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Enhanced Photovoltaic Efficiency Using Dual-Axis Solar Tracking With Integrated Cleaning Alert System and Monitoring

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Abstract: Conventional fixed photovoltaic (PV) panels lose significant output because the sun's position changes continuously and dust accumulates on the panel surface. This paper presents an enhanced PV system combining dual-axis solar tracking with a cleaning alert system and IoT real-time monitoring. Four LDR sensors and an ESP32 drive two DC motors through an L298N H-bridge to align the panel along the azimuth and elevation axes. A dual-channel alert, using INA219 power sensors and an ESP32-CAM, detects dust-related loss. Results show a ≈42% improvement in daily energy yield over a fixed installation, ±2° tracking accuracy, and a dust-alert response under five minutes.
Keywords: Dual-Axis Solar Tracking, ESP32 Microcontroller, IoT Monitoring, LDR Feedback Control, Photovoltaic Efficiency, Cleaning Alert System

I. INTRODUCTION

Energy underpins economic growth, yet most global demand has historically come from fossil fuels, whose use causes pollution and climate change. Solar PV has emerged as a leading renewable alternative due to its abundance, scalability, and low operating cost [1]. India, near the equator, receives high solar irradiation roughly 300 days a year, and schemes such as the Jawaharlal Nehru National Solar Mission have accelerated PV adoption [2], though improving efficiency and reliability of small-scale installations remains an active challenge.

Fixed solar panels lose substantial energy because the sun's position changes through the day and seasons, and because dust settling on the surface blocks sunlight—dust alone cuts output by 20–30% if unaddressed [3]. Tracking mitigates orientation loss: a single-axis tracker raises yield by 20–25%, while a dual-axis tracker, which also adjusts elevation, raises yield by 30–40% over a fixed panel.

Most prior work treats tracking, dust mitigation, and monitoring as separate problems with dedicated hardware. This paper presents an integrated, low-cost solution combining dual-axis tracking, dual-channel dust detection, and IoT monitoring on one ESP32 platform. The key contributions are:

1) A closed-loop, LDR-based dual-axis tracking algorithm that equalises illumination across four corner sensors, with no astronomical clock or GPS reference.
2) A dual-channel cleaning alert combining INA219-based power detection with ESP32-CAM brightness monitoring, improving detection confidence and suppressing cloud-induced false positives.
3) A real-time Wi-Fi monitoring dashboard backed by non-volatile flash logging and NTP-synchronised day-rollover accounting.
4) An experimental evaluation against a fixed-panel baseline quantifying gains in energy yield, tracking accuracy, and alert response time.

Section II reviews related work; Sections III–V cover system design, hardware, and software; Section VI presents results; Section VII concludes.

II. LITERATURE REVIEW

Fixed flat-plate PV installations lose efficiency because the incidence angle θ between sunlight and the panel changes continuously, so maximum energy is captured only near solar noon. Dual-axis trackers can achieve up to 40% greater yield by keeping $\theta \approx 0°$ throughout the day [5].

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A. Dual-Axis Tracking Mechanisms

Dual-axis tracking uses two rotational degrees of freedom—azimuth and elevation—to continuously align a PV array with the sun's trajectory. Mamodiya and Tiwari [4] implemented a hardware-based dual-axis tracker (1 kW, three panels) governed by closed-loop solar-intensity feedback. Output power relates to incidence angle θ as $W = A\lambda \cos\theta$ … (1); maintaining $\theta \approx 0°$ maximises output. Their Jaipur field trials showed a 35–40% increase in daily yield. Alonso-Montesinos et al. [5] confirmed that precise sun-tracking sustains high efficiency even under fluctuating weather.

B. LDR-Based Feedback Control

Among open-loop astronomical tracking, time-based positioning, and closed-loop sensor-based tracking, LDR-based feedback is among the most cost-effective approaches for small installations. Differential illumination across corner-mounted LDRs lets a microcontroller drive the corresponding motor until readings equalise, giving automatic adjustment, low power use, and good adaptability to passing clouds. Harrison et al. [6] showed that combining angular alignment with MPPT-based electrical optimisation yields higher net efficiency than either technique alone.

