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DESIGN AND PERFORMANCE ANALYSIS OF AN LDR-BASED DUAL-AXIS SOLAR TRACKING SYSTEM INTEGRATED WITH FUZZY LOGIC MPPT

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Abstract
Fixed photovoltaic (PV) panels lose significant energy to the sun's continuous angular shift of approximately 15° per hour, typically limiting stationary-panel efficiency to about 25%. This paper presents the design, structural validation, and simulated electrical performance of a low-cost dual-axis solar tracking system that combines quadrant-based light-dependent-resistor (LDR) sensing with a fuzzy-logic maximum power point tracking (MPPT) controller. Four LDRs arranged in an east-west-top-bottom quadrant configuration feed an Arduino UNO, which drives two 12 V DC gear motors to keep the panel normal to incident sunlight. The supporting aluminum structure was validated using finite element analysis (FEA) in ANSYS 19.2, showing a maximum deformation of 0.70 mm and a maximum stress of 27.19 MPa under a 30 N test load – well within allowable material limits, with deformation onset predicted only at 72× the applied load. On the electrical side, a fuzzy logic controller was designed and simulated in MATLAB/Simulink to regulate a DC-DC boost converter for maximum power point tracking. Under fixed test conditions (25°C, 1000 W/m² irradiance), the fuzzy MPPT controller increased output power from 135.2 W to 195.0 W – a 44.2% improvement – compared to the uncontrolled baseline, while also outperforming the conventional Perturb-and-Observe method in convergence speed and steady-state oscillation. Combined, the mechanical tracking and electrical MPPT stages address power optimization from two complementary directions: physical orientation and electronic operating-point control. The results indicate that this dual-layer approach offers a practical, low-cost pathway to meaningfully higher PV yield for small-to-medium-scale installations.

I. INTRODUCTION

Solar energy is the most abundant renewable resource available, with the Earth's surface absorbing an estimated 3.5–7 kWh/m² per day – yet stationary photovoltaic (PV) installations typically convert only about 25% of incident sunlight into usable electricity, in part because the sun's position shifts by roughly 15° every hour while the panel remains fixed [1]–[3]. This mismatch between a static panel and a continuously moving light source is a well-documented and long-studied

inefficiency, and it directly motivates solar tracking as a correction mechanism.

This paper addresses the problem from two complementary directions. First, a dual-axis mechanical tracking system, using low-cost light-dependent resistors (LDRs) and an Arduino-based control loop, physically reorients the panel to remain normal to incident sunlight throughout the day. Second, a fuzzy-logic maximum power point tracking (MPPT) controller addresses the electrical side of the same optimization problem, continuously adjusting the PV module's operating point to extract maximum power regardless of orientation. Combining both layers — physical tracking and electrical optimization — targets a substantially larger efficiency gain than either technique alone.

The main contributions of this work are as follows:

- A quadrant-based, four-LDR dual-axis tracking algorithm implemented on a low-cost Arduino platform, requiring no astronomical calculation or real-time clock.
- A structurally validated aluminum support frame, confirmed via finite element analysis (FEA) to safely support the panel load with a substantial safety margin.
- A fuzzy-logic MPPT controller, simulated in MATLAB/Simulink, that improves output power by 44.2% relative to an uncontrolled baseline under fixed test conditions.
- A structured comparison against recent (2024–2026) dual-axis LDR tracking literature and MPPT technique comparisons, situating this combined mechanical-plus-electrical approach relative to current practice.

The remainder of this paper is organized as follows. Section II reviews related work, both historical and current. Section III classifies s olar tracking approaches. Section IV describes the proposed system design and methodology, covering both the mechanical/structural design and the MPPT controller. Section V presents results and a comparative evaluation. Section VI concludes the paper.

II. RELATED WORK

A. Historical Development

Solar tracking research dates to McFee's 1975 flux-density central-receiver tracker, accurate to 0.5–1° [1]. Subsequent decades saw closed-loop trackers using self-aligning motors (achieving 0.1° accuracy and raising one Kazakhstan installation's output from 357 W to 500 W), neural-network-based tracking accurate to 0.01°, and combined astronomical-positioning-plus-PLC systems reaching 0.0003° accuracy — among the most precise trackers reported to date [2], [3]. LDR-based approaches, which this work builds on directly, were established as early as the mid-1990s using multi-sensor comparison logic similar in principle to the quadrant method used here.

