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SuryaRakshak: An IoT-Enabled, Solar-Powered Spoilage Monitoring System for MSME Storage Facilities

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Abstract: Spoilage of stored grain, produce and packaged goods is a persistent source of loss for micro, small and medium enterprises (MSMEs), yet most commercial cold-chain solutions are refrigeration-based and priced beyond the reach of small storage operators.

This paper presents SuryaRakshak, a solar-powered retrofit monitoring kit designed to prevent spoilage in unrefrigerated MSME storage rooms rather than to refrigerate them, positioning it in the affordable, non-refrigeration tier that is underserved by players such as Inficold and Ecozen. The system pairs an STM32F401 "Black Pill" microcontroller with a Sensirion SHT31-DIS temperature-and-humidity sensor, a CN3791 MPPT solar charge regulator, and a 6000 mAh LiFePO4 backup cell to provide continuous, off-grid environmental monitoring.

A SIM800L GPRS module gives the unit cellular alerting independent of Wi-Fi availability, while front-panel status LEDs and an onboard display give operators an at-a-glance read of Power, Solar, Normal, Warning and Critical states. The enclosure, standoffs and sensor housing are 3D-printed in PETG/ABS and sealed to an IP54 standard. This paper documents the objectives, literature context, problem identification, system architecture.

I. INTRODUCTION

Post-harvest and post-production spoilage remains one of the most persistent and least visible sources of loss for India's MSME sector. Grain, spice, and packaged-food storage rooms operated by small enterprises are frequently unrefrigerated, unmonitored, and staffed intermittently, so a slow rise in humidity or an unnoticed temperature excursion can silently degrade an entire batch of stored material before anyone intervenes.

The commercial response to this problem has largely come from refrigeration-first vendors, whose systems are effective but carry capital and running costs that place them out of reach for the smallest operators.

SuryaRakshak addresses the gap between "no monitoring at all" and "full refrigeration" by focusing purely on early detection and alerting. Rather than actively cooling a storage room, the system continuously tracks temperature and relative humidity, classifies the reading against configurable thresholds, and escalates through on-device indication and, where conditions warrant it, a cellular SMS/alert, so that an operator can intervene while the stored goods are still recoverable. Because the unit is solar-powered with a LiFePO4 battery buffer, it can be deployed in storage rooms without reliable grid power, and because it communicates over GPRS rather than Wi-Fi, it does not depend on the facility having its own internet connection.

II. OBJECTIVES

1) Provide continuous, real-time monitoring of temperature and humidity inside unrefrigerated MSME storage rooms.
2) Operate independently of grid power using a solar panel, MPPT charge regulator and LiFePO4 backup battery.
3) Alert operators of abnormal storage conditions through on-device status indication and cellular (GSM/GPRS) messaging, without depending on a Wi-Fi connection.
4) Keep the bill of materials low enough to serve the affordable, non-refrigeration tier of the market that is presently underserved by refrigeration-first vendors.
5) Package the electronics in a retrofit-friendly, IP54-rated enclosure that can be wall-mounted in an existing storage room with minimal installation effort.

III. LITERATURE REVIEW

1) *A. Nanwatkar et al., "IoT Based Food Cold Storage Monitoring and Controlling System," ResearchGate, 2024.*

This work automates temperature control in a cold-storage setting and layers real-time monitoring on top of it, reporting that continuous tracking of environmental parameters improves food-safety outcomes and helps minimise wastage. SuryaRakshak adopts the same emphasis on real-time environmental sensing but deliberately omits active refrigeration, targeting the unrefrigerated segment that this class of system does not address.

2) *"Design of a Smart IoT-Based Control System for Remotely Managing Cold Storage Facilities," PMC / NCBI.*

This review surveys several IoT cold-storage schemes, including low-cost solar-powered installations and sensor nodes built around commodity microcontrollers, and notes recurring use of temperature, humidity and light sensing for spoilage prediction. The survey's emphasis on low-cost, solar-powered sensing nodes closely parallels the architecture chosen for SuryaRakshak's Control Logic Board and Storage Env Sensor pairing.

