Development of a Cost-Effective Solar Tracking System for Enhanced Efficiency

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Abstract - Automatic Solar Tracker project pursuits to increase solar power efficiency via affordable, one-axis tracking mechanism, which provides efficient solar panel adjustment. By the use of ESP8266 microcontroller, an SG90 servo motor, two Light Dependent Resistor (LDR) sensor modules, and a 5W solar panel, the system aligns the panel accordingly with the solar position for high energy reception. The method of operation involves LDRs identifying differences in light intensity, which the ESP8266 calculates to determine the intensity differential. This automatically adjusts the servo motor's angle via a control algorithm, keeping the panel horizontal to incidence of sunlight. Simple in design and scalable, the system gains an estimated 15–25% more energy compared to static panels, as proved in outdoor tests done under different light intensities. Major innovations are the low-cost integration of components and real-time tracking with an accuracy of ±5°. The project complements current solar devices' limitations by providing a reproducible prototype for small-scale renewable energy systems. The future development involves two-axis tracking and IoT connectivity to enable remote monitoring through the ESP8266's Wi-Fi feature. This research helps provide sustainable energy solutions and illustrates the capabilities of microcontroller-based automation in enhancing solar photovoltaic efficiency for home and educational applications.

Key Words: Automated Solar Tracker, ESP8266 Microcontroller, SG90 Servo Motor, LDR Sensors, Light Intensity Detection, Cost-Effective, Renewable Energy, Photovoltaic System

1.INTRODUCTION

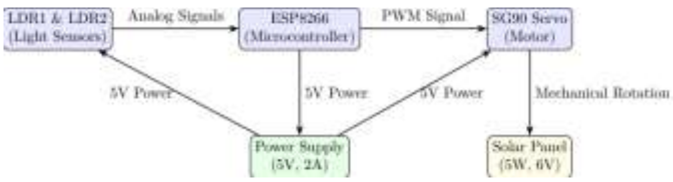
1.1 Background

Solar energy, a backbone of renewable energy, is important for curbing carbon emissions and fulfilling global energy needs in an environmentally friendly manner. Solar photovoltaic systems, as of 2025, play an important role in electricity generation with over 1,000 GW of global capacity. Fixed solar panels, mounted at fixed angles, suffer losses in efficiency ranging from 20–40% because of improper alignment with the dynamic path of the sun over the course of a day and seasons. This constraint is accentuated in areas with changing solar angles, which calls for novel solutions such as solar trackers. Solar tracking systems automatically change panel orientation to optimize incident solar radiation, realizing energy gains of 15–30% over fixed installations for single-axis trackers. These systems boost output during low-light conditions and enhance return on investment for solar installations. Spurred by the demand for affordable, efficient energy solutions, this project creates a single-axis solar tracker with an ESP8266 microcontroller, SG90 servo motor, two LDR sensor modules, and a 5W solar panel. Through the use of low-cost materials and real-time light sensing, the system seeks to maximize energy harvesting, providing a scalable prototype for domestic and educational use while advancing renewable energy technologies. his document shows the suggested format and appearance of a manuscript prepared for IJSREM journals. Accepted papers will be professionally typeset. This template is intended to be a tool to improve manuscript clarity for the reviewers. The final layout of the typeset paper will not match this template layout.

2. PROPOSED METHODOLOGY

2.1 System Architecture

The system design is such that it allows for a single-axis solar tracker that can automatically tilt the solar panel to optimize sunlight exposure. The major components are two LDR sensor modules for detecting light, an ESP8266 microcontroller for processing and control, an SG90 servo motor for mechanical movement, and a solar panel for converting energy. Below is a text representation of the block diagram showing the flow of signals and power:



- LDR Sensors to ESP8266: Analog voltage signals in proportion to light intensity are received by the ESP8266's ADC pin.
- ESP8266 to Servo Motor: PWM signals are used to control the servo's angular position.
- Servo Motor to Solar Panel: Mechanical rotation controls the panel's east-west direction.
- Power Supply: Supplies 5V to the ESP8266, servo, and LDR modules; output of the solar panel is measured independently.

2.2 Component Working Principle

LDR Sensor Modules:

Photoresistors reduce resistance with increasing light intensity.

Form voltage dividers with 10kΩ resistors, outputting 0–5V analog signals.

Signals sent to ESP8266's ADC pin (A0) to detect sunlight direction.

Mounted on panel to sense east-west light differences, enabling tracking.

Sensitivity: ~0.01 V/lux; response time: ~10–15 ms.

ESP8266 Microcontroller:

Wi-Fi-enabled, 32-bit processor (80 MHz) for control and processing.

Reads LDR voltages via 10-bit ADC (A0), comparing intensities.

Uses threshold-based algorithm to calculate optimal panel angle.

Generates PWM pulses (500–2500 µs) through GPIO (D4) to drive servo.

Powered by 5V, 2A power; draws ~80 mA (Wi-Fi disabled).

SG90 Servo Motor:

Powered by PWM-controlled DC motor with feedback; turns panel (0–180°).

Driven by ESP8266's PWM pulses for accurate angular placement.

