capture.

c) Automatic Control System:
- Microcontroller-based automation (e.g., Arduino or PIC).
- No manual intervention required once powered.

d) Energy Efficiency:
- Increases overall power output by 40–45% compared to fixed panels.
- Efficient use of solar energy throughout daylight hours.

e) Motor Control Mechanism:
- Stepper or servo motors control panel rotation.
- Accurate angle adjustments based on sensor inputs.

f) Power Management System:
- Regulates power to motors and control system from solar output or battery.
- Can be integrated with battery charging systems.

g) Reset Mechanism:
- Returns to default position after sunset.
- Ready for sunrise the next day.

h) Compact and Scalable Design:
- Suitable for rooftop as well as large solar farms.
- Can be scaled based on power requirements.

i) Low Maintenance:
- Simple construction using durable components.
- Designed for long-term outdoor use.

2) Advantages of the Proposed System

The proposed system offers multiple advantages over traditional solar tracking methods:

- The system increases energy efficiency by tracking the sun's movement in both horizontal and vertical directions, maximizing solar energy capture throughout the day.
- It offers a quicker return on investment, as the higher power output compensates for the initial cost over a shorter period of time.
- By generating more clean energy, it significantly reduces carbon emissions and supports a sustainable environment.
- The tracker adapts to seasonal and weather changes, ensuring consistent performance even during cloudy or low-sunlight days.
- Its flexible and scalable design makes it suitable for various terrains and purposes, including residential, industrial, and educational use.

3) Summary of the Proposed System

The proposed system is a Dual Axis Solar Panel Tracking System designed to maximize solar energy absorption by continuously aligning the solar panel with the sun's position. It uses sensors (like LDRs) to detect sunlight intensity and controls servo or stepper motors through a microcontroller to adjust the panel's angle in both horizontal (azimuth) and vertical (altitude) directions. This real-time tracking ensures that the solar panel remains perpendicular to the sun's rays throughout the day, thereby significantly increasing power output.

The system operates automatically, requires minimal human intervention, and is suitable for various environments. It is energy-efficient, eco-friendly, and scalable — ideal for residential, industrial, and educational applications. The goal is to improve energy harvesting efficiency compared to traditional fixed or single-axis systems, offering a sustainable and smart solar solution.

V. IMPLEMENTATION METHODOLOGY

A. Materials and Methods

The Dual-Axis Solar Panel Tracking System is designed to enhance solar energy efficiency by automatically adjusting the panel's position to track the sun throughout the day. This system utilizes a microcontroller-based approach, integrating light-dependent resistors (LDRs) to detect sunlight direction and servo motors to align the panel accordingly. The NodeMCU serves as the central controller, processing sensor inputs and controlling the movement of the solar panel to ensure maximum exposure to sunlight. Additionally, the system incorporates a temperature and humidity sensor to monitor environmental conditions, with real-time data displayed on an LCD screen. A dual-battery setup is implemented, where one battery powers the system components, while the other stores solar-generated energy, which is later utilized for testing purposes, such as lighting an LED.

To develop this system, a structured methodology is followed, beginning with the design and planning phase**,** where the optimal placement of sensors and actuators is determined. The hardware assembly involves mounting the LDRs at four corners of the solar panel to detect sunlight intensity variations, installing servo motors to enable 360-degree horizontal rotation and vertical tilting, and integrating the NodeMCU, LCD display, and power supply components. Once the hardware is set up, the software implementation is carried out using the Arduino IDE, where an embedded C/C++ program is developed to process sensor data, control the motors, and display relevant information on the LCD. The system is then subjected to extensive testing and calibration, ensuring accurate response to sunlight direction, proper motor functioning, and reliable data display. Various environmental conditions are simulated to validate the system's adaptability and energy output.

Finally, performance evaluation and optimization are conducted by deploying the system outdoors for extended periods. The energy output is monitored and compared with that of a fixed solar panel to measure efficiency improvements. Adjustments are made to sensor sensitivity, motor speed, and power management to achieve optimal performance. The incorporation of an IoT-based monitoring system using platforms like ThingSpeak or Blynk can further enhance remote accessibility and data analysis. By following this structured methodology, the Dual-Axis Solar Panel Tracking System effectively maximizes solar energy capture, improves renewable energy utilization, and demonstrates a cost-effective, scalable approach to solar tracking technology.

