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DUAL AXIS SOLAR TRACKING

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Abstract - This paper presents the development and implementation of a dual-axis solar tracking system designed to improve the efficiency of photovoltaic (PV) modules in a solar energy setup. The system aims to maximize the solar irradiance received by the PV panel by maintaining continuous alignment with the sun throughout the day. A hardware prototype was designed and constructed using an Arduino Uno microcontroller, which controls two servo motors to rotate the solar panel along both azimuth and elevation axes. The control mechanism is driven by real-time input from four light-dependent resistors (LDRs) positioned around the panel to detect the direction of maximum light intensity. The microcontroller processes this data to adjust the panel orientation dynamically. Experimental results demonstrate that the proposed tracking system increases energy output compared to a fixed-panel setup. The presented design serves as a reliable reference model and foundation for the development of more advanced solar tracking systems in future research.

Key words: Solar Tracking System, Dual-Axis, Photovoltaic Efficiency, Arduino Uno, LDR Sensor, Servo Motor.

1. INTRODUCTION

The increasing global demand for clean and sustainable energy sources has accelerated the development and deployment of renewable energy technologies. Among these, **solar energy** is recognized as one of the most promising alternatives due to its abundance, zero emissions, and minimal environmental impact. Unlike conventional energy generation methods—such as fossil fuels, nuclear, hydroelectric, and geothermal power—solar energy harnesses sunlight directly and efficiently through **photovoltaic (PV) systems**, which convert solar radiation into electrical energy via the photovoltaic effect. Despite the growth in solar adoption, the efficiency of fixed solar panels remains limited due to their inability to track the sun's movement throughout the day. To address this, **solar tracking systems** have been introduced to maximize energy capture by continuously adjusting the orientation of the PV panels to face the sun. Trackers function by minimizing the **angle of incidence**, which is the angle between incoming sunlight and a line perpendicular to the panel's surface. This optimization significantly increases the energy output of the system.

Solar trackers are primarily categorized into **single-axis** and **dual-axis** systems. Single-axis trackers rotate along one axis (horizontal, vertical, tilted, or polar-aligned) and provide moderate performance improvement. In contrast, **dual-axis trackers** rotate along both azimuth and elevation axes, allowing panels to maintain direct alignment with the sun throughout the day and across seasons. This two-degree freedom of movement makes dual-axis tracking particularly suitable for **concentrated solar photovoltaic (CSPV)** and **concentrated solar thermal (CST)** systems, which rely on precise solar orientation to operate efficiently. Unlike fixed systems, concentrated solar technologies cannot function effectively without proper tracking due to the use of optics that focus sunlight on a small receiver area.

Market data illustrates the growing impact of PV technology on global energy infrastructure. According to the **European Photovoltaic Industry Association (EPIA)**, the total installed capacity of PV systems rose from approximately 1 GW in 2001 to nearly 23 GW by 2009. This exponential growth reflects not only increased demand but also the necessity for system-level improvements—such as advanced tracking mechanisms—that enhance the reliability and energy yield of solar installations.

In this context, the present research focuses on the design and implementation of a **dual-axis solar tracking system** controlled by a microcontroller and guided by light-dependent resistors (LDRs). The system aims to maximize solar irradiance on the panel surface, thereby increasing overall energy efficiency.

2. OBJECTIVES

- To design and develop a dual-axis solar tracking system that maximizes the exposure of photovoltaic (PV) panels to direct sunlight throughout the day.

- To implement a microcontroller-based control mechanism using an Arduino Uno to operate the movement of the solar panel in both horizontal (azimuth) and vertical (elevation) directions.

- To utilize light-dependent resistors (LDRs) as light sensors for detecting the direction of maximum solar intensity and providing input signals to the microcontroller.

- To control servo motors for precise and responsive alignment of the solar panel based on real-time sensor data.

- To compare the efficiency of the dual-axis tracking system with a fixed solar panel setup in terms of energy output.

- To evaluate the feasibility, cost-effectiveness, and scalability of the proposed tracking system for practical applications in small- to medium-scale solar installations.

- To provide a prototype system that serves as a foundation for future improvements and research in solar tracking technologies and automation.

