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IoT Street Lighting System with Real-Time Fog and Light Intensity Sensing and Cloud-Enabled Data Monitoring for Smart Cities

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Abstract: Today's urbanization has led us to the need of conservation of energy. One of the routine applications is city street lighting system for road safety. This paper proposes a low budget environment friendly street light controller that activates lighting automated to darkness and fog presence. The system uses ESP32 microcontroller interface with LDR to measure light intensity and DHT22 sensor to monitor temperature and humidity. The algorithm for fog detection used a threshold of humidity exceeding 90% and temperature lowering to 20°C. Data from multiple sensors are processed at real time, which is controlling a LED to simulate the status of street light on/off. Parallel to this a code is transmitting environment readings, activation status to a Google Sheet via Wi-Fi (serverless webhook for real time cloud logging). A series of test cases are collected for accuracy and responsiveness of the system. Comparative analysis demonstrates advantages of this system over traditional one. The proposed system is cost effective, scalable, easy to deploy. Future enhancement includes solar power integration, predictive analysis using machine learning, user friendly dashboards. This work gives a feasible effective solution for adaptive urban or rural area street lighting.
Keywords: Internet of Things (IoT), Embedded System, ESP32, Arduino Software, Automation, Smart Street Lighting.

I. INTRODUCTION

In Infrastructures are continually evolving through the integration of smart technologies aimed at enhancing public safety and energy efficiency. A notable component of this evolution is the development of intelligent street lighting systems. Traditional systems often rely on fixed schedules or simple light sensors, which do not adapt to dynamic environmental conditions such as unexpected fog or fluctuating ambient light levels. As a result, these systems may either consume excess energy or fail to provide adequate illumination when visibility is compromised [1].

Recent developments in the Internet of Things (IoT) for real-time environmental monitoring and automated decision-making are key focus areas in smart city applications development [2]. An inexpensive intelligent street lighting control system has been proposed wherein lights are turned on selectively depending on real-time environmental conditions. The system is designed to activate on two key conditions of low ambient light (darkness) and foggy conditions, which is determined by a combination of high humidity (>90%) and low temperature (<20°C), a correlation widely used for measuring fog [3].

The system centers around an ESP32 microcontroller interfacing with an LDR; and a DHT22 temperature-humidity sensor. Situated inside the microcontroller, the silicon chip reads the measurements of the sensors. Then, they are compared against a set of initial values to decide whether to switch on a street light, which in simulation is represented by an onboard LED. At the beginning of every operation cycle, through the invocation of a webhook, the system pushes into a Google Sheet all relevant environmental parameters along with lighting status and the activation criteria. Employing Google Sheets thereby provides a simple yet serverless and inexpensive logging mechanism; this sort of remote access to data is extremely useful to urban planners, environmentalists, and maintenance planners of smart cities [4].

The use of an LDR provides a reliable method for ambient light detection, while the DHT22 offers accurate readings for temperature and humidity. The system architecture is adaptable to standard Wi-Fi networks for real-world deployment. This project exemplifies the practical use of IoT in creating responsive, data-driven infrastructure. By ensuring that street lights are only activated when genuinely needed, the system contributes to energy conservation without compromising public safety. The proposed solution, due to its simplicity, affordability, and cloud integration, is particularly well-suited for implementation in resource-constrained urban or rural settings.

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II. RELATED WORK.

Smart street lighting technologies have received substantial focus owing to their ability to decrease energy usage and provide public safety. Many of the existing systems rely on passive infrared (PIR) sensors, motion detection, or ambient light sensing to control lighting [1][5]. These techniques work well under normal conditions but often lack the ability to respond accurately to environmental phenomena such as fog or sudden low-visibility scenarios, which are critical for road safety.

Several IoT-based implementations have incorporated microcontrollers like Arduino or ESP8266 along with cloud platforms for remote control and data logging. For instance, researchers have demonstrated the use of cloud-based dashboards for monitoring light status and energy usage [4]. Other efforts include solar-powered smart lights with PIR motion sensors [6], but these often operate on binary logic (on/off) based on limited parameters and do not take environmental factors like temperature and humidity into account.