3) *"An AI-Integrated Renewable-Powered Cold Storage System with Advanced Environmental Sensing for Smallholder Farmers," Engineering, Technology & Applied Science Research (ETASR), 2025.*

This study combines solar PV power with multi-sensor environmental monitoring and an edge machine-learning model for spoilage prediction, aimed at smallholder farmers who lack affordable cold-storage infrastructure. It reinforces the case for solar autonomy in off-grid storage monitoring, though its cooling and AI-prediction layers add cost and complexity that SuryaRakshak intentionally avoids in favour of a simpler threshold-based alerting approach.

4) *"Cold Chain Monitoring with IoT Sensors: A Data-Driven Approach to Reducing Spoilage in Temperature-Sensitive Supply Chains," 2025.*

This paper builds a conceptual framework that combines IoT sensing, cloud analytics and decision-support to reduce spoilage risk across cold-chain logistics, drawing on data from food and pharmaceutical shipments. It underscores the value of continuous data capture for traceability, a principle SuryaRakshak applies at a single-node, single-room scale rather than across a distributed logistics network.

5) *"Solar-Thermoelectric Mobile Storage System Integrated with Electric Vehicles for Reducing Postharvest and Microbial Losses in Agro Produce Transportation," Scientific Reports, 2025.*

This work designs a solar-powered micro cold-storage unit for transporting agricultural produce and evaluates its effect on microbial load and postharvest loss, noting the outsized contribution of the MSME sector to national GDP as motivation. It confirms that solar power is a practical energy source for MSME-scale storage interventions, which SuryaRakshak applies to a stationary monitoring context rather than a mobile cooling one.

6) *"An IoT Smart System for Cold Supply Chain Storage and Transportation Management," Engineering, Technology & Applied Science Research (ETASR).*

This paper proposes a global framework, built around low-cost, low-energy-consumption devices, for monitoring storage and transport conditions across a cold supply chain. The preference for low-cost, low-power hardware mirrors the component choices made for SuryaRakshak's Control Logic Board, sensor and cellular alert module.

IV. PROBLEM IDENTIFICATION

Existing spoilage-prevention options for MSME storage rooms fall into two broad categories, neither of which fits the smallest operators well:

1) Refrigeration-first systems (such as those offered by established cold-storage vendors) prevent spoilage by actively cooling the space, but the capital and running cost of compressors, insulation and continuous power draw is prohibitive for many small storage operators.
2) No monitoring at all, which is the default state for a large share of unrefrigerated MSME storage rooms, leaves temperature and humidity excursions undetected until the stored goods are visibly damaged.

Additional constraints specific to this segment compound the problem: many MSME storage rooms have unreliable or absent grid power, are not connected to Wi-Fi, and are checked in person only intermittently by staff who may be occupied elsewhere on the premises. A viable solution therefore needs to be self-powered, network-independent for alerting, low in upfront cost, and simple enough to retrofit onto an existing storage room without structural modification. SuryaRakshak is scoped specifically to this gap.

V. METHODOLOGY

Define Objectives

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Literature Review & Problem Identification

↓

System & Electrical Architecture Design

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Component Selection (MCU, Sensor, Power, Module, Display)

↓

Fabricate (3D-printed mounts, enclosure, standoffs, cable gland)

↓

Wire (power harness, I²C bus, UART, status LEDs, continuity check)

↓

Bring-Up (battery voltage, firmware flash, GSM AT test, LED calibration, solar-charging validation)

↓

Assemble & Seal Enclosure (IP54 gasket, front cover)