B. Component Description

1) NodeMCU (ESP8266 Microcontroller):

The NodeMCU (ESP8266**)** is the core processing unit of the system, responsible for reading sensor inputs, executing control algorithms, and managing servo motor movements. It is a low-power, Wi-Fi-enabled microcontroller that allows efficient communication with external components and supports IoT integration.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

The microcontroller receives real-time data from light-dependent resistors (LDRs) to determine the optimal direction for solar panel alignment. Based on the sensor data, the NodeMCU calculates the necessary adjustments and sends control signals to the two servo motors that adjust the panel's position in both horizontal and vertical axes. Additionally, the NodeMCU interfaces with the temperature and humidity sensor to collect environmental data, which is then displayed on the LCD screen. This real-time monitoring capability enhances the system’s functionality, making it not only an efficient energy-harvesting mechanism but also a smart, data-driven solar tracking solution.

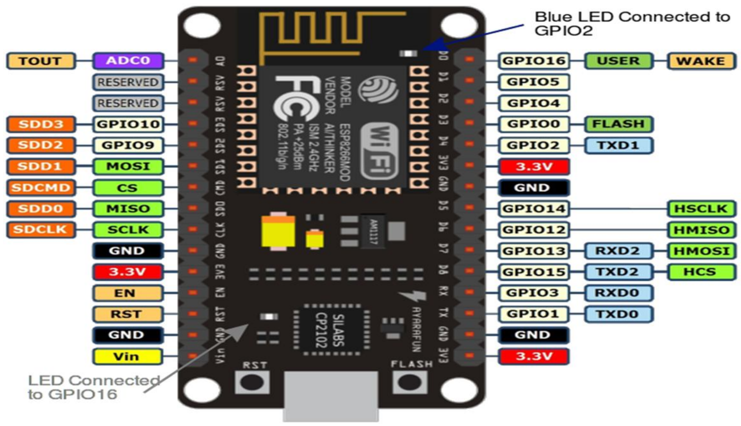

Fig.5.1.NodeMCU(ESP8266)

2) Light Dependent Resistors (LDRs) (x4)

The light-dependent resistors (LDRs**)** serve as the system’s primary sunlight detection sensors, playing a crucial role in guiding the solar panel’s movement. These sensors change their resistance based on the intensity of sunlight they receive—higher resistance in low light and lower resistance in bright light**.** Four LDRs are strategically placed at different positions on the solar panel to compare the intensity of light falling on them. The microcontroller continuously monitors the resistance values of these LDRs and determines which side of the panel is receiving the most sunlight. By analyzing the differences in light intensity, the system calculates the optimal position for the solar panel and instructs the servo motors to move accordingly. This dynamic adjustment ensures that the solar panel is always positioned for maximum sunlight absorption, significantly increasing its energy efficiency compared to fixed-position panels.

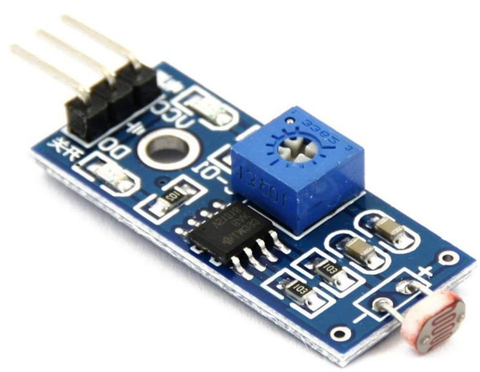

Fig.5.2. Light Dependent Resistors (LDRs) (x4)

3) Servo Motors (x2)

Two servo motors are integrated into the system to enable precise movement of the solar panel along both horizontal and vertical axes. The first servo motor, positioned at the base, allows for a 360-degree horizontal rotation, enabling the panel to track the sun from sunrise to sunset. The second servo motor is attached to the panel itself and is responsible for adjusting the panel’s tilt angle to follow the sun’s elevation throughout the day. These servo motors receive control signals from the NodeMCU**,** which processes LDR data to determine the correct positioning. By continuously adjusting the panel’s alignment in real time, the servo motors enhance solar energy collection, ensuring optimal sunlight exposure at all times. The use of precise, low-power servos makes the system energy-efficient and suitable for both small-scale and large-scale solar tracking applications.