Fog detection has traditionally been implemented using computer vision or LiDAR-based systems, which, while accurate, are expensive and require complex setups unsuitable for mass deployment in developing or budget-constrained areas [7]. Alternative low-cost methods using humidity and temperature readings have been proposed, but their integration into real-time street lighting control systems remains limited in the literature.

III. SYSTEM DESIGN AND ARCHITECTURE

A. System Overview

This is a smart street lighting controller designed to dynamically adjust to the ambient conditions through a combination of sensors and cloud-logging. The decision criteria rest mostly on low ambient light or foggy weather. If anything else happens, the streetlight will be turned on automatically (represented by an LED). The system architecture centers on an ESP32 microcontroller, which gathers light intensity data from a Light Dependent Resistor (LDR) and temperature and humidity readings from a DHT22 sensor. The decision logic is then executed locally, and the processed data, including sensor readings, activation status, and cause, are then sent to a Google Sheet via a webhook, in real time.

This architecture allows for intelligent suggestions for lighting control that are very cheap to implement and provide a serverless data-logging infrastructure-all great for any smart city or rural infrastructure

B. Block Diagram

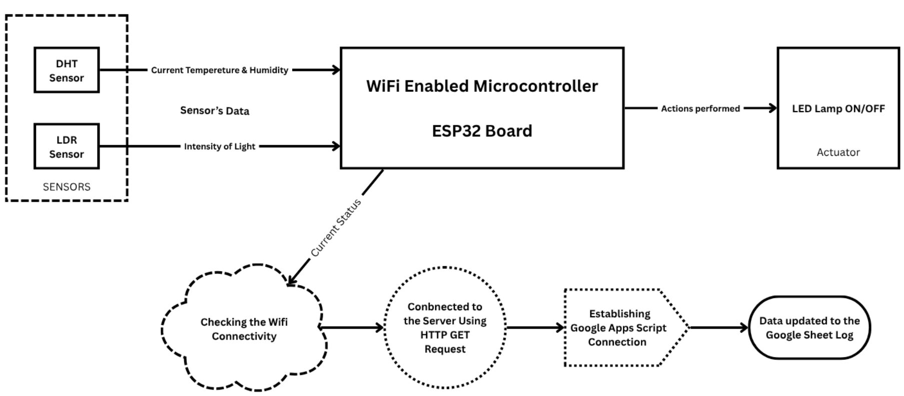

Fig. 1. System Architecture of IoT-Based Environmental Monitoring and Control Using ESP32

C. Component Descriptions and Justification

The system employs a dual-core ESP32 microprocessor equipped with Wi-Fi and Bluetooth capabilities, thus providing a perfect environment for IoT applications requiring interfacing with sensors and cloud communication simultaneously. Hence, ESP32 is considered better in performance and more GPIO pins can be used for interfacing when compared to other microcontrollers such as the Arduino Uno or an ESP8266. An LDR is used for sensing the ambient light level; it changes its resistance according to the amount of light falling on it. This analog signal from the LDR is fed to the ADC of ESP32 for sensing darkness, i.e., if the ADC output is more than 3000, it stands for darkness. The LED used for light simulation is connected to a resistor to give a visual indication of the streetlight condition.

The LEDs are sometimes switched ON and OFF based upon the LDR data and DHT22 sensor data on temperature and humidity. These sensor data, together with data reflecting the working logic of streetlight activation under different conditions, are simultaneously sent to Google Sheets via Webhook using a Google Apps Script. This allows for serverless, structured, cloud-based data logging, timestamping, temperature, humidity, light level, activation reason, and system status as parameters.