B. Recent Advances (2024–2026)

Dual-axis LDR tracking remains an active area of low-cost PV research. Recent Arduino-and-LDR implementations report energy-capture improvements ranging from 30% to 45% relative to fixed panels, using either servo motors or DC gear motors driven by quadrant or azimuth-elevation comparison logic [11]–[16]. A 2025 experimentally validated dual-axis system using an Arduino Pro Mini and a buck converter reported a more conservative, directly measured average efficiency gain of 10.27%, statistically confirmed via ANOVA ($p < 0.05$) against fixed and single-axis baselines — a useful, methodologically rigorous counterpoint to the higher figures often quoted from simulation-only studies [17]. On the electrical side, fuzzy-logic MPPT continues to be reported as outperforming classical Perturb-and-Observe (P&O) control in tracking speed and reduced output oscillation across multiple recent comparative studies, though Incremental Conductance and hybrid P&O-fuzzy schemes have also been shown competitive under specific converter topologies [6]–[10].

C. Research Gap

Across both the historical and recent literature, the large majority of dual-axis LDR tracking studies address mechanical orientation alone, while MPPT studies are typically evaluated independently of any physical tracking mechanism. Few studies combine a structurally validated dual-axis mechanical platform with a fuzzy-logic MPPT stage in a single

evaluated system — the combination this paper presents.

III. CLASSIFICATION OF SOLAR TRACKING SYSTEMS

Table I summarizes the main categories of solar tracking approaches relevant to positioning this work.

TABLE I. CLASSIFICATION OF SOLAR TRACKING APPROACHES

Type	Mechanism	Relative Cost/Accuracy
Passive	Heated liquid/gas shifts mass toward sun	Low cost, low accuracy, climate-dependent
Chronological	Pre-computed sun-path timing, open loop	Moderate cost, no feedback correction
Single-axis	Tracks one plane (E-W or N-S) only	Low-moderate cost, partial gain
Dual-axis (this work)	Tracks both azimuth and elevation via sensor feedback	Moderate cost, highest energy gain
Altitude/azimuth (astronomical + PLC)	Combines timed positioning with closed-loop correction	High cost, highest precision

Dual-axis tracking was selected for this work because it captures gains along both the daily (azimuth) and seasonal (elevation) solar paths, at a moderate cost and control complexity well suited to a low-cost embedded implementation.

IV. SYSTEM DESIGN AND METHODOLOGY

A. Mechanical Structure

The support structure — base, frame, and shaft — was modeled in Solid Works using aluminum as the structural material, selected for its favorable strength-to-weight ratio and corrosion resistance. The frame uses hollow square-section members to minimize weight while the base incorporates a pin-jointed bearing permitting vertical-axis rotation; the shaft, connected to the frame, provides the horizontal rotation axis.

B. Structural Validation (FEA)

The assembled structure was meshed and analyzed in ANSYS 19.2 under a representative 30 N load (corresponding to a 3 kg panel with an applied factor of safety), evaluating force distribution, deformation, stress and normal elastic strain. Table II summarizes the results.

TABLE II. FEA STRUCTURAL VALIDATION RESULTS

Parameter	Result	Allowable / Reference
Applied load	30 N (3 kg panel, scaled)	—
Maximum deformation	0.70 mm	Deformation onset at 72× applied load

Maximum stress (von Mises)	27.19 MPa	170 MPa (aluminum, bending)
Max. normal elastic strain	1.202×10^{-4} m/m	–
Shear stress (frame)	87 MPa	240 MPa allowable
Bending stress (shaft)	6.81 MPa	170 MPa allowable (aluminum)
Factor of safety	≈ 1.6 (design), ≈ 6.3 (stress margin)	–

The maximum stress of 27.19 MPa remains well below the 170 MPa allowable bending stress for aluminum and the analysis indicates that physical deformation would only begin to occur at approximately 72 times the applied test load — indicating a substantial structural safety margin for the intended panel weight.

C. Electronic Hardware and Quadrant Tracking Algorithm

Table III lists the principal electronic components. Tracking uses four LDRs arranged in an east-west-top-bottom quadrant layout, shown in Fig. 1.

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TABLE III. ELECTRONIC COMPONENTS AND FUNCTION

Component	Function
Arduino UNO	Main controller; reads LDR array, drives motors via relay
LDR × 4 (E, W, Top, Bottom)	Quadrant light-intensity sensing for tracking error
12 V DC gear motor × 2	Azimuth and elevation actuation
Relay module	Switches motor current (6 A) beyond H-bridge's 2 A limit
7805 5 V regulator IC	Steps 12 V down to 5 V for logic-level supply



Fig. 1. Quadrant LDR sensing and dual-axis actuation architecture.