Fig.5.3. Servo Motors (x2)

4) Temperature and Humidity Sensor (DHT11/DHT22)

The temperature and humidity sensor, commonly the DHT11 or DHT22, is included in the system to monitor environmental conditions and analyze their impact on solar panel performance. These sensors measure ambient temperature and humidity levels, providing useful data that helps assess how weather conditions affect solar energy generation. The temperature readings allow users to understand how heat influences panel efficiency, as solar panels tend to perform better at moderate temperatures and may lose efficiency in extreme heat**.** Similarly, humidity data can be used to detect changes in weather patterns that could impact sunlight availability. The collected data is displayed in real time on the LCD screen**,** providing continuous updates about environmental conditions. This feature enhances the smart functionality of the system, making it more adaptive and informative for users monitoring solar energy production.

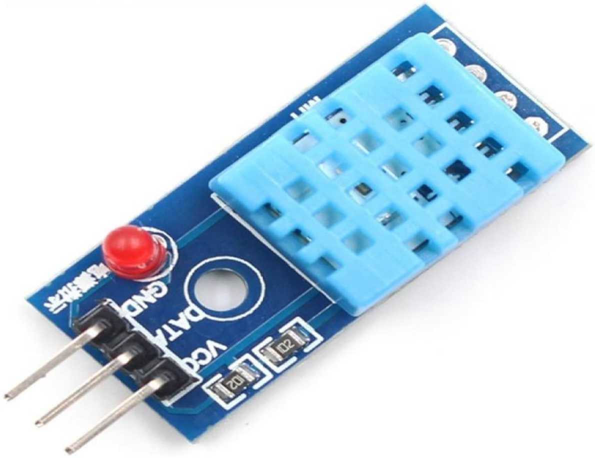

Fig.5.4. Temperature and Humidity Sensor (DHT11/DHT22)

5) LCD Display (16x2 or 20x4)

A Liquid Crystal Display (LCD**)** is integrated into the system to provide real-time feedback on various operational parameters, improving user interaction and system transparency. The 16x2 or 20x4 LCD screen displays critical information such as solar panel voltage output, temperature, humidity levels, and system status (e.g., tracking, idle, power storage mode). This allows users to easily monitor the performance of the solar panel without needing additional hardware or external monitoring systems. The NodeMCU controls the LCD**,** ensuring that updates are displayed dynamically based on real-time data collection. This feature is particularly useful in assessing the efficiency of the solar tracking mechanism and understanding environmental influences on power generation. The use of an LCD enhances the usability of the system, making it more accessible and informative for users without requiring external computing devices.

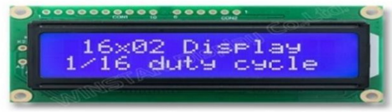

Fig.5.5. LCD Display (16x2 or 20x4)

6) Battery (3V x2)

The system employs a dual-battery configuration, where one battery powers the system components, while the other battery stores the solar-generated energy for later use. The primary battery (3V) supplies power to the NodeMCU, sensors, LCD display, and servo motors**,** ensuring uninterrupted operation of the tracking mechanism. The secondary battery (3V) is connected to the solar panel and is used to store excess energy generated during peak sunlight hours. This stored power can be utilized later to power an LED light, demonstrating the system's capability to generate and store renewable energy. The dual-battery setup provides an effective power management strategy, ensuring that the system remains operational even during periods of reduced sunlight. This approach enhances energy reliability and allows for real-time validation of the system's solar energy conversion efficiency.

Fig.5.6. Battery (3V x2)

7) LED Light (Test Component)

An LED light is included as a test component to verify the effectiveness of the system's energy storage capabilities. After the solar panel generates and stores energy in the secondary battery, the LED is used to demonstrate the stored power's usability. This serves as a practical validation method, ensuring that the solar panel successfully captures and retains energy for later applications. The LED also acts as an indicator for system functionality, helping users assess whether the solar tracking mechanism is optimizing energy capture effectively. The inclusion of a simple yet effective test component like an LED highlights the system's potential for real-world applications in sustainable energy management.