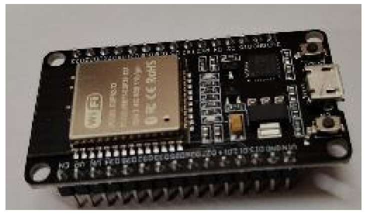

Fig. 2. ESP32 Microcontroller

Fig. 3. DHT22 Temperature and Humidity Sensor

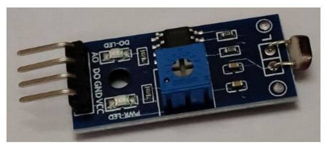

Fig. 4. Light Dependent Resistor (LDR)

D. Design Rationale

The entire system design manifests a tradeoff between utility, cost-effectiveness, and ease of deployment. The pairing of ESP32, DHT22, and LDR supplies enough data granularity for environmental parametric monitoring. With integration into Google Sheets, the logging mechanism becomes very transparent and accessible in remote manners without requiring cloud infrastructure, backend development, or paid services. Hence, the system is not only technically sound but also socially relevant, especially for budget-constrained local governments.

IV. METHODOLOGY / IMPLEMENTATION

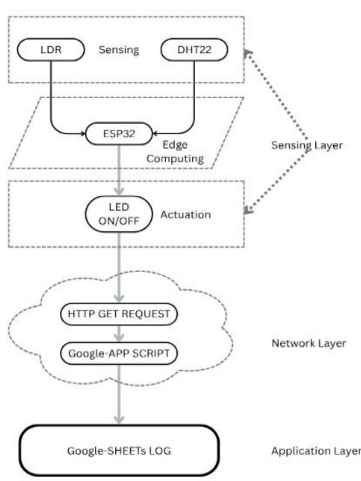

Fig. 5. Layered Architecture of an IoT Monitoring and Control System.

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A. Pseudo Code

Step 1: LDR (GPIO 34), DHT22 (GPIO 15), LED (GPIO 2) sensors, serial communication & Wi-Fi has been initialized.
Step 2: A Loop has been created for every 10 seconds:Read the LDR_value, temperature value and humidity percentage.
Step 3: Check the condition:
If LDR_value > 3000, set condition = "Dark"
Else if humidity > 90 and temperature < 20, set condition = "Foggy"
Else, set condition = "Clear"
Step 4: Actuation of the LED:
If condition = "Dark" or "Fogg", turn on the LED and set LED_status = "ON"
Else, turn off the LED and set LED_status = "OFF"
Step 5: Create the URL with Temperature, Humidity, LDR Reason and Light Status. Then send the data through HTTP GET to Google Script.
Step 6: Print all the values on the serial monitor.
Step 7: Wait for 10 seconds and repeat Step 3.

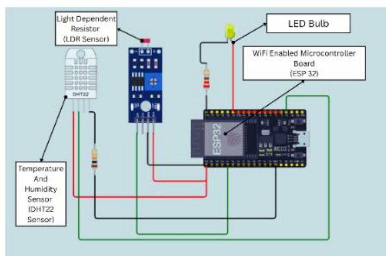


Fig. 6. Circuit Diagram of ESP32-Based IoT Sensing and Actuation System

V. EXPERIMENTAL RESULTS AND DISCUSSION

This section presents the results obtained from testing the proposed smart street lighting system under various environmental conditions. The experimental evaluation focused on validating the functionality of the fog detection logic, light sensing mechanism, and cloud-based data logging.