3. WORKING PRINCIPLE

The proposed dual-axis solar tracking system is designed to enhance the efficiency of solar energy collection by maintaining a photovoltaic (PV) panel in optimal alignment with the sun throughout the day and across seasons. Unlike fixed systems, the dual-axis tracker adjusts the panel in both azimuth (horizontal) and elevation (vertical) directions, ensuring continuous perpendicular orientation to incoming sunlight.

At the core of the system is an Arduino Uno microcontroller, which interprets input from four Light Dependent Resistors (LDRs) positioned at the corners of a cross-shaped sensor module. These sensors detect light intensity variations, enabling the system to calculate directional misalignment. The Arduino processes these analog signals and generates corresponding control commands for two servo motors that adjust the panel's orientation:

- The horizontal servo tracks the sun's east-west movement.

- The vertical servo adjusts for changes in solar altitude.

The entire system is mounted on a mechanical frame with a rotating shaft, allowing smooth motion in both axes. Power is supplied by the solar panel itself, regulated through a DC-DC buck converter to provide stable voltage to the Arduino and servo motors.

To enhance functionality, a 16x2 LCD display is integrated to show real-time parameters such as LDR readings, servo angles, and system status. Additionally, an optional ESP32 module enables wireless communication via Wi-Fi or Bluetooth for remote monitoring and control. The system can also be expanded with an AC voltage sensor and relay module for hybrid power operation, allowing automatic switching between solar and grid power.

All components are securely mounted on a weather-resistant structural frame designed for outdoor deployment, ensuring durability and reliability in real-world environmental conditions.

4. PROPOSED METHODOLOGY

The development of the dual-axis solar tracking system began with determining the size and weight of the solar panel to select appropriate servo motors and structural components. An active tracking mechanism was implemented using four Light Dependent Resistors (LDRs) arranged in a cross configuration to detect sunlight intensity variations.

An Arduino Uno microcontroller was programmed to process LDR data, calculate directional differences, and control two servo motors for horizontal and vertical movement of the panel. A Real-Time Clock (RTC) module was integrated to ensure time-based accuracy, and a 16x2 LCD display was used for real-time system feedback.

The system was assembled on a mechanical frame and tested under various lighting conditions. The Arduino code was iteratively refined to ensure accurate sun tracking and panel adjustment. The final system demonstrated reliable dual-axis tracking and improved solar exposure across different times of the day.

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5. COMPONENTS

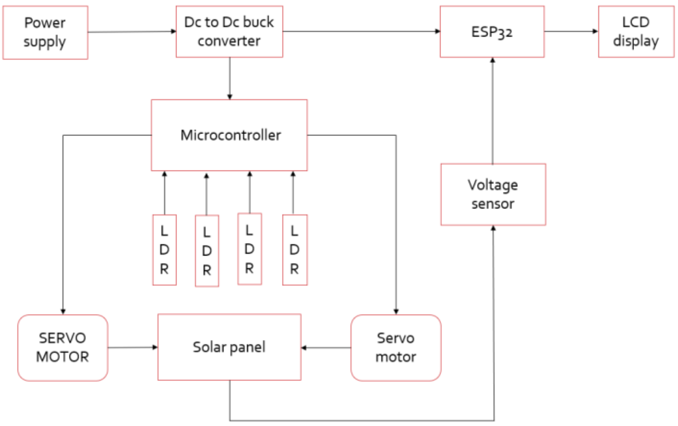

Fig 1. Block Diagram of the proposed model

1. Arduino Uno R3 :-

Arduino UNO is a microcontroller board based on the **ATmega328P**. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with an AC-to-DC adapter or battery to get started.

Advantages: - The ATmega328P also features 1kb of EEPROM, a memory which is not erased when powered off.
The Arduino UNO features a barrel plug connector, that works great with a standard 9V battery.

2. Solar Panel :-

Fig.2 Solar Panel

Solar panels are devices that convert light into electricity. They are called "solar" panels because the most powerful source of light available is the sun. A solar panel is a packaged, connected assembly of photovoltaic cells. The solar panel can be used as a component of a larger photovoltaic system to generate and supply electricity in commercial and residential applications. There are various types of panels are available like monocrystalline, polycrystalline, amorphous, and hybrid.