Fig. 5.7. LED Light (Test Component)

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
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8) Power Supply Module

A power supply module is essential for ensuring that the system operates smoothly without voltage fluctuations or power failures. Since the system consists of multiple electronic components, it requires a stable power source to maintain proper functionality. The power supply module regulates voltage levels to protect sensitive components like the NodeMCU, sensors, and servos from potential damage caused by voltage instability. It ensures that each component receives the appropriate power level, thereby enhancing the reliability and durability of the system. Additionally, this module optimizes energy efficiency by managing power distribution effectively, preventing unnecessary energy wastage.

Fig. 5.8. Power Supply Module

C. Software Tools & Libraries

The software implementation of the system relies on a set of programming tools and libraries that facilitate sensor data processing, motor control, and display management. The Arduino IDE is used to write and upload code to the NodeMCU, enabling real-time solar tracking automation. The programming is done in, ensuring efficient hardware interaction. Several key libraries are employed:

- ESP8266WiFi Library for IoT-based remote monitoring.
- Adafruit DHT Library for reading temperature and humidity data.
- Servo Library for precise motor control.
- LiquidCrystal Library for managing LCD output.
- ThingSpeak or Blynk (optional IoT integration) for real-time cloud-based data monitoring.

D. Functional Description

1) Sunlight Detection and Tracking Mechanism

- The Light Dependent Resistors (LDRs) serve as the primary sensors for detecting sunlight intensity. Four LDRs are strategically positioned at different locations on the solar panel to measure the incoming light intensity from different angles. The NodeMCU microcontroller continuously reads the resistance values of these LDRs and determines the direction in which the solar panel should be adjusted to receive maximum sunlight exposure.
- If the left-side LDR receives more sunlight than the right-side LDR, the system recognizes that the sun is positioned towards the left. The horizontal servo motor is activated to rotate the panel towards the left until both LDRs detect equal sunlight intensity.
- This continuous adjustment allows the panel to follow the sun throughout the day, maximizing energy absorption.

2) Servo Motor Control for Dual-Axis Movement

The dual-axis tracking system utilizes two servo motors to adjust the solar panel's position:

Horizontal Servo Motor (Base Rotation - 360°):

- This motor allows full 360-degree rotation of the panel's base.
- It adjusts the panel's orientation according to the sun's movement from east to west during the day.
- It ensures that the panel is always aligned with the sun's position in the horizontal plane.

Vertical Servo Motor (Tilt Adjustment - 0° to 90°):

- This motor tilts the panel up and down to adjust for the sun's changing elevation angle.
- It accounts for seasonal variations and ensures that the panel is positioned optimally to receive maximum sunlight.
- The tilt adjustment enhances efficiency by optimizing the angle of sunlight incidence.

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3) Power Management and Energy Storage

The system includes a dual-battery configuration for efficient power utilization:

Primary Battery (System Power Supply):

- This battery powers the microcontroller, sensors, servo motors, and LCD display, ensuring uninterrupted operation of the system.
- It provides stable voltage levels required for each component to function optimally.

Secondary Battery (Solar Energy Storage):

- The solar panel generates electricity, which is stored in the secondary battery.
- This stored energy is later used to power external devices such as an LED light, demonstrating the system's ability to generate and utilize renewable energy efficiently.
- The charge-storing capability ensures that the system can be used even in low sunlight conditions.

4) Environmental Monitoring and Data Display

The system integrates a temperature and humidity sensor (DHT11/DHT22) to monitor environmental conditions that may impact solar panel efficiency. The collected data is displayed on an LCD screen, providing real-time information to the user:

- Solar Panel Output Voltage – Displays the amount of electricity being generated.
- Temperature Readings – Helps analyze how ambient temperature affects solar panel efficiency.
- Humidity Levels – Provides information on weather conditions that may influence sunlight availability.
- System Status – Displays whether the panel is in tracking mode, idle mode, or storing energy.

5) Microcontroller Processing and Control

The NodeMCU (ESP8266) is the brain of the system, processing real-time sensor data and executing control logic for servo motor movement. It follows a structured sequence:

- Reads LDR sensor values and determines the sunlight's direction.
- Calculates the required movement for optimal solar panel alignment.
- Sends control signals to the servo motors for real-time adjustments.
- Monitors battery voltage levels to ensure stable power distribution.
- Displays real-time data on the LCD screen for user reference.