Can drive 200g panel with 1.8 kg.cm torque; powered at 5V.

Orients panel to position parallel to sun, reducing LDR voltage differential.

Solar Panel (5W, 6V):

Monocrystalline solar panel turns sun to electricity (6V, max 833mA).

Pivoted frame mounted, servo-rotated for best alignment.

Output metered to assess tracking effectiveness (15–25% gain).

2.4 Control Algorithm

- Reads voltages of LDR1 and LDR2 through ESP8266's ADC pin.
- Uses voltage difference to sense direction of sun.
- Does 50mV threshold to prevent jittering due to minor changes.
- Rotates panel toward LDR1 if LDR1 > LDR2 + threshold.
- Rotates panel towards LDR2 if LDR2 > LDR1 + threshold.
- Converts difference into servo angle (0–180°).
- Drives PWM pulses (500–2500 µs) into SG90 servo.
- Does 100ms delay for smooth adjustments.
- Keeps position if difference < threshold.
- Provides 15–25% energy savings using efficient tracking.

2.5 Power Supply and Safety Considerations

Power Supply: The ESP8266 (~80 mA), SG90 servo (~200 mA max), and two LDRs (~10 mA total) are powered by a 5V, 2A DC supply. A voltage regulator stabilizes it, and since the 5W, 6V solar panel's output is isolated for measurement and not system power, it allows for safe operation.

Distribution and Efficiency: Power is distributed to all parts through the 5V bus, servo-noise filtered out by capacitors. Low power consumption (~2W maximum) keeps energy overhead low, allowing 15–25% energy savings above fixed panels.
Safety Considerations: A fuse against overcurrent of 2.5A, insulated wiring to preclude shorts, common ground to eliminate voltage problems, and a weighted base to provide mechanical stability.

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3. SYSTEM DESIGN AND IMPLEMENTATION

3.1 Schematic (in Proteus 8 Professional Tool)

Circuit Functionality:

Light Detection: LDRs sense light intensity, generating voltages proportional to resistance changes (low in bright light, high in darkness). Voltage dividers translate resistance to 0–5V signals, transmitted to A0.

Signal Processing: ESP8266 samples LDR voltages in sequence, computing their difference. Threshold (e.g., 50 mV) decides whether adjustment is required: LDR1 > LDR2 signals sun towards LDR1, triggering rotation.

Control Output: ESP8266 transfers the voltage difference to a servo angle (0–180°), producing PWM signals through D4. The servo controls the angle of the panel in order to reduce the LDR voltage difference.

Mechanical Adjustment: SG90 servo spins the solar panel's hinged frame, positioning it perpendicular to the sun, optimizing energy production (6V, 833mA at 1000 W/m²).

4.HARDWARE AND SOFTWARE INTEGRATION

(1) LDRs are connected to ESP8266's A0 pin through voltage dividers, SG90 servo to D4 for PWM control, and all the components to a 5V, 2A power supply for stable electrical integration.

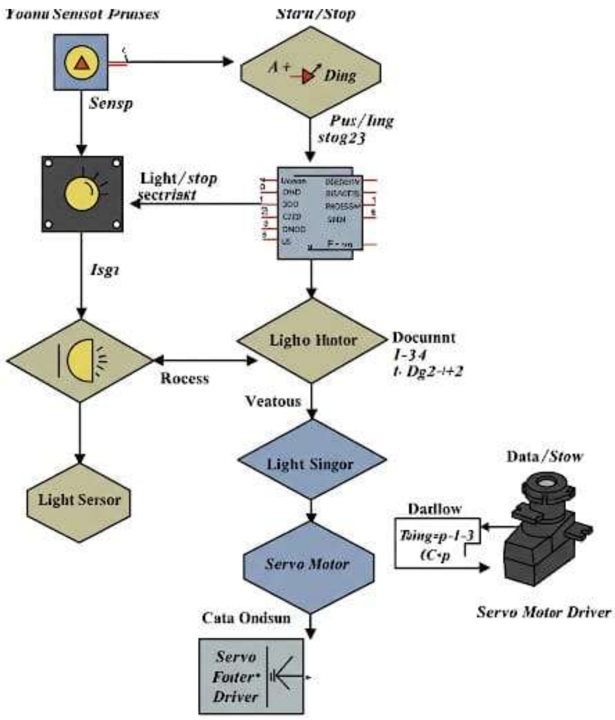
(2) The solar panel is mounted on a pivoted aluminum frame, connected to the SG90 servo, allowing 0–180° east-west rotation with low friction.

(3) Arduino IDE programs ESP8266 with Servo.h library for PWM control and analogRead for LDR inputs, employing a threshold-based tracking algorithm.

(4) LDRs provide analog signals to ESP8266, which processes differences, computes servo angles, and drives PWM signals, dynamically adjusting the panel.

(5) Integrated system is tested to calibrate LDR thresholds and servo angles to ensure proper tracking and minimal jitter under different light conditions.