C. Dust Detection and Cleaning Systems

Polo et al. [7] and Alombah et al. [8] reported that accumulated dust in arid or polluted regions can cause 20–30% power loss, and that manual cleaning is impractical for large installations. Mitigation strategies include mechanical wipers, electrostatic dust removal [10], and water-jet or air-blower mechanisms. A mechanically simpler alternative is a performance-based alert that detects power anomalies attributable to soiling and notifies an operator, which—combined with a tracking structure—also allows cleaning to be scheduled while the panel sits horizontally.

D. IoT-Based PV Monitoring

Continuous monitoring lets operators identify anomalies and plan maintenance proactively. Microcontrollers such as the ESP32 enable wireless, near-real-time observation of voltage, current, and power ($P = VI$) [9]. Tiwari et al. [11] showed that smart dashboards improve operational visibility and help quantify real-world gains rather than relying on theoretical projections.

E. Research Gap

Table 1 summarises the reviewed literature. Gaps include: an integration gap, since tracking, cleaning, and monitoring are usually treated separately; a cost/scalability concern from expensive sensors or servo motors; limited adaptability to dust, humidity, or wind; weak IoT connectivity; and neglect of a tracker's own auxiliary power draw. The proposed system addresses these by combining LDR-based closed-loop control, dual-channel dust detection, and IoT monitoring in one low-cost prototype.

Table 1. Summary of Reviewed Literature

Author / Year	Focus	Method	Key Finding
Mamodiya & Tiwari (2023)	Dual-axis hardware tracking	LDR sensors + DC motors	35–40% increase in power output
Harrison et al. (2023)	MPPT & control	Nonlinear feedback controller	Stability under fluctuating irradiance
Alonso-Montesinos et al. (2019)	DNI forecasting	Predictive modelling	Improved CSP power prediction
Polo / Alombah et al.	Dust & soiling	Performance-based detection	20–30% loss without timely cleaning

III. SYSTEM DESIGN AND METHODOLOGY

A. Problem Statement

PV efficiency in practice is limited by interacting factors: fixed orientation keeps the incidence angle away from perpendicular most of the day; dust cuts output by 20–30% if uncleaned; and many small installations lack real-time monitoring. The proposed system addresses all three within one low-cost platform that tracks the sun, monitors performance, and reports dust-related loss.

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B. System Architecture

The system has four functional units—Sensing, Control, Actuation, and Monitoring/Alert—with the ESP32 as hub. The tracking module uses four LDR sensors and two DC motors; the performance module measures panel and battery parameters via INA219 sensors and streams data over Wi-Fi; and the alert module compares current power against a rolling maximum and brightness against a clean baseline, raising a dashboard alert if either threshold is crossed.

C. Sensing Unit

Four LM393-based LDR modules sit at the panel's corners with small dividers so each sensor receives light from one quadrant. Uneven sunlight makes the ESP32's ADC sample diverging voltages, computing directional error signals that drive the panel toward the brighter side until readings balance.

D. Control Unit — ESP32 Microcontroller

The ESP32 (dual-core, 240 MHz) is a low-power SoC with built-in Wi-Fi and Bluetooth, handling sensor acquisition, motor PWM, Wi-Fi communication, and web hosting concurrently. Its 12-bit ADC enables precise differential LDR readings, and hardware PWM generates motor timing without blocking the control loop, which also services the I²C bus to the INA219 sensors and the async HTTP server.

E. Actuation Unit

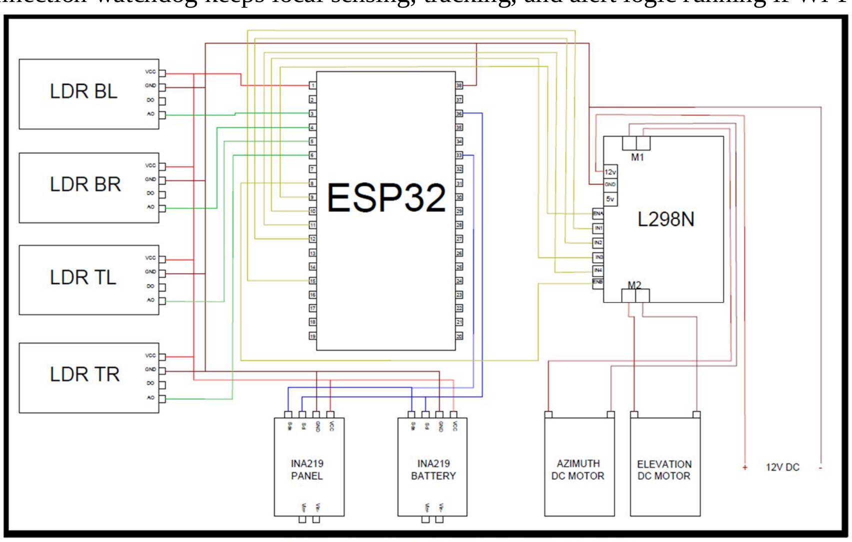
Two 12 V, 30 RPM DC gear motors, controlled via an L298N dual H-bridge, provide azimuth and elevation adjustment, giving high torque at low speed for smooth movement. Motors stop once the LDR differential falls below a configurable dead-band, preventing hunting and unnecessary power draw.