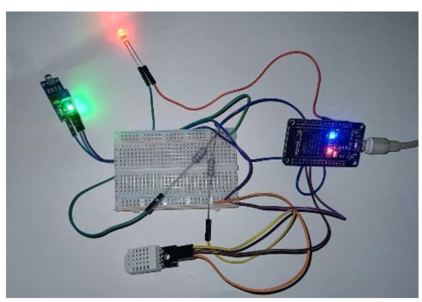


Fig. 7. Fog and Light Intensity detection embedded system with its components

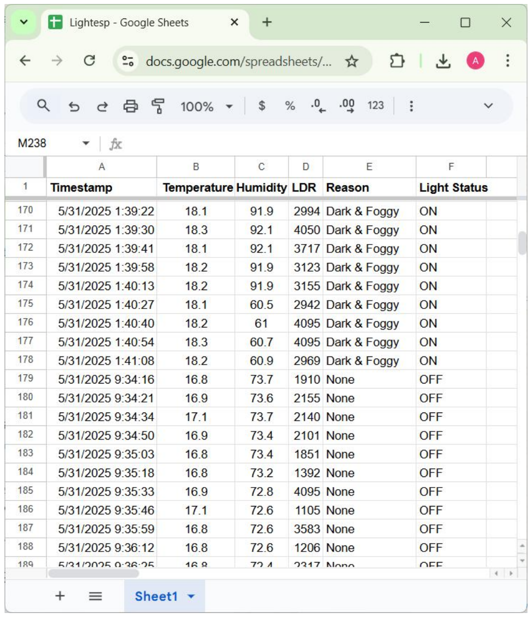
A. Testing Conditions and Setup

The evaluation has been implemented using the Arduino IDE, and configured using the following components[12]:

- ESP32 Dev Board for processing and control the system
- DHT22 sensor for sensing real-time temperature and humidity
- LDR sensor for determining the real-time ambient light intensity
- LED to simulate a real street light

The Development environment used local Wi-Fi for the Internet connection. The cloud integration had been implemented using a Google Apps Script Webhook connected to a Google Sheet for real-time data logging. The system was tested under controlled manual input scenarios.

B. Observations and Data Collection



	Timestamp	Temperature	Humidity	LDR	Reason	Light Status
170	5/31/2025 1:39:22	18.1	91.9	2994	Dark & Foggy	ON
171	5/31/2025 1:39:30	18.3	92.1	4050	Dark & Foggy	ON
172	5/31/2025 1:39:41	18.1	92.1	3717	Dark & Foggy	ON
173	5/31/2025 1:39:58	18.2	91.9	3123	Dark & Foggy	ON
174	5/31/2025 1:40:13	18.2	91.9	3155	Dark & Foggy	ON
175	5/31/2025 1:40:27	18.1	60.5	2942	Dark & Foggy	ON
176	5/31/2025 1:40:40	18.2	61	4095	Dark & Foggy	ON
177	5/31/2025 1:40:54	18.3	60.7	4095	Dark & Foggy	ON
178	5/31/2025 1:41:08	18.2	60.9	2969	Dark & Foggy	ON
179	5/31/2025 9:34:16	16.8	73.7	1910	None	OFF
180	5/31/2025 9:34:21	16.9	73.6	2155	None	OFF
181	5/31/2025 9:34:34	17.1	73.7	2140	None	OFF
182	5/31/2025 9:34:50	16.9	73.4	2101	None	OFF
183	5/31/2025 9:35:03	16.8	73.4	1851	None	OFF
184	5/31/2025 9:35:18	16.8	73.2	1392	None	OFF
185	5/31/2025 9:35:33	16.9	72.8	4095	None	OFF
186	5/31/2025 9:35:46	17.1	72.6	1105	None	OFF
187	5/31/2025 9:35:59	16.8	72.6	3583	None	OFF
188	5/31/2025 9:36:12	16.8	72.6	1206	None	OFF

Fig. 8. Cloud Data (Google Sheet) for Sensor's data and Current Street Light (ON/OFF) Status.

Several iterations were conducted with varying combinations of temperature, humidity, and light intensity. The key performance indicators (KPIs) were the LED state (ON/OFF), activation reason, and logging consistency.