↓

Testing, Iteration and Documentation

VI. SYSTEM DESIGN AND ARCHITECTURE

A. *Electrical Architecture*

The electrical system is organised around five functional groups — an MCU (Control Logic Board), a Sensor (Storage Env Sensor), Power (Solar Charge Regulator and Main Backup Battery), a communication Module (Cellular Alert Module) and a Display group (Front Panel Status LEDs). The STM32F401 "Black Pill" Control Logic Board sits at the centre of the design: it reads temperature and humidity from the Sensirion SHT31-DIS over an I²C bus, drives the front-panel status LEDs over GPIO, and exchanges AT commands with the SIM800L GPRS Cellular Alert Module over a UART link. Power is drawn from a 6000 mAh LiFePO4 32700 cell that is kept charged by a CN3791 MPPT solar charge regulator, giving the unit an autonomous power budget independent of the grid.

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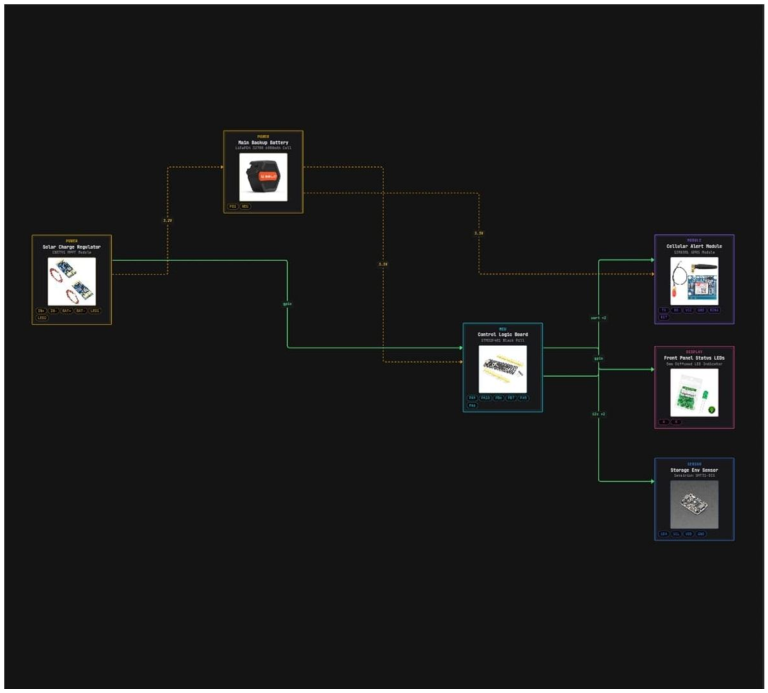

Fig. 1. Electrical block diagram showing power (dashed), data (solid green) and ground connections between the Main Backup Battery, Solar Charge Regulator, Control Logic Board, Cellular Alert Module, Front Panel Status LEDs and Storage Env Sensor.

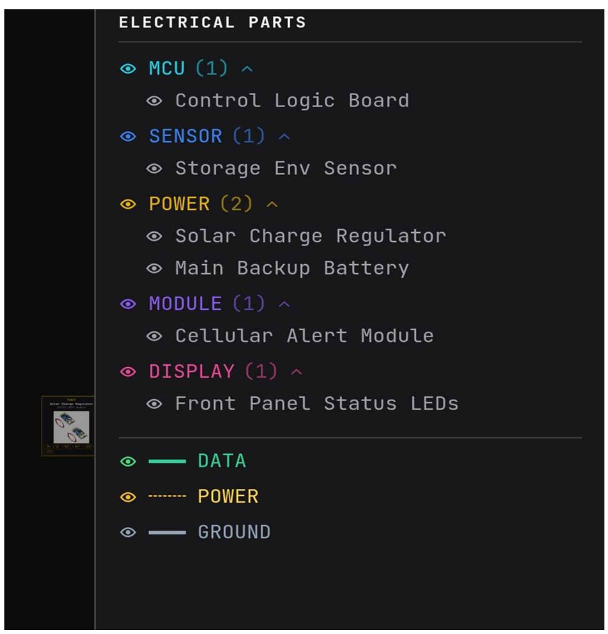

Fig. 2. Electrical parts categorised by function — MCU, Sensor, Power, Module and Display — with the Data / Power / Ground connection legend used in the block diagram.