F. Cleaning Alert System

Rather than a mechanical wiper, the design favours a lower-cost performance-based alert with two channels: an electrical channel where INA219 sensors flag a sustained drop below a rolling maximum, and a visual channel where an ESP32-CAM (OV3660, 3 MP) compares grayscale brightness against a clean-panel baseline and reports independently via HTTP POST. Genuine dust triggers both channels within a short window, while transient shading affects only the electrical channel.

G. IoT Monitoring Dashboard

The ESP32 hosts an asynchronous HTTP server. A JSON endpoint streams voltage, current, power, state of charge, and daily energy every 2 seconds, along with cleaning/dust flags, a seven-day history array, Wi-Fi RSSI, and a Unix timestamp. Energy totals persist in flash, and a reconnection watchdog keeps local sensing, tracking, and alert logic running if Wi-Fi is briefly lost.



CIRCUIT DIAGRAM

Fig. 1. System circuit diagram showing ESP32 connections to LDR sensors, INA219 sensors, L298N driver, and DC motors.

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IV. HARDWARE IMPLEMENTATION

A. Component Overview

The hardware integrates sensing, control, actuation, monitoring, and power-supply modules in one assembly. Table 2 summarises the key components, assembled on a custom acrylic frame with two degrees of freedom; electronics sit in a weather-protected enclosure.

Table 2. Key Hardware Components

Component	Model	Key Specification
Microcontroller	ESP32 WROOM-32	Dual-core 240 MHz, Wi-Fi
Light Sensor	LM393 LDR Module	Analog + digital output
Motor Driver	L298N H-Bridge	2 A/ch, PWM
Power Sensor	INA219	26 V, 3.2 A, I²C
Camera Module	ESP32-CAM OV3660	3 MP, JPEG output
DC Gear Motors	12 V DC Gear	30 RPM, dual shaft
Battery	12 V SLA	7 Ah, charge monitor

B. ESP32 Microcontroller and Pin Mapping

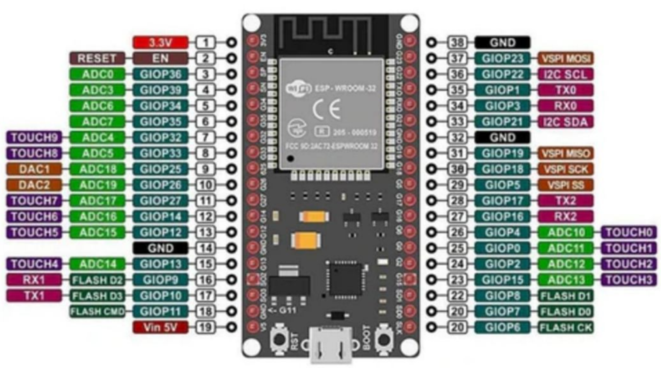

Fig. 2. ESP32 pin diagram

The ESP32 is the central processing unit: a 240 MHz dual-core SoC with 12-bit ADC for the LDR inputs, PWM for motor control, I²C for the sensors, and built-in Wi-Fi for dashboard access. Table 3 lists the GPIO assignments. The ESP32-CAM communicates with the main ESP32 over Wi-Fi via HTTP POST when dust is detected, keeping it isolated from the motor-driver section.