Table 1. Observations and Data Collection

Temp (°C)	Humidity (%)	LDR Value	Condition Detected	LED Status	Reason Logged
19.5	91.2	2500	Foggy	ON	Fog
25.0	45.0	3500	Dark	ON	Dark
26.3	50.0	1200	Clear	OFF	Clear
18.0	93.5	3400	Foggy & Dark	ON	Fog

These values demonstrate the system's accurate response to:
- High humidity + low temperature → LED ON (fog condition)
- Low light alone → LED ON (dark condition)
- Clear weather + sufficient light → LED OFF

C. System Behavior Analysis
- Responsiveness: The LED responded immediately (<1 second delay) to changes in sensor input due to the efficient polling cycle (every 10 seconds).
- Data Accuracy: The LDR and DHT22 sensors provided stable and reliable readings in the simulated environment.
- Cloud Integration: Google Sheets logged all transmitted parameters accurately, including timestamps (via script function) and status indicators.

D. Conclusion from Results
The system proves to be effective in detecting low-visibility conditions and dynamically controlling street lighting. Its low cost, energy efficiency, and real-time cloud logging capabilities make it suitable for urban as well as semi-rural smart city applications

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VI. COMPARATIVE ANALYSIS

To position the proposed system within the landscape of existing smart street-lighting solutions, we compare key attributes across representative implementations.

Table 2. Comparative Highlights of the Proposed System

Feature	PIR/Motion-Based Systems [1]	Vision/LiDAR-Based Fog Detection [2]	Solar-PIR Hybrid Lights [3]	Proposed System
Primary Sensing	Motion detector (PIR)	Camera/LiDAR	PIR + ambient light sensor	LDR + DHT22 (humidity & temperature)
Fog Detection	Not supported	Yes (high accuracy, high cost)	Not supported	Yes (humidity > 90% & temp < 20 °C)
Control Logic	Binary on/off via motion	Complex image processing or range	Binary on/off via motion + light	Multi-parameter threshold logic
Connectivity & Logging	Local control only	Often local or edge processing	Local control only	Real-time cloud logging via webhook
Cost	Low–medium	High (specialized sensors + compute)	Medium (solar panels + battery + PIR)	Very low (ESP32 + inexpensive sensors)
Energy Efficiency	Moderate	Depends on compute	Good (solar-powered)	High (only active when needed)
Scalability	Good	Limited by infrastructure	Moderate	Very high (serverless cloud logging)

VII. APPLICATIONS AND FUTURE WORK

Importantly, there exist man promising applications for this system in various fields. In smart cities, it may be used for adaptive lighting in urban roads, pedestrian walkways, and parking lots, with real-time data being integrated into centralized city management dashboards through cloud APIs. From the point of view of rural electrification, where there are limited infrastructures, this system offers a cheap solution, especially when integrated with solar-powered or battery-operated LEDs to achieve maximum lighting availability. Campuses and industrial plants can also retrofit existing lighting fixtures under IoT-based control for energy usage tracking and maintenance scheduling efficiently on a continuous data-logging basis. Further, in the future, some expected enhancements would include solar integration for off-grid purposes and data-backed machine learning models for predictive fog conditions and automated activation of lights. There will be a mobile/Web dashboard for remote control, live monitoring, and alerts. Edge analytics and mesh networking would give the lighting nodes group decision power, improving efficiency even further. Extending sensing possibilities towards air-quality and particulate matters monitoring could trigger lighting based on environmental hazards, further extending the system relevance for public health and safety. All these aim to place the solution as a scale-able, intelligent, and sustainable lighting infrastructure for the future.

VIII. CONCLUSION

This paper presented a low-cost, IoT-based street light control system that intelligently responds to ambient light and fog conditions using an ESP32 microcontroller, DHT22 sensor, LDR, and serverless cloud logging via Google Sheets. Experimental evaluation in a simulated environment demonstrated reliable fog detection (humidity > 90% & temperature < 20 °C), accurate light sensing (LDR threshold = 3000 ADC), and robust real-time data transmission. Comparative analysis showed significant advantages over traditional PIR- or vision-based systems in terms of cost, simplicity, and scalability. The proposed architecture holds promise for smart city deployments, rural electrification projects, and facility management applications. Ongoing and future work will focus on solar integration, predictive analytics, and user-centric dashboards, further enhancing the system's autonomy and utility.