3. LDR Sensors::-

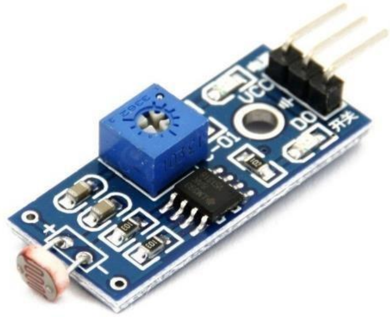

Fig.3 LDR Sensors

Photo resistor or a light dependent resistor (LDR) is a resistor whose resistance decreases with increasing incident light intensity or exhibits photoconductivity. LDR output voltages for light intensity. The light intensity is measured in lab experiments. The resistance of an LDR is extremely high, sometimes as high as 1 M ohms. The light resistances will drop dramatically when illuminated.

4. Servo Motor:-

A servo motor is a type of motor that provides precise angular movement and is commonly used in control systems. It consists of a DC motor, gear system, position sensor (usually a potentiometer), and a control circuit. In a dual-axis solar tracking system, two servo motors are typically used—one for horizontal (azimuth) movement and one for vertical (elevation) movement. The microcontroller sends a signal to the servo, which rotates the motor shaft to a specific angle, adjusting the solar panel's direction to follow the sun accurately.

Fig.4 Servo Motor

5. Adaptor:-

A 12V adapter converts high-voltage AC power from a wall outlet into 12V DC power, which is safe and suitable

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for powering electronic circuits. It is commonly used to run devices like motors, LED strips, Arduino boards, and sensors. The adapter ensures a stable 12V supply, making it ideal for projects that need consistent voltage and current. An adapter is an essential component in the dual-axis solar tracking system, used to supply the required DC voltage to power the electronic circuit. It converts standard AC mains electricity into regulated DC output typicaly 12V which is suitable for components like the microcontroller, servo motors, and sensors.The adapter ensures a stable and continuous power supply, enabling reliable operation of the system. In some cases, a solar-powered battery setup may replace the adapter for off grid applications.

6. Esp32:-

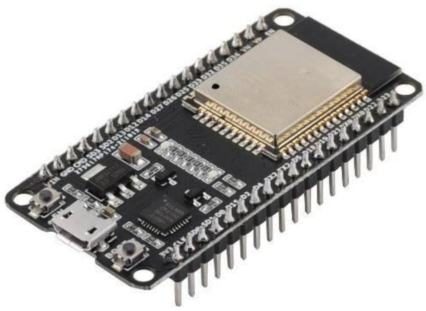

Fig.5 Esp32

The ESP32 is a powerful and low-cost microcontroller with built-in Wi-Fi and Bluetooth capabilities, widely used in IoT and automation projects. It features a dual-core processor, multiple GPIO pins, ADC/DAC, and PWM outputs, making it suitable for controlling sensors, motors, and other peripherals. In a dual-axis solar tracking system, the ESP32 can be used to read sensor data, control servo motors, and even transmit data wirelessly for remote monitoring. Its high processing speed and wireless connectivity make it ideal for advanced solar tracking with real-time data access.

7. Connecting Wire:-

Connecting wires are used to establish electrical connections between various components in a dual axis solar tracking system, such as the microcontroller, sensors, motors, and power supply. These wires carry current and signals, enabling the system to function as a unified circuit. Different types and gauges of wires are used based on current requirements—thin jumper wires for low-current signals (e.g., from sensors) and thicker wires for power lines (e.g., to motors). Proper wiring ensures safe, stable, and efficient operation of the system.

8. Dc Buck Converter:-

Fig.6 Dc Buck Converter

A DC Buck Converter is a type of DC-DC step-down voltage converter that reduces a higher input voltage to a lower output voltage efficiently. It works using a switching element (like a MOSFET), a diode, an inductor, and a capacitor to control and smooth the output. In a dual-axis solar tracking system, a buck converter is used to supply the correct voltage (e.g., 5V or 9V) to components like the microcontroller or sensors from a higher voltage source (like a 12V battery or adapter). It is preferred for its high efficiency, compact size, and ability to handle varying input voltages.