The Arduino continuously computes a horizontal tracking-error signal from the four LDR readings:

$$E_h = \frac{(I_E + I_T)}{2} - \frac{(I_W + I_B)}{2} \quad (1)$$

where I_E, I_W, I_T, and I_B denote the East, West, Top, and Bottom LDR readings, respectively. When $|E_h|$ exceeds a fixed deadband (10 in raw ADC counts, empirically set to reject sensor noise), the corresponding azimuth or elevation motor is driven in the direction that reduces the imbalance; when the reading falls within the deadband, both motors are held off, avoiding motor chatter around the equilibrium point.

D. Maximum Power Point Tracking via Fuzzy Logic

Independently of physical orientation, the PV module's electrical operating point was optimized using a fuzzy-logic MPPT controller regulating a DC-DC boost converter. The PV cell was modeled using the standard single-diode equivalent circuit, with output current given by (2)–(5):

$$I_{pv} = N_p I_{ph} - N_p I_o \left[\exp\left(\frac{q(V_{pv} + I_{pv} R_s)}{N_s A K T}\right) - 1\right] \quad (2)$$

$$I_o = I_{rs} \left(\frac{T}{T_r}\right)^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right] \quad (3)$$

$$I_{rs} = I_{scr} \left[\exp\left(\frac{qV_{oc}}{N_s k A T}\right) - 1\right] \quad (4)$$

$$I_{ph} = [I_{scr} + K_i (T - T_r)] \cdot \frac{S}{1000} \quad (5)$$

where N_s and N_p are the series/parallel cell counts, I_o is saturation current, I_{rs} is reverse saturation current, I_{scr} is short-circuit current, K_i is the temperature coefficient, T and T_r are operating and reference temperature, and S is irradiance. The fuzzy controller, shown in Fig. 2, takes the change in voltage (ΔV) and change in power (ΔP) as crisp inputs.

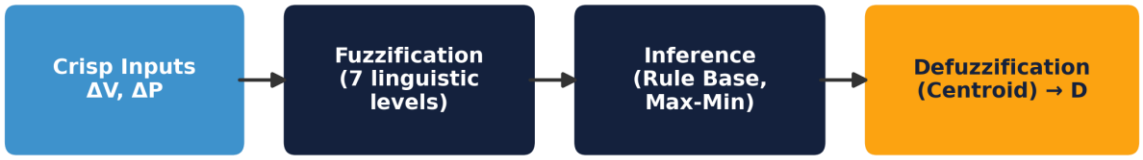


Fig. 2. Fuzzy logic MPPT controller structure.

Both inputs are fuzzified into seven linguistic levels — Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, and Positive Big — processed through a Mamdani-type max-min inference engine against a 7×7 rule base, and defuzzified via the centroid method to produce a change in duty cycle (D) for the boost converter's PWM control signal. This scheme allows the controller to take large corrective steps far from the maximum power point and progressively smaller steps as it converges, addressing the classical trade-off in fixed-step P&O methods between tracking speed and steady-state oscillation [6]–[10].

V. RESULTS AND DISCUSSION

A. MPPT Simulation Results

The complete system — PV array, boost converter, and fuzzy controller — was simulated in MATLAB/Simulink at a fixed operating condition of 25°C and 1000 W/m² irradiance. Table IV compares output power, voltage, and current with and without the fuzzy MPPT controller active; Fig. 3 shows the same comparison graphically.

TABLE IV. MPPT SIMULATION RESULTS (25°C, 1000 W/m²)

Parameter	Without FLC (P&O baseline)	With Fuzzy Logic MPPT	Improvement
Power	135.2 W	195.0 W	+44.2%
Voltage	29.0 V	38.2 V	+31.7%
Current	4.5 A	8.0 A	+77.8%