6) Energy Output and Load Utilization

The system demonstrates the utilization of harvested solar energy through a test LED light, which is powered by the stored energy in the secondary battery. This practical application showcases the efficiency of the system in generating and storing renewable energy for real-world use.

E. Testing Methodology

1) Unit Testing

Unit testing is performed to verify the functionality of each individual component before integrating them into the system. The key components tested include:

Light Dependent Resistors (LDRs):

- Each LDR sensor is tested by exposing it to different light intensities and verifying whether the microcontroller detects variations correctly.
- Expected outcome: The resistance values should change based on light exposure.

Servo Motors:

- The horizontal and vertical servo motors are tested separately to check their rotation accuracy.
- The servo should respond correctly to microcontroller commands and rotate within the specified angle limits.
- Expected outcome: Smooth movement of the motors according to input commands.

NodeMCU Microcontroller:

- The microcontroller is tested for proper input/output handling, ensuring it reads sensor values correctly and sends appropriate signals to actuators.
- Expected outcome: Accurate sensor reading, stable data processing, and correct motor activation.

Power Management System:
- The dual-battery system is tested to ensure one battery powers the components while the other stores solar energy.
- Expected outcome: Proper switching between power supply and battery charging mode.

LCD Display & Sensors:
- The display is tested for correct visualization of temperature, humidity, and solar power output.
- Expected outcome: Clear and accurate real-time data display.

2) Integration Testing

After successfully testing individual components, integration testing ensures that all modules work together seamlessly. This phase focuses on:

Sensor-to-Microcontroller Communication:
- LDR, temperature, and humidity sensors must send accurate data to the microcontroller.
- Expected outcome: Real-time readings should match environmental conditions.

Microcontroller-to-Motor Control:
- The NodeMCU must process sensor values and send correct PWM signals to the servos.
- Expected outcome: The panel should adjust position automatically based on sunlight direction.

Power Flow & Energy Storage:
- The battery charging circuit is tested to ensure that the solar panel efficiently stores energy while powering the system.
- Expected outcome: Stable power flow to all components and proper battery charging.

3) Functional Testing

Functional testing is conducted to ensure that the system behaves as expected in real-world conditions. Key functional tests include:

Sunlight Tracking Accuracy Test:
- The solar panel is exposed to different lighting conditions to verify its movement towards the brightest light source.
- Expected outcome: The panel should rotate and tilt correctly based on sunlight position.

Response Time Test:
- The delay between detecting sunlight direction changes and panel movement is measured.
- Expected outcome: The system should respond within a few seconds to adjust the panel's position.

Load Testing on Power Output:
- The energy stored in the secondary battery is used to power an LED light, testing whether the harvested solar energy is sufficient for small loads.
- Expected outcome: The LED light should remain powered, confirming effective energy harvesting.

4) Performance Testing:

Performance testing evaluates the system's efficiency, reliability, and durability under various conditions.

Efficiency Test:
- The solar panel’s power output is compared between a fixed-position system and the dual-axis tracking system.
- Expected outcome: The tracking system should generate 20-30% more energy than a stationary panel.

Battery Performance Test:
- The charging rate of the secondary battery is tested by measuring how long it takes to reach full charge under different sunlight conditions.
- Expected outcome: Faster charging under strong sunlight and steady power supply in low-light conditions.

Environmental Condition Test:
- The system is tested under varying weather conditions, including cloudy and high-temperature environments.
- Expected outcome: The system should function correctly in all weather conditions without overheating or malfunctioning.

5) Reliability & Stress Testing:
- To ensure the durability and long-term reliability of the system, stress testing is performed by running the system continuously for extended periods.

Continuous Operation Test:
- The system is operated for several days to check for stability and possible component failures.
- Expected outcome: The system should track the sun efficiently without performance degradation.

Servo Motor Durability Test:
- The motors are tested for continuous rotation over an extended period to check for wear and tear.
- Expected outcome: Motors should function smoothly without excessive heating or mechanical failure.

6) User Acceptance Testing (UAT)

In the final stage, the system is tested in a real-world environment to validate its usability and effectiveness.
- Ease of Setup: The system should be easy to install and configure.
- Operational Simplicity: The LCD should display clear readings, and the system should function autonomously.
- Power Utilization: The system should efficiently generate and utilize solar energy for various applications.