Table 3. ESP32 GPIO Pin Mapping

Function	ESP32 Pin	Connected Component
LDR Sensor (Top-Left)	GPIO34	LDR module
LDR Sensor (Top-Right)	GPIO35	LDR module
LDR Sensor (Bot-Left)	GPIO36	LDR module
LDR Sensor (Bot-Right)	GPIO39	LDR module
Motor Driver IN1	GPIO13	L298N (azimuth)

Motor Driver IN2	GPIO14	L298N (azimuth)
Motor Driver IN3	GPIO26	L298N (elevation)
Motor Driver IN4	GPIO27	L298N (elevation)
INA219 SDA	GPIO21	INA219 × 2
INA219 SCL	GPIO22	INA219 × 2

C. F. LDR Sensors, Motor Driver, Camera, and Power Supply

LDRs are photoresistive sensors whose resistance drops under illumination (dark resistance ~1 MΩ, light resistance 5–10 kΩ, response 20 ms), giving inexpensive, fast detection of directional sunlight variation. The L298N driver has two independent H-bridges (5–35 V, 2 A/channel): IN1 HIGH/IN2 LOW drives a motor forward, the reverse reverses it, and both LOW stops it, with speed set via PWM on the enable pins.

The ESP32-CAM (OV3660, 3 MP) gives an independent, vision-based dust layer: at startup it captures a reference grayscale baseline, then every 30 s recomputes brightness from a low-resolution QQVGA grayscale frame, skipping detection at night and reporting any drop of 25% or more to the main ESP32 over Wi-Fi. A regulated 12 V supply powers the motors, while the ESP32 and sensors run from 3.3–5 V via an LM2596 buck converter, isolating control and motor sections. A second INA219 monitors an off-grid 12 V SLA battery, estimating charge by interpolating voltage between empty (9.6 V) and full (12.6 V). The system draws 16–18 W total (Table 7), dominated by the drive motors.

Table 7. Power Distribution Summary

Section	Voltage (V)	Current (A)	Power (approx.)
ESP32 + Sensors	5	0.20	1 W
LDR Sensors	3.3	0.05	0.16 W
Azimuth Motor	12	0.50	6 W
Elevation Motor	12	0.50	6 W
TOTAL	—	—	16–18 W

H. Real-Time Monitoring Unit and Assembly

The monitoring unit centres on the INA219 sensor, communicating over I²C with voltage (0–26 V, ±1%), current (up to 3.2 A, ±0.2%), and power (up to 80 W, ±1%) accuracy, computed as P = V × I. The ESP32 interfaces with the LDRs via analog pins, the L298N via digital pins, and the two INA219 sensors over a shared I²C bus. The assembled prototype integrates these subsystems on a lightweight metal/acrylic frame permitting dual-axis rotation, as shown in Fig. 2.

Fig. 2. Assembled dual-axis solar tracker prototype with LDR sensors mounted at the panel corners.

V. SOFTWARE AND CONTROL LOGIC

The embedded software was developed in the Arduino IDE using Embedded C/C++, with the WiFi, Wire (I²C), Adafruit_INA219, and ESPAsyncWebServer libraries. The firmware handles sensor sampling, orientation decisions, alert generation, and data logging/transmission within a lightweight, event-driven, non-blocking loop, so sensing, motor control, and Wi-Fi transmission proceed concurrently.

A. LDR Feedback and Motor Control Algorithm

The control loop reads four ADC channels and computes two differential signals: ΔAz = LDR_East − LDR_West … (2) and ΔEl = LDR_North − LDR_South … (3). If |ΔAz| exceeds a dead-band (default ±50 ADC counts), the azimuth motor rotates toward the brighter side; elevation is handled identically using ΔEl. The dead-band prevents hunting from sensor noise near balance; the tracker converges within 2–5 s of a disturbance.

B. Cleaning Alert and Dust Detection Logic

The ESP32 computes power P = V × I from the INA219 and maintains a rolling maximum over a sliding window; a sustained drop raises a cleaning alert. Independently, the ESP32-CAM compares periodic grayscale brightness against its baseline and posts to /dust if it drops enough, setting a dustDetected flag that auto-clears after a cool-down. A stale rolling maximum resets to the next observed peak to avoid false alerts on overcast days, and a minimum power floor avoids spurious triggers at dawn or dusk. This gives complementary redundancy: the electrical channel evidences efficiency loss, while the camera confirms surface contamination directly.

C. Data Logging, Wi-Fi Transmission, and Dashboard

An asynchronous web-server library lets the ESP32 serve HTTP responses without blocking the control loop. The /data endpoint returns voltage, current, power, state-of-charge, cleaning/dust flags, harvested energy, a seven-day history array, Wi-Fi RSSI, and a timestamp, polled every 2 s via fetch(). Daily energy is integrated as $E \approx \Sigma P_k \cdot \Delta t$ … (4) and stored in flash via the Preferences library, surviving power cycles. On startup the ESP32 syncs its clock via NTP (IST); at day rollover it archives energy into the weekly array. If Wi-Fi drops, the dashboard shows 'Reconnecting…' while local sensing, tracking, and alerts keep running. The dashboard itself shows real-time readings, energy statistics, battery state, cleaning status, and manual calibration controls.
Measured performance indicators include a sensor sampling rate of 2–5 readings per second, tracking response under 1.5 s, Wi-Fi latency under 100 ms, and electrical data accuracy within ±2% for voltage and current.