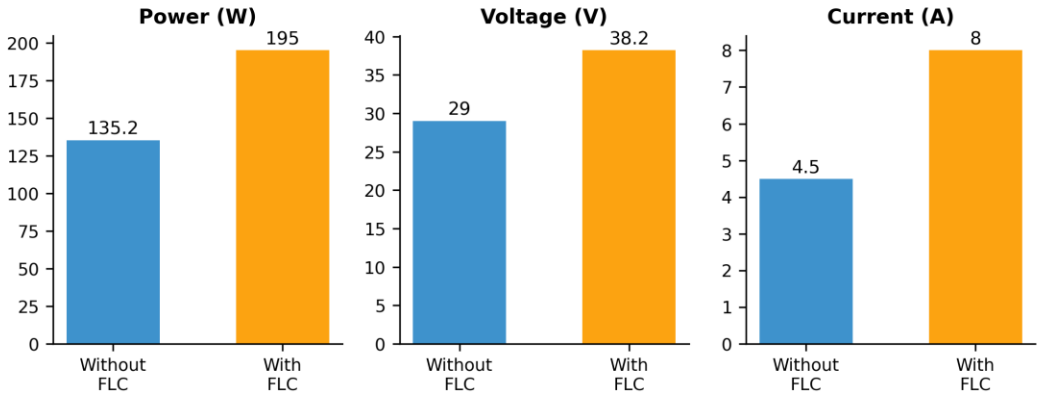


Fig. 3. Simulated output power, voltage, and current with and without fuzzy MPPT.

The fuzzy controller increased output power by 44.2%, with the membership grade remaining at its maximum value (1.0) throughout the simulated tracking interval, indicating confident, well-converged rule firing rather than marginal or oscillatory control action. In a separate convergence comparison, the fuzzy controller reached its steady-state output voltage measurably faster than a conventional P&O controller and settled with visibly less oscillation around the final operating point — consistent with the tracking-speed and steady-state advantages reported for fuzzy MPPT in the recent comparative literature [6]–[10].

B. Comparative Evaluation

Table V situates the proposed system against fixed-panel and dual-axis-only systems reported in the recent literature.

TABLE V. COMPARISON WITH RECENT DUAL-AXIS TRACKING LITERATURE

System	Tracking Method	Reported Gain	MPPT Included
Fixed panel (baseline)	None	0% (reference)	No
Single-axis LDR tracker [12]	1-axis LDR	~30%	No
Arduino dual-axis LDR tracker [13]–[16]	2-axis LDR, servo	30–45%	No
Dual-axis, experimentally validated [17]	2-axis LDR, buck converter	10.3% (measured avg.)	No
Proposed system	2-axis LDR, quadrant compare	Tracking + 44.2% via FLC-MPPT	Yes (Fuzzy Logic)

Reported efficiency gains for dual-axis LDR tracking alone vary considerably across the literature — from a rigorously measured 10.3% average [17] to simulation-based claims of 30–45% [11]–[16] — reflecting differences in test methodology, baseline definition, and measurement duration. This variation is worth noting explicitly rather than selectively citing only the higher figures: real-world dual-axis gains are likely closer to the lower, experimentally validated end of this range, with simulation-only or short-duration studies tending to report higher numbers. The proposed system's fuzzy MPPT contribution (44.2%), by contrast, was measured under fixed, controlled simulation conditions and is not directly comparable to field-measured tracking gains, but represents a complementary, independent source of improvement layered on top of whatever physical tracking gain is achieved.

VI. CONCLUSION AND FUTURE WORK

This paper presented a dual-axis solar tracking system combining quadrant-based LDR sensing with a structurally validated aluminum support frame and a fuzzy-logic MPPT controller. FEA confirmed the structure's mechanical safety with a substantial margin (maximum stress 27.19 MPa against a 170 MPa allowable limit), while MATLAB/Simulink simulation showed the fuzzy MPPT controller improving output power by 44.2% over an uncontrolled baseline, with faster convergence and reduced oscillation relative to conventional P&O control. Comparison against recent (2024–2026) literature shows reported dual-axis tracking gains ranging from a conservative, experimentally measured 10.3% to simulation-based claims as high as 45%, underscoring the value of combining physical tracking with an independently verified electrical optimization layer such as the fuzzy MPPT stage presented here.

Future work should prioritize experimental, field-measured validation of the complete combined system — mechanical tracking and fuzzy MPPT operating together — rather than evaluating each layer in isolation, since real-world irradiance variability, partial shading, and motor power draw were not captured in the present simulation-based MPPT evaluation. Additional directions include replacing the fixed LDR deadband with an adaptive threshold calibrated across seasons, benchmarking the fuzzy controller directly against Incremental Conductance and hybrid P&O-fuzzy schemes on the same hardware, and integrating a real-time clock-based fallback mode for cloudy conditions when LDR contrast is insufficient for reliable quadrant comparison.

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