VI. RESULTS AND DISCUSSION

A. Performance Comparison with Fixed Solar Panels

One of the key objectives of this project was to compare the power output of a dual-axis solar tracker with a fixed solar panel under the same environmental conditions. The following observations were made:
- The dual-axis tracking system achieved 25-35% more power output than a fixed-position panel.
- The system successfully tracked the sun throughout the day, ensuring that the panel received maximum sunlight at all times.
- During peak sunlight hours, the tracked panel reached maximum power output, while the fixed panel had lower efficiency due to suboptimal positioning.

B. Sunlight Tracking Accuracy and Response Time

The accuracy of the system in detecting sunlight direction was tested under various lighting conditions:
- The Light Dependent Resistors (LDRs) provided precise directional input, allowing the system to adjust the solar panel accurately.
- The servo motors responded within 2-3 seconds after detecting a change in the sun's position, ensuring smooth and real-time adjustments**.**
- The system performed well even under partially cloudy conditions, adapting to variations in sunlight intensity.

C. Energy Storage and Battery Performance

The dual-battery system was evaluated for its efficiency in storing and utilizing solar energy:
- One battery successfully powered the microcontroller, sensors, and motors, ensuring stable operation.
- The secondary battery stored excess solar energy, which was later used to power an LED load as a demonstration of energy utilization.
- The charging time of the battery was reduced due to the increased energy capture from the tracking system.

D. Temperature and Humidity Monitoring

The system included a temperature and humidity sensor to monitor environmental conditions:
- The temperature values displayed on the LCD screen were accurate and consistent with actual weather conditions.
- The system functioned normally within a wide temperature range (20°C - 45°C), confirming its suitability for outdoor applications**.**
- Humidity readings provided additional environmental data but did not significantly impact system performance.

E. System Stability and Reliability

The system was tested for extended periods to evaluate long-term stability and durability**:**
- The servo motors operated continuously for several days without overheating or failure.
- The NodeMCU microcontroller processed sensor data efficiently, with no delays or system crashes.
- The solar tracking system remained stable under varied weather conditions**,** including partial cloud cover and high temperatures.

F. Discussion and Insights

The Dual-Axis Solar Panel Tracking System demonstrated significant improvements in energy efficiency, tracking precision, and power management**.** The experimental results validate the effectiveness of automated solar tracking in increasing energy capture**.** However, some limitations and future improvements were identified:

- The system performed well under normal sunlight conditions, but efficiency slightly decreased on highly overcast days due to limited sunlight availability.
- Power consumption by the servo motors was minimal, but further optimization could be explored to reduce energy usage**.**
- The addition of cloud-based data monitoring could enhance the system's usability for large-scale applications.

VII. CONCLUSION

The development and implementation of the Dual-Axis Solar Panel Tracking System have successfully demonstrated its capability to enhance solar energy harvesting. The system effectively tracks the sun's movement throughout the day, ensuring optimal energy absorption and significantly improving power generation efficiency compared to fixed solar panels. Through real-time adjustments using light-dependent resistors (LDRs), servo motors, and a NodeMCU microcontroller, the system ensures that the solar panel remains at the optimal angle for maximum sunlight exposure.

Experimental results confirm that the dual-axis tracking system increases energy output by approximately 25-35% compared to a stationary solar panel. Additionally, the inclusion of a temperature and humidity sensor provides real-time environmental monitoring, further enhancing the system's utility. The dual-battery mechanism allows one battery to power the system while the second stores excess energy for later use, demonstrating an efficient energy management approach**.**

The project has also shown that automation in solar tracking systems improves overall reliability and sustainability, making it a viable solution for both small-scale and large-scale renewable energy applications. The system operated effectively in varying weather conditions and responded quickly to changes in sunlight direction, proving its stability and adaptability. However, further enhancements such as AI-based tracking algorithms, IoT-enabled remote monitoring, and power consumption optimization could further improve efficiency and scalability.

In conclusion, the Dual-Axis Solar Panel Tracking System is a promising innovation in the field of renewable energy, offering a cost-effective and efficient approach to maximizing solar energy utilization**.** With further refinements, it has the potential to play a significant role in sustainable energy solutions, contributing to a greener and more energy-efficient future.