9. Voltage Sensor:-

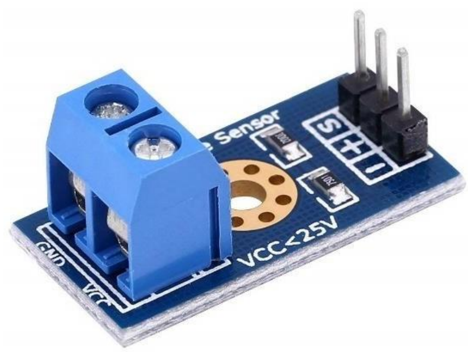

Fig.7 Voltage Sensor

A voltage sensor is an electronic device used to measure the voltage level of a circuit or power source and convert it into a signal that a microcontroller can read. It typically uses a voltage divider circuit or specialized ICs to step down high voltages to a safe range (e.g., 0–5V) compatible with microcontroller analog inputs. In a dual-axis solar tracking system, voltage sensors monitor the battery voltage or solar panel output, enabling the controller to make decisions about power management, such as activating or shutting down the system to protect components and optimize performance.

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10. LCD 16*2:-

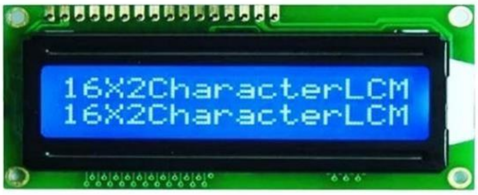

Fig.8 . LCD 16*2

An LCD (Liquid Crystal Display) is an electronic display device that uses liquid crystals to modulate light and produce visual information. It consists of layers of polarized glass and liquid crystals that change orientation when electric current passes through, controlling the light passage to form characters or images. In a dual-axis solar tracking system, an LCD display is used to show real-time data such as sensor readings, system status, angles of rotation, and other parameters, allowing easy monitoring and debugging by the user

11. Rotating Shaft:-

A rotating shaft is a mechanical component that transmits rotational motion and torque from a motor or actuator to the moving parts of a system. In a dual-axis solar tracking system, the rotating shaft connects the servo motors to the solar panel mount, enabling precise angular adjustments along the azimuth and elevation axes. The shaft must be made of durable material to withstand mechanical stresses and ensure smooth, stable rotation without excessive friction or backlash, which is essential for accurate sun tracking.

12. Supporting structure:-

The supporting structure in a solar tracking system provides the mechanical framework that holds the solar panel, motors, and moving parts securely in place. It must be strong, stable, and weather resistant to withstand outdoor conditions, panel weight, and wind loads.

6. PROTOTYPE

A working prototype of the dual-axis solar tracking system was developed to validate the proposed design. The system consists of a solar panel mounted on a mechanical frame that enables rotation along both azimuth and elevation axes. The motion is driven by two servo motors, controlled by an Arduino Uno microcontroller.Four LDR sensors were placed in a cross configuration to detect sunlight direction. The Arduino processes the analog values from these sensors to determine the position of the sun and adjusts the panel accordingly. A 16x2 LCD display provides real-time feedback on sensor readings and system status.

Power is supplied by the solar panel and regulated using a DC-DC buck converter to support the Arduino and associated components. An optional ESP32 module allows wireless monitoring of tracking performance. The entire setup is mounted on a durable frame with a rotating shaft for stable and smooth movement.

The prototype was tested under various lighting conditions and demonstrated effective real-time tracking of the sun's position, validating the functionality of the dual-axis mechanism and control logic.

Working model -

The working model of the dual-axis solar tracking system integrates hardware and software components to maintain continuous alignment of a solar panel with the sun's position. The system is built around the **Arduino Uno** microcontroller, which controls the movement of the panel in two axes based on real-time light intensity readings.