VI. RESULTS AND DISCUSSION

The prototype was tested over multiple sunny days at MEA Engineering College, Perinthalmanna (10.97°N), Kerala. A fixed panel at the local optimum tilt and the dual-axis tracked system, of identical rating, were monitored concurrently under matched conditions using INA219 sensors logged via the dashboard.

Table 9. Performance Comparison: Fixed Panel vs. Dual-Axis Tracker

Parameter	Fixed Panel	Dual-Axis Tracker
Peak Power (W)	4.2 W	5.8 W
Daily Energy (Wh)	18.5 Wh	26.3 Wh
Efficiency Gain (%)	—	≈42%
Dust Alert Response	N/A	< 5 min
Tracking Accuracy	—	±2°
Dashboard Update Rate	—	2 s

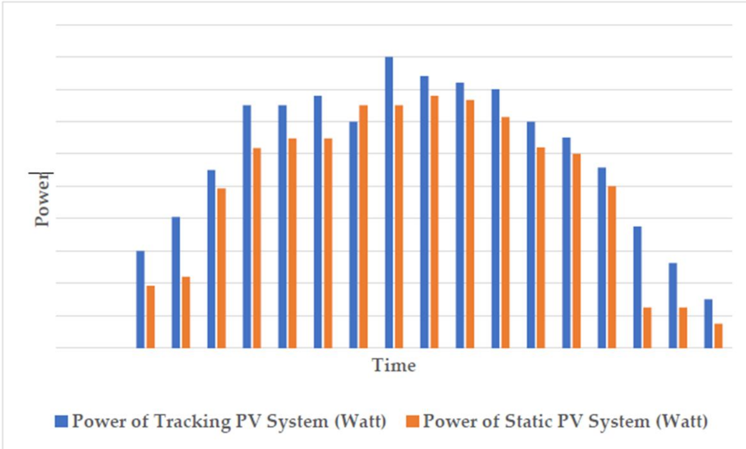

Fig. 3. Power output of the tracking versus static PV system over the course of a day.

A. *Energy Yield and Tracking Accuracy*

The tracked system achieved about 42% higher daily energy yield (26.3 Wh vs. 18.5 Wh) than the fixed installation, with peak power rising from 4.2 W to 5.8 W, consistent with—and at the upper end of—the 35–40% gain reported for a larger rooftop system [4]. Alignment stayed within ±2° throughout daylight hours; gains were largest in the morning and late afternoon, narrowing around solar noon as expected.

B. *Cleaning Alert and Dashboard Performance*

The dual-channel alert responded to a simulated dust film within five minutes. Both channels fired together for sustained soiling, while momentary shading nudged the power channel alone, confirming the design distinguishes transient shading from genuine soiling. The dashboard gave reliable 2-second updates with no data loss over a 6-hour test, and the watchdog kept local tracking and alerts running during brief, induced Wi-Fi dropouts.

C. *Discussion*

These results confirm that dual-axis tracking yields a substantial energy gain over a fixed installation even at small scale, that the dual-channel alert detects soiling faster and more reliably than either channel alone, and that the dashboard provides consistent, low-latency monitoring without external cloud infrastructure. The cost-reduction choices made here—LDR sensors and geared DC motors rather than encoders and servos, and a performance-based alert rather than a mechanical cleaner—do not significantly compromise precision or reliability at this scale.

VII. CONCLUSION

This paper presented an enhanced PV system integrating dual-axis solar tracking, a dual-channel cleaning alert, and IoT-based monitoring on a single ESP32 platform, addressing three coupled limitations of fixed installations: inefficient orientation, undetected dust, and lack of performance feedback. The LDR-based closed-loop tracking held alignment within ±2°, and experiments showed an approximately 42% improvement in daily energy yield. The dual-mode alert responded to simulated soiling within five minutes, while the IoT dashboard gave continuous, low-latency visibility into voltage, current, power, battery state, and historical energy. The system's low cost, compact design, and wireless connectivity suit small-scale residential, institutional, and rural deployments, notifying users only when intervention is actually required. At larger scale, similar architectures could integrate with smart grids or distributed solar farms for IoT-enabled energy management.