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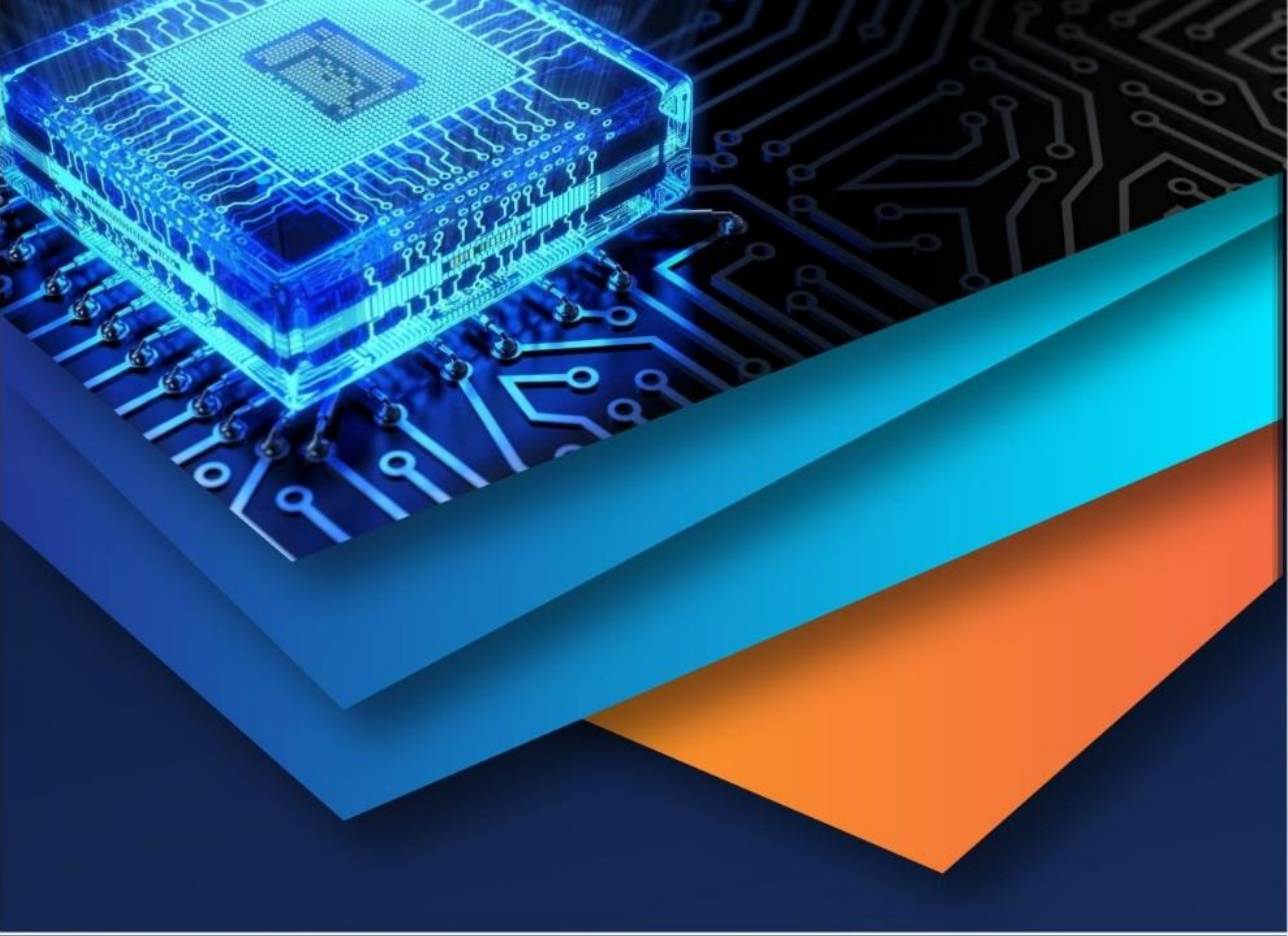

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