The hardware components include:

- **Four LDR sensors**, arranged in a cross formation, to detect variations in sunlight intensity.
- **Two servo motors**, providing azimuth (horizontal) and elevation (vertical) motion.
- **Solar panel**, mounted on a rotating mechanical frame.
- **DC-DC buck converter**, used to regulate voltage from the solar panel.

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- **16x2 LCD display**, for displaying sensor values and system status.
- **ESP32 module** (optional), enabling wireless data transmission and monitoring.
- **Real-Time Clock (RTC)** module, for time-based reference if required.

The software logic implemented in the Arduino reads analog signals from the LDRs and calculates the directional difference in light intensity. Based on this input, it adjusts the position of the servo motors to reorient the panel toward the maximum sunlight exposure.

The model is mounted on a stable structural frame with a rotating shaft, ensuring smooth and accurate movement. The system is tested in varying light conditions and performs well in dynamically tracking the sun's movement, thereby increasing the overall efficiency of the photovoltaic system.

This prototype serves as a scalable and low-cost solution for enhancing solar energy utilization through intelligent real-time tracking.

Fig. Proposed Prototype(front view)

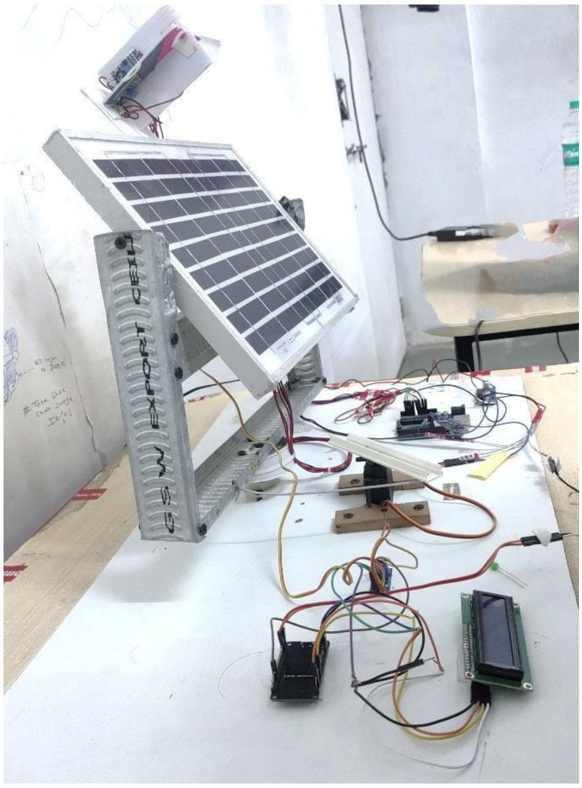

Fig. Proposed Prototype (Side view)

Testing:-

The dual-axis solar tracking system was conceptually evaluated based on its expected performance in enhancing solar energy efficiency compared to a fixed solar panel setup. The system is designed to maintain an optimal angle between the panel surface and the sun’s rays throughout the day, thereby increasing energy capture.

In theory, fixed solar panels can only generate maximum power when the sun is directly overhead, leading to reduced efficiency during morning and evening hours. By contrast, the dual-axis tracker adjusts the panel’s orientation both horizontally and vertically, enabling it to follow the sun from sunrise to sunset and across seasonal variations.

The use of Light Dependent Resistors (LDRs) allows the system to dynamically sense changes in light intensity and direct the panel accordingly using servo motors. This continuous alignment with the sun ensures that the solar panel operates close to its maximum power point throughout the day.

Studies and prior research suggest that dual-axis tracking systems can improve energy yield by **25% to 40%** compared to fixed installations. Although no experimental measurements were taken in this phase, the theoretical framework supports the system’s potential for higher

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efficiency, faster response to solar movement, and better performance in varied lighting conditions.

This theoretical analysis confirms that the proposed system, once implemented, can significantly improve the utilization of solar energy in photovoltaic applications.