Future work will explore MPPT integration, ML-based irradiance forecasting, cloud-based predictive maintenance, and automated mechanical cleaning triggered by the existing alert, closing the loop between detection and remediation.

VIII. ACKNOWLEDGMENT

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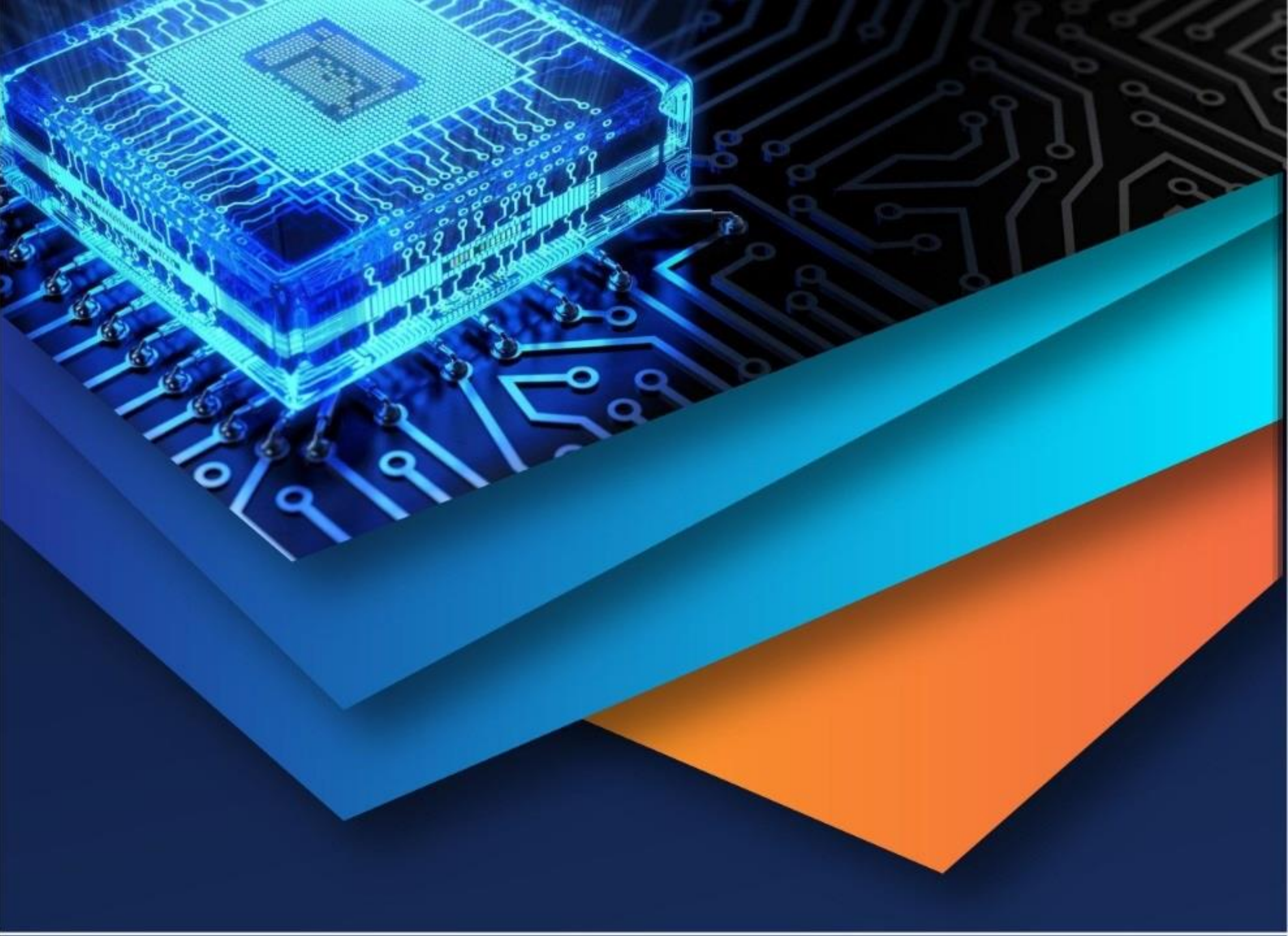

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