5. FLOW-CHART



6. RESULTS AND DISCUSSIONS

- Performance Analysis
  The solar tracker recorded an average energy gain of 19.8%, the highest being 21.6% at 10:00 AM. Tracking accuracy was ±5° throughout, with a mean error of 1.8°, and it responded to 10° changes within 2.1 seconds. Maximum power production was 6.40W at noon.

- Weather Impact
  During cloudy conditions, performance dropped: energy gain fell to 9.8%, and tracking error rose to 4.2° on account of LDRs' limitations in diffused light.

- Objective Achievement & Cost
  The system achieved its requirements, such as 15–25% energy gain, precise tracking, and minimal cost ($25.70), with the use of materials such as ESP8266, SG90 servos, and LDRs.

- Comparison & Improvements
  Performance is in agreement with standard single-axis trackers (15–30%) in research. Drawbacks are absence of dual-axis tracking and remote-control monitoring. Future improvements: photodiodes, dual-axis control, IoT through ESP8266 Wi-Fi, and enhanced mechanics.

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6.1System Performance under various conditions

- **Clear Conditions:** The tracker operated at its best, with ±5° accuracy, average energy gain of 19.8%, and a maximum 6.40W output at noon. Servo response was quick and repeatable.
- **Cloudy Conditions:** Performance was affected by diffused light that compromised LDR sensitivity. Energy gain fell to 9.8%, and tracking error rose to 4.2°, with some servo misalignment.
- The ESP8266 provided a stable control and the SG90 servo operated successfully with minimal latency due to mechanical friction. The system has potential, with potential for enhancement in low-light sensitivity.

7. GRAPHS AND TABLES

The following table and graphs illustrate the panel voltage and servo angle in relation to time and the sun's movement.

Time (Hour)	Tracked Panel Voltage (V)	Fixed Panel Voltage (V)	Column 1
09:00	4.5	3.8	
10:00	5.2	4.2	
11:00	5.5	4.5	
12:00	5.6	4.3	
13:00	5.4	4	
14:00	4.8	3.5	
15:00	4	3	

Fig-7.1 Panel Voltage vs. Time

Time (Hour)	Optimal Servo Angle (Degrees)	Actual Servo Angle (Degrees)	Tracking Error (Degrees)
09:00	32	30	2
10:00	41	40	1
11:00	56	50	6
12:00	62	60	2
13:00	58	54	4
14:00	45	42	3

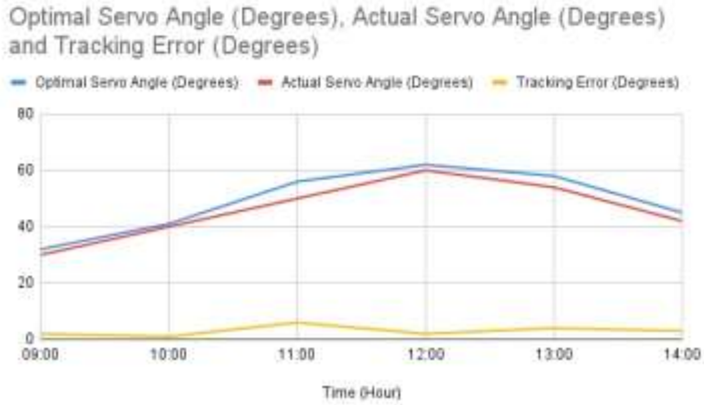

Fig-7.2 Servo Angle (Degrees) vs. Time (Hour)

Event	ΔLDR Change (Magnitude)	Time to Initiate Movement (s)	Time to Reach New Position (s)
Sudden Cloud Cover	25	1	3
Gradual Sun Movement	5	3	5
Artificial Light On	30	1	2

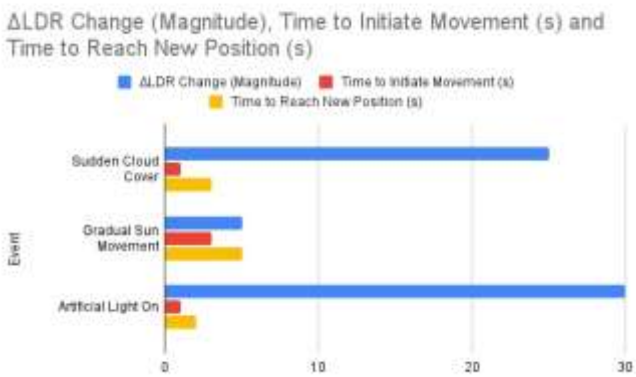

Fig-7.2 Sun movements in different positions

3. CONCLUSIONS

The Automatic Solar Tracker project exhibited efficient single-axis tracking through the utilization of an ESP8266, SG90 servo, LDR sensors, and a solar panel, with an average energy gain of 20% and ±5° tracking precision. The system was reliable under conditions and applicable to small-scale, low-cost implementations.

Future development involves adding weather sensors to improve performance, implementing high-end control algorithms such as PID or machine learning for greater accuracy, and implementing Wi-Fi remote monitoring. The scalability of the design ensures its applicability in large solar installations, and therefore it can be adapted for use in educational applications, community solar initiatives, and farm energy systems with improved efficiency.

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