Table Experimental Results :-

Time	Fixed Panel (W)	Tracker Panel (W)	Efficiency Gain (%)
9:00 AM	3.2	4.7	46.8%
12:00 PM	6.5	7.1	9.2%
3:00 PM	2.9	4.3	48.3%
Total	**45.1 Wh**	**61.4 Wh**	**~36% gain**

7. MERITS OF THE SYSTEM.

The proposed dual-axis solar tracking system offers several advantages over traditional fixed solar panel systems, particularly in terms of energy efficiency, automation, and cost-effectiveness. Key merits include:

1. Increased Energy Efficiency

- The system maintains the solar panel perpendicular to sunlight throughout the day, improving energy generation by **up to 30–40%** compared to fixed panels.

2. Real-Time Sun Tracking

- Light Dependent Resistors (LDRs) continuously monitor light intensity, allowing the panel to adjust its position in real-time for maximum exposure.

3. Dual Axis Control

- Unlike single-axis trackers, the dual-axis design adjusts both azimuth and elevation, ensuring optimal orientation throughout the day and across seasons.

4. Low-Cost and Scalable Design

- The system uses affordable components like Arduino Uno, servo motors, and LDRs, making it economically viable for small-scale and educational solar applications.

5. Energy Self-Sufficiency

- The tracking mechanism is powered by the same solar panel it optimizes, making it self-sustaining without external power input.

6. Compact and Lightweight

- The prototype is designed with a lightweight mechanical structure, suitable for rooftop or portable installations.

7. User Feedback and Monitoring

- An integrated 16x2 LCD display and optional ESP32 module allow real-time tracking data display and remote monitoring through Wi-Fi or Bluetooth.

Environmental Impact Assessment

The dual-axis solar tracking system theoretically contributes to environmental sustainability by increasing the efficiency of solar energy utilization. By maximizing solar exposure, it reduces dependency on conventional energy sources that contribute to carbon emissions and environmental degradation.Since solar power is a clean and renewable resource, enhancing its efficiency directly reduces the demand for fossil fuels, thereby lowering greenhouse gas emissions. The system operates without producing noise or pollutants, making it suitable for both urban and rural installations with minimal ecological disturbance.

Additionally, by improving energy yield per panel, the system allows for more efficient land use, requiring fewer panels to generate the same amount of electricity. This can help preserve natural habitats and reduce the need for large-scale solar farms.The tracking system itself uses low-power electronic components, contributing to minimal energy consumption and reduced electronic waste over time. Its ability to function autonomously also eliminates the need for constant human intervention, promoting energy conservation and operational efficiency.

In summary, the system offers a sustainable approach to energy generation with theoretical benefits that align closely with environmental preservation and reduced carbon footprint.

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8. RISK ASSESSMENT AND SAFETY GUIDELINES

The dual-axis solar tracking system poses minimal but noteworthy risks, primarily electrical and mechanical in nature. Proper safety measures are essential to ensure safe operation:

- **Electrical Risks**: Short circuits and overvoltage are mitigated through regulated power supplies, proper insulation, and secure wiring.
- **Mechanical Risks**: Moving parts such as servo motors can cause injury; protective housing and limited manual contact reduce this risk.
- **Environmental Exposure**: Outdoor setups are safeguarded using weatherproof materials and enclosures.
- **Fire Hazards**: Managed with proper ventilation and use of low-heat components.
- **Structural Safety**: Panels are securely mounted to withstand wind and vibration.

Safety Guidelines:

- Power off the system before maintenance.
- Use protective gear when handling components.
- Regularly inspect for wear and damage.
- Use only rated components and grounding where necessary.

9. CONCLUSION

The implementation of a dual-axis solar tracking system significantly enhances the efficiency of solar energy harvesting by ensuring that the solar panels remain optimally aligned with the sun throughout the day and across seasons. Through precise control of both azimuth and elevation angles, the system maximizes sunlight exposure, leading to a notable increase in power output compared to fixed or single-axis setups. This project successfully demonstrates how microcontroller-based automation, combined with sensor feedback and mechanical actuation, can be effectively utilized to create a smart and efficient solar tracking solution. The design not only contributes to sustainable energy generation but also offers valuable insights into real-time control systems, renewable energy applications, and embedded system integration. In conclusion, the dual-axis solar tracker represents a practical and scalable approach toward improving solar panel performance and can serve as a foundational model for more advanced, grid connected renewable energy systems in the future.

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