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Reward Based Smart Waste Segregation System

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Abstract: The rapid increase in solid waste and the lack of proper segregation at the source have led to serious environmen-tal and public health challenges. Conventional waste management systems rely heavily on manual sorting, which is inefficient, time-consuming, and prone to human error.

This paper presents a Reward-Based Smart Waste Segregation System that integrates Deep Learning (DL) and Internet of Things (IoT) technologies to automate the process of waste classification and disposal. The proposed system utilizes a Convolutional Neural Network (CNN) model to classify waste materials in real time using images captured by a camera module. Based on the classification results, the system employs hardware components such as a Raspberry Pi, ESP32 microcontroller, sensors, and motor mechanisms to automatically segregate waste into appropriate categories. Additionally, sensors like ultrasonic modules and load cells are used to monitor bin levels and measure waste input. To encourage user participation, a reward management system is incorporated, where users receive points based on weight of the waste disposed. The integration of intelligent software with em-bedded hardware ensures accurate segregation, reduced human intervention, and improved efficiency in waste management. The system aims to promote sustainable practices, enhance recycling rates, and contribute to cleaner and smarter environments.

Index Terms: Waste Segregation, Deep Learning (DL), Convolutional Neural Network (CNN), EfficientNetV2S, Internet of Things (IoT), Raspberry Pi, ESP32, Image Classification, Sensor-Based System, Reward Management System

I. INTRODUCTION

The rapid growth of municipal solid waste, particularly in urban areas, has led to significant environmental and manage-ment challenges. Improper segregation at the source results in contamination of recyclable materials, increased landfill usage, and serious health risks. Conventional waste management practices are largely manual, inefficient, and dependent on public awareness, leading to poor waste handling and reduced recycling efficiency[7], [11]. To address these issues, this project proposes a Reward-Based Smart Waste Segregation System that leverages Artificial Intelligence (AI) and the Internet of Things (IoT) for automated and intelligent waste classification. The system utilizes a Raspberry Pi as the primary processing unit and an ESP32 microcontroller for hardware control and communication. An ESP32-CAM module is used to capture images of waste, which are analyzed using a Convolutional Neural Network (CNN) for accurate classification. Additional hardware components include a load cell inte-grated with an HX711 amplifier for measuring waste weight, and an HC-SR04 ultrasonic sensor for monitoring bin levels. A NEMA 17 stepper motor with a driver module is employed for precise compartment alignment, while a servo motor enables automatic lid operation, ensuring a hygienic and contactless disposal process. By integrating advanced hardware with AI-based classification and an incentive-driven approach, the proposed sys-tem enhances waste segregation accuracy, reduces manual intervention, and promotes sustainable waste management practices.

II. RELATED WORKS

Our project combines advancements in AI, IoT, and smart waste management. It uses deep learning for waste classifica-tion and sensors for automation. A reward system encourages proper waste disposal, making the solution efficient and user-friendly.

A. Deep Learning-Based Waste Classification

Some studies use multiple deep learning models like AlexNet, VGG, and ResNet together to improve classification performance. By combining features from different models, the system can better identify complex patterns in waste images. This fusion approach improves robustness and reduces classification errors.

It also helps in handling variations in lighting, shape, and texture of waste materials. These systems achieve accuracy above 90%, but they require high computa-tional resources and longer training time.[5]

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B. Specialized CNN Models for Waste Segregation

Customized CNN models such as RWC-Net are specifically designed for waste classification tasks. These models combine efficient architectures like DenseNet and MobileNet to balance speed and accuracy[6]. Techniques like data augmentation, normalization, and transfer learning further improve model performance. These models are capable of classifying waste into multiple categories effectively. However, their perfor-mance depends heavily on the quality and diversity of the training dataset used[1], [2].

C. IoT-Based Waste Monitoring and Route Optimization

IoT-based systems use sensors to monitor bin levels continuously and send real-time data to a centralized server. This data is processed using optimization algorithms such as genetic algorithms to determine efficient waste collection routes. These systems help reduce fuel consumption, operational cost, and time. They also improve the efficiency of waste collection services. Additionally, real-time monitoring helps prevent overflow and maintains cleanliness in urban areas[3], [11].Several studies focus on the design and development of advanced automated waste segregation systems to improve operational efficiency [8].

D. Integrated AI and IoT Waste Management Systems

Research combines AI with IoT devices such as Raspberry Pi, camera modules, and sensors to build automated waste management systems. Earlier systems implemented simple automated waste segregation mechanisms using embedded systems and sensors [10].These systems can classify waste using CNN models while also monitoring bin status in real time. This integration reduces human intervention and improves accuracy. It also enables continuous monitoring and data collection for analysis. Such systems are widely used in smart city applications to enhance waste management efficiency[4], [13].