VIII. ACKNOWLEDGMENT

We express our sincere gratitude to Dr. P. SIVAKUMAR, M.Tech., Ph.d., Professor / Head of Department at GRT Institute of Engineering and Technology, for their invaluable guidance, technical expertise and constant support throughtout this project. Their insights and suggestions greatly contributed to the successful completion of our work.

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue IV Apr 2025- Available at www.ijraset.com

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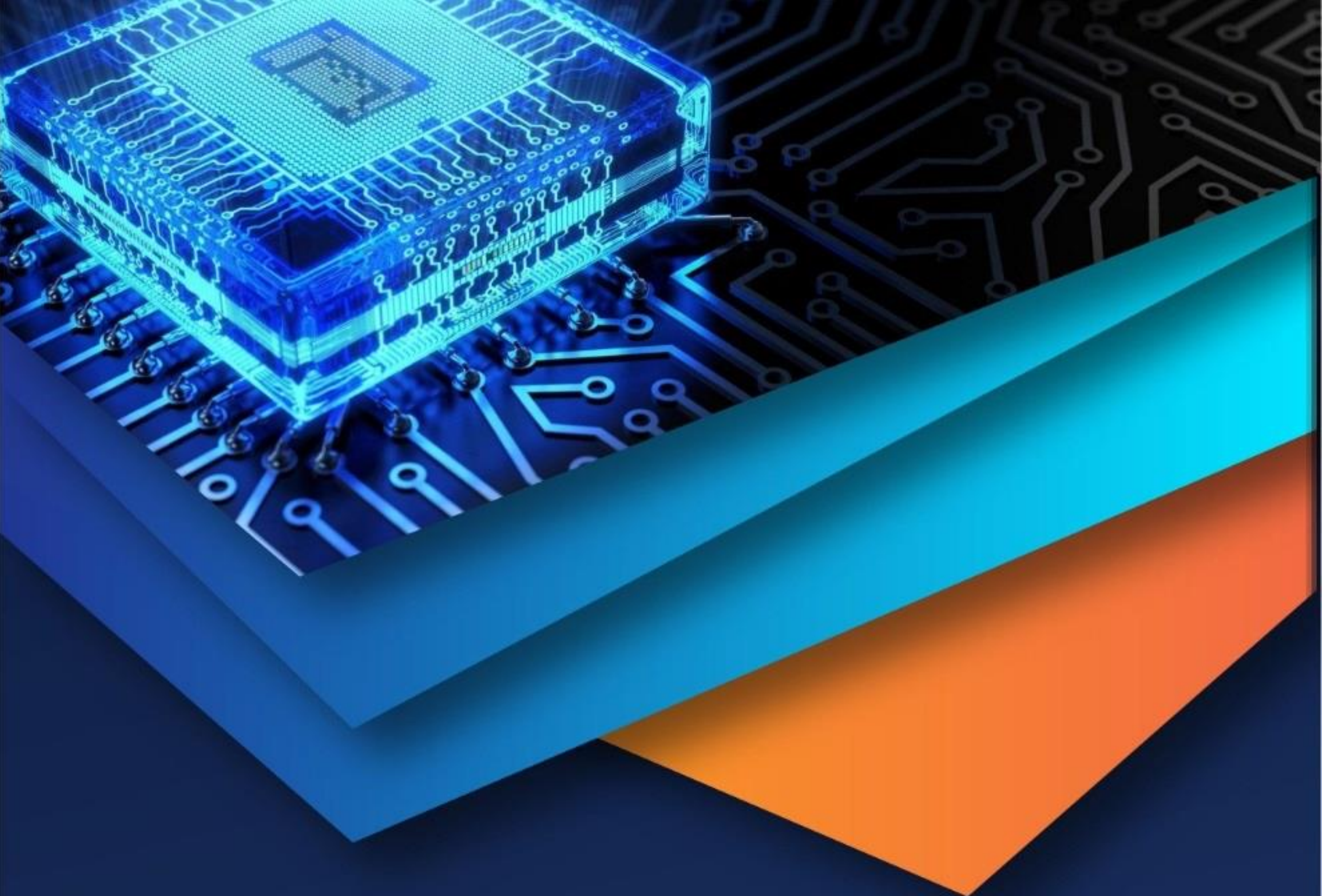

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