B. Mechanical Design and Enclosure

All structural and mounting parts — the Isolated Sensor Housing, LiFePO4 Battery Cradle, Control Logic Board Mount, Cellular Alert Module Mount and Front Panel Status LEDs Mount — are 3D-printed in PETG, with wall counts and infill chosen per part (for example, the Isolated Sensor Housing is printed with two walls and 15% infill to keep it light and vented, while the Battery Cradle uses four walls and 30% infill for structural load-bearing).

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These mounts bolt into a UV-resistant ABS Main Enclosure Base, which incorporates an IP54 gasket channel around its perimeter, and are closed off by a Front Cover Plate with integrated light pipes for the status LEDs and cut-outs for diagnostics. Cable entry is sealed with four IP68 M16 marine cable glands, and the electronics board is raised on brass M3 standoffs inside the base. An adjustable, powder-coated steel bracket allows the solar panel to be tilt-mounted on the same wall or roof structure as the enclosure.

Fig. 3. Rendered assembly of the SuryaRakshak unit, showing the tilt-adjustable solar panel, the main enclosure with Power / Solar / Normal / Warning / Critical status LEDs, the temperature-humidity-status display, the SERVICE/RESET button, and the externally mounted alarm/speaker module.

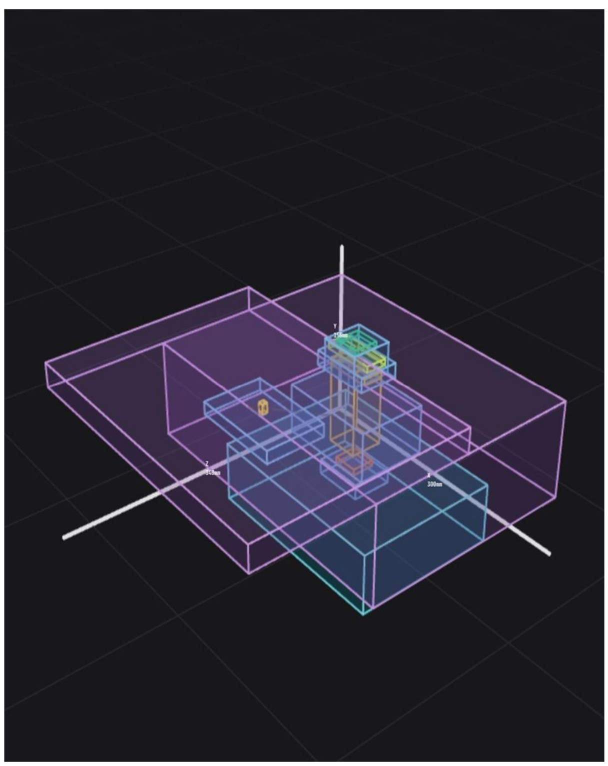

Fig. 4. CAD envelope of the assembled unit (approx. 300 mm × 150 mm × 340 mm), showing the nested placement of the Control Logic Board, Battery Cradle and Sensor Housing within the Main Enclosure Base.

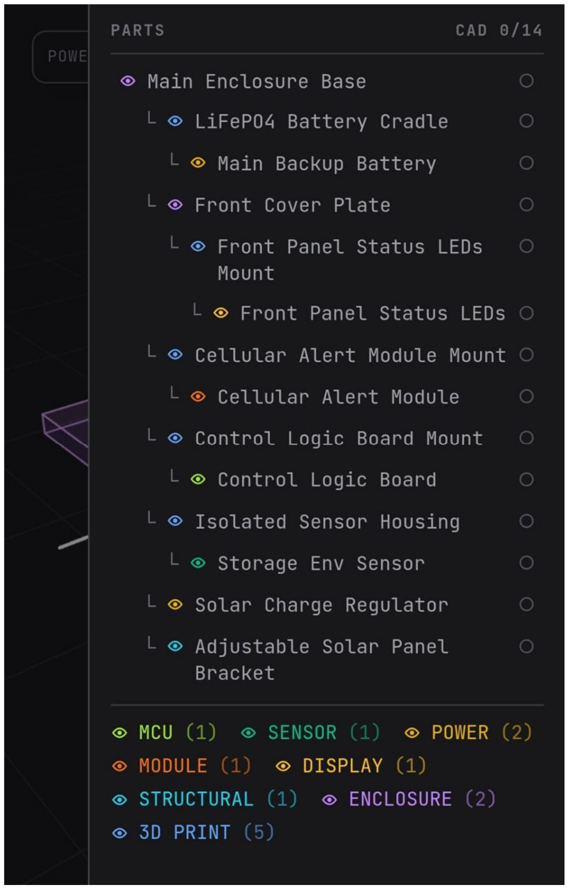

Fig. 5. Parts hierarchy / bill of materials tree, showing how each 3D-printed mount nests its corresponding electrical component within the Main Enclosure Base.

C. *Fabrication and Assembly Procedure*

Assembly follows a four-phase build sequence — Fabricate, Wire, Bring-up and Assemble — summarised below.

1) Fabricate: 3D-print the internal mounts and sensor housing (Control Logic Board Mount, Cellular Alert Module Mount, Front Panel Status LEDs Mount, LiFePO4 Battery Cradle, Isolated Sensor Housing); print the enclosure body and front cover (Main Electronic Chassis / Main Enclosure Base and Front Cover Plate); install brass M3 PCB standoffs into the enclosure base; and drill mounting holes and fit the IP68 M16 cable gland.
2) Wire: Solder the battery power harness from the LiFePO4 cell to the CN3791 MPPT solar controller; build the power distribution rail feeding the Control Logic Board and Cellular Alert Module; wire the I²C bus between the Control Logic Board and the SHT31-DIS sensor; connect the UART lines between the Control Logic Board and the SIM800L module; solder the status LEDs to the Control Logic Board's GPIO pins; and finish with a continuity and short-circuit check across the battery, regulator and logic board.
3) Bring-up: Verify the battery voltage output from the solar controller with a multimeter; flash firmware to the Control Logic Board and confirm I²C sensor detection; test the GSM module's AT-command responsiveness; calibrate the status-LED GPIO output levels; and validate the solar-charging LED logic loop end to end.
4) Assemble: Mount the electronic components to their internal brackets; secure all internal modules into the enclosure base; install the external, tilt-adjustable solar bracket; and seal the enclosure with the IP54 perimeter gasket and front cover.

VII. WORKING PRINCIPLE

In normal operation, the solar panel feeds DC power through the CN3791 MPPT regulator, which both conditions the input for maximum-power-point tracking and manages charge/discharge of the 6000 mAh LiFePO4 backup cell, so that the unit continues to run through the night or during overcast periods.

The STM32F401 Control Logic Board periodically polls the SHT31-DIS sensor over I²C for temperature and relative humidity inside the storage room and compares each reading against configured thresholds. Under normal conditions the front-panel "Power", "Solar" and "Normal" LEDs stay lit and the onboard display shows the live temperature, humidity and status. If a reading crosses into a Warning band, the corresponding LED is activated as an early-warning cue; if it crosses into a Critical band, the Control Logic Board additionally drives the externally mounted alarm/speaker unit and issues an alert over UART to the SIM800L GPRS module, which sends an SMS notification to the registered operator independent of any local Wi-Fi network. A SERVICE/RESET button on the front panel lets an operator acknowledge an alert or reset the unit after intervening.

VIII. BILL OF MATERIALS

The prototype bill of materials, covering the electrical components, structural/enclosure hardware and 3D-printed parts, totals approximately ₹9,450 (at ~₹95/US$) as summarised in Table I.

TABLE I. SURYARAKSHAK BILL OF MATERIALS

Component	Part	Qty	Approx. Unit Cost
Control Logic Board	STM32F401 "Black Pill"	1	~₹475
Storage Env Sensor	Sensirion SHT31-DIS	1	~₹760
Solar Charge Regulator	CN3791 MPPT Module	1	~₹570
Main Backup Battery	LiFePO4 32700 6000mAh Cell	1	~₹1,140
Cellular Alert Module	SIM800L GPRS Module	1	~₹665
Front Panel Status LEDs	5mm Diffused LED Indicator	5	~₹48
Adjustable Solar Panel Bracket	Powder-coated steel, tilt-adjustable	1	~₹1,140
Main Enclosure Base	UV-resistant ABS chassis, IP54 gasket channel	1	~₹1,758
Front Cover Plate	Faceplate with integrated LED light pipes	1	~₹760
M3 PCB Standoffs	Brass hexagonal standoffs	8	~₹14
IP54 Perimeter Gasket	Adhesive-backed EPDM rubber seal	1	~₹333
Cable Gland	IP68 M16 marine cable gland	4	~₹114
Isolated Sensor Housing	3D-printed (PETG), labyrinth-vented	1	~₹190
LiFePO4 Battery Cradle	3D-printed (PETG)	1	~₹285
Control Logic Board Mount	3D-printed (PETG)	1	~₹190
Cellular Alert Module Mount	3D-printed (PETG)	1	~₹190
Front Panel Status LEDs Mount	3D-printed (PETG)	1	~₹190
		Total Estimated Cost	~₹9,453

IX. ADVANTAGES

1) Low prototype cost (approximately ₹9,450 in components) relative to refrigeration-based alternatives.
2) Fully solar-powered with a LiFePO4 buffer, so it can be deployed in storage rooms without reliable grid power.
3) Cellular (GSM/GPRS) alerting works even where the storage facility has no Wi-Fi or internet connection.

4) Retrofit-friendly, IP54-rated enclosure that mounts onto an existing storage room without structural changes.
5) Simple front-panel status indication (Power / Solar / Normal / Warning / Critical) with a SERVICE/RESET button for straightforward day-to-day operation by non-technical staff.

X. DISADVANTAGES / LIMITATIONS

1) Cellular alerting depends on local GSM/GPRS network coverage, which can be inconsistent in some rural locations.
2) Solar charging performance depends on panel placement, orientation and seasonal weather conditions.
3) A single sensor node provides one reading per unit; larger or unevenly ventilated storage rooms may need more than one unit to capture spatial variation.
4) The 3D-printed enclosure and gasket require periodic inspection to maintain the IP54 seal over time.
5) The system detects and alerts on adverse conditions but, unlike refrigeration-based systems, does not itself correct temperature or humidity.

XI. APPLICATIONS

1) Unrefrigerated MSME storage rooms for grain, spices and packaged foods.
2) Warehouses and godowns without reliable grid power or internet connectivity.
3) Small dairy collection centres and agri-produce aggregation points.
4) Small-format retail and pharmacy back-room storage where full refrigeration is not economically viable.

XII. CONCLUSION

1) SuryaRakshak targets the affordable, non-refrigeration tier of MSME storage monitoring that is presently underserved by refrigeration-first vendors such as Inficold and Ecozen.
2) Solar power with an LiFePO4 buffer gives the unit off-grid autonomy suited to storage rooms with unreliable electricity.
3) I²C-based temperature/humidity sensing paired with GPRS alerting provides continuous monitoring and remote notification without depending on facility Wi-Fi.
4) A 3D-printed, IP54-sealed enclosure keeps the bill of materials low (~₹9,450) wh
5) ile remaining retrofit-friendly.
6) Overall, SuryaRakshak offers a low-cost, self-powered early-warning system that helps MSME operators intervene before stored goods are damaged, rather than bearing the capital cost of full refrigeration.

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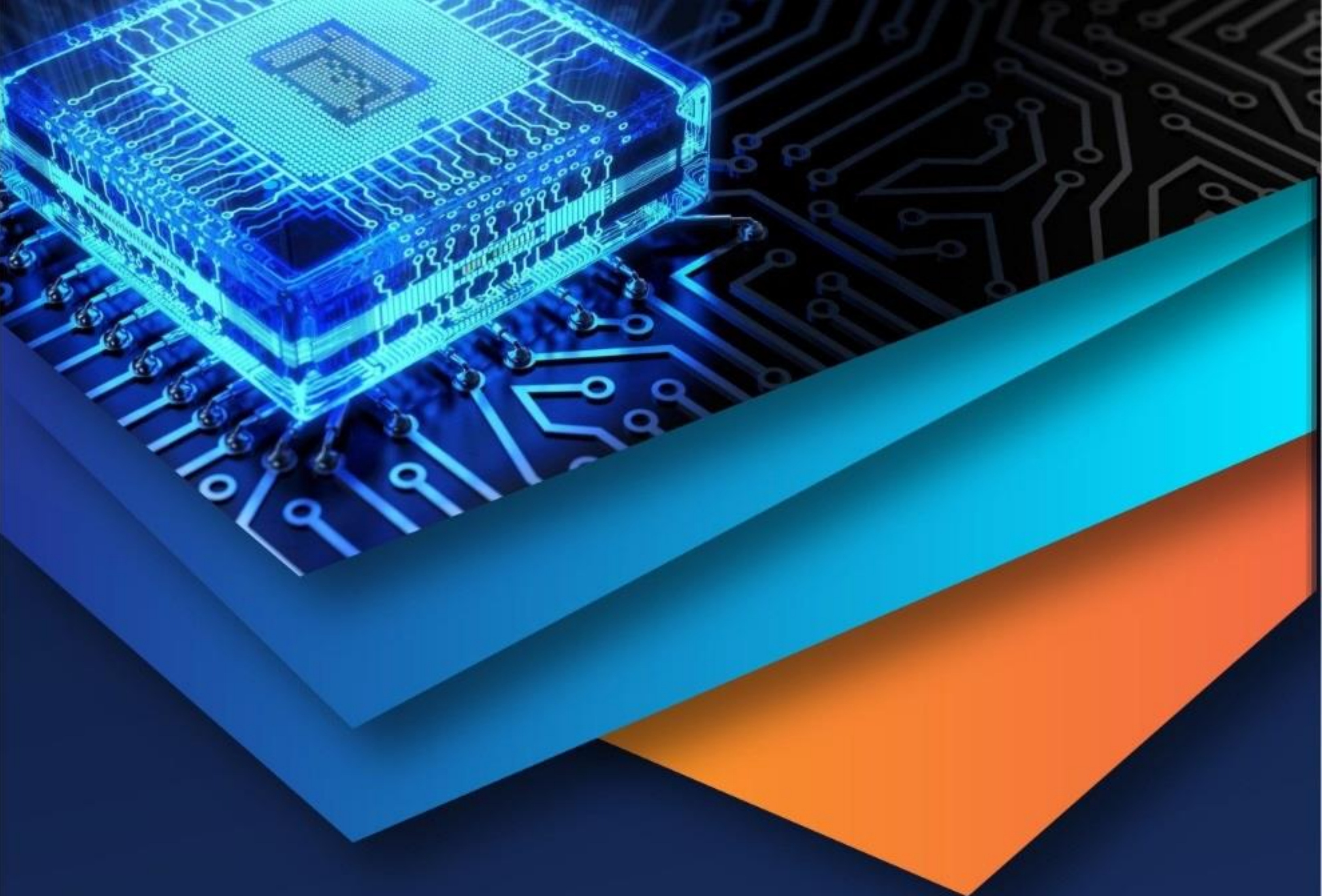

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