III. SYSTEM ARCHITECTURE

We designed the system using a modular and efficient architecture to ensure better performance and scalability. The workload is divided between a web-based application on the frontend and an AI-based processing system on the backend. The frontend allows users to interact with the system, view rewards, and monitor bin status. The backend, powered by a Raspberry Pi and a CNN model, handles waste classification and data processing.

A. Smart Bin Unit

The Smart Bin Unit acts as the primary interface between the user and the system. It consists of hardware components such as ESP32 microcontroller, ESP32-CAM module, ultra-sonic sensor, load cell, servo motor, and stepper motor.

When a user deposits waste into the bin, the system initiates data collection. The ESP32-CAM captures an image of the waste, while the load cell measures its weight and the ultrasonic sensor monitors the bin level.

B. Image Capture and AI Classification Module

The captured image is transmitted to the Raspberry Pi, which acts as the processing unit. A Convolutional Neural Network (CNN) model is used to classify the waste into categories such as plastic, metal, food waste, and miscellaneous.

$$\text{Waste Image} \rightarrow \text{CNN Model} \rightarrow \text{Waste Category} \qquad (1)$$

The classification result is used to control the segregation mechanism.

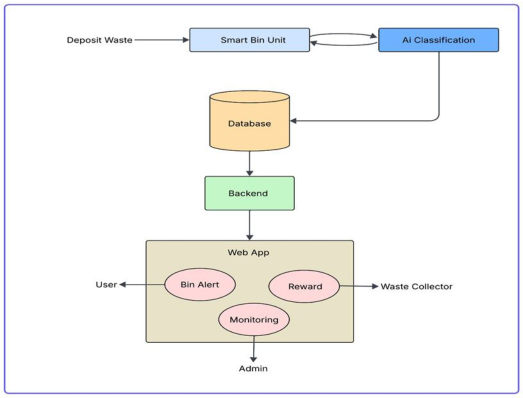

Fig. 1. System Architecture and Data Flow.

C. Segregation Mechanism

Based on the classification output, the system activates the motor control unit. A stepper motor aligns the correct compartment, and a servo motor controls the opening and closing of the bin lid. This automated mechanism ensures accurate waste segrega-tion without human intervention.

D. Sensor and Data Acquisition Module

The system integrates multiple sensors to collect real-time data required for efficient operation. A load cell combined with the HX711 module is used to measure the weight of the waste, which is essential for reward calculation. An ultrasonic sensor is employed to detect the fill level of the bin and prevent overflow conditions. The ESP32 controller processes the data obtained from these sensors and manages communication with other system components. These sensors continuously monitor system conditions and transmit the collected data to the processing unit for analysis and decision-making.

E. Backend and Database System

The backend system is developed using Node.js and Ex-press.js, which act as a communication layer between the hard-ware components and the web application. It is responsible for managing system operations and ensuring smooth data flow across different modules. Data such as waste type, weight, timestamp, and user information are stored in a database such as MongoDB. The backend performs several critical functions, including data processing, reward point calculation, user authentication, and API communication, thereby enabling seamless integration and efficient system performance.

F. Web Application Interface

The web application is developed using React.js along with HTML, CSS, and JavaScript to provide an interactive and user-friendly interface. It serves as a platform for users, administrators, and waste collectors to interact with the system efficiently. The application enables user authentication and QR-based bin access, allowing secure and controlled usage. It also displays reward points earned by users and maintains their activity records. Additionally, the system supports real-time monitoring of bin status and generates alert notifications for administrators, ensuring timely waste collection and effective system management.

G. Reward Management System

The system includes a reward mechanism that encourages proper waste disposal. Reward points are calculated based on waste type and weight[9], [12].

$$\text{Reward Points} = f(\text{Waste Type, Weight}) \quad (2)$$

Users can redeem accumulated points for rewards or coupons.

H. System Workflow

The overall workflow of the system begins when the user scans a QR code to access the smart bin and deposits the waste. Once the waste is placed inside, an image is captured using the camera module. This image is then processed by the CNN model to classify the type of waste. Simultaneously, sensors measure the weight of the waste and monitor the bin fill level. Based on the classification result, the system automatically activates the segregation mechanism to direct the waste into the appropriate compartment. All relevant data, including waste type, weight, and timestamp, are stored in the database. Subsequently, reward points are calculated and assigned to the user for proper waste disposal. The system also updates the bin status, allowing the administrator to monitor it and receive alerts when necessary.

IV. IMPLEMENTATION DETAILS

A. Frontend Architecture (Web Mobile Interface)

The user interface of the system is designed to provide a simple, responsive, and engaging experience for users, administrators, and waste collectors. The frontend is developed using modern web technologies to ensure smooth interaction and real-time updates.

1) Dynamic UI/UX: The application follows a modern card-based layout with a dark theme to enhance visual appeal and usability. As shown in the reward dashboard Fig. 2 users are welcomed with a personalized interface dis-playing their profile and accumulated reward points. The system highlights reward points prominently to motivate user participation.
2) User Interaction Handling: The system employs a QR-based authentication mechanism using a QR code scan-ning module integrated within the web/mobile interface to enable secure user access to the smart bin. User actions, including QR scanning

and waste disposal events, are captured and processed in real time through REST API requests. The processed data is used to update activity logs and reward points in the database, ensuring accurate tracking and efficient reward accumulation.

3) Data Visualization: The interface presents key infor-mation such as disposal history, reward trends, and bin status using graphical components and structured layouts. Visualization is implemented using the Chart.js library, enabling clear and interactive representation of system data. These visual components assist users and adminis-trators in effectively analyzing system performance and usage patterns in real time.
4) Connectivity: The frontend communicates with the back-end server through REST API calls, enabling real-time synchronization of user data, reward updates, and system notifications. The system supports both local server de-ployment and cloud-based hosting, providing flexibility in testing and large-scale implementation.

B. Backend Modules and Processing

The backend system manages data processing, hardware interaction, and communication between different components using embedded controllers and AI-based modules.

1) Sensor Integration: The system integrates multiple hard-ware components including the ESP32-CAM module for image acquisition, a Load Cell interfaced with the HX711 amplifier for weight measurement, and an Ultrasonic Sensor (HC-SR04) for bin level detection. These sensors continuously provide real-time data to the processing unit to ensure accurate monitoring and input acquisition.
2) Waste Classification: A Convolutional Neural Network (CNN) model deployed on the Raspberry Pi is used to classify waste into categories such as plastic, metal, and organic materials. The classification is performed in real time using captured images, enabling automated decision-making [5].
3) Segregation Control: Based on the classification output, the system controls Servo Motors through the microcon-troller to direct waste into the appropriate compartment. This automated mechanism ensures accurate segregation without human intervention.
4) Reward Processing: The system computes reward points based on the waste category and measured weight. The calculated values are processed through backend logic and updated in real time within the database, enabling users to track rewards instantly via the interface.
5) Data Management: All system data, including user details, disposal records, and reward points, are stored in a centralized database using backend services. Data communication between modules is handled through REST API endpoints, ensuring efficient data retrieval, synchronization, and system monitoring [13].

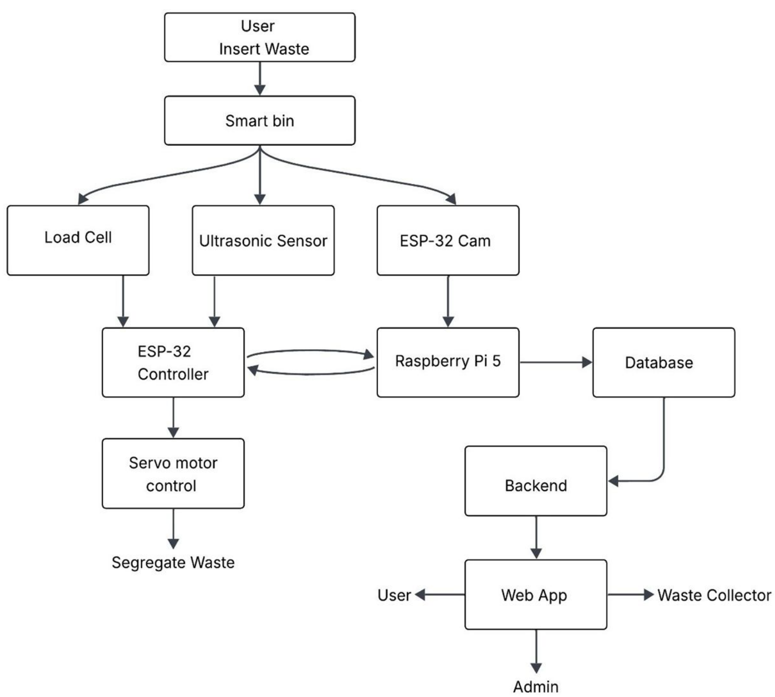

Fig. 2. Block Diagram

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V. HARDWARE COMPONENTS

A. Raspberry PI 5

The Raspberry Pi 5 is a powerful Linux-based system used for multitasking, AI, and data processing. In a smart bin, it processes images from the ESP32-CAM, classifies waste, and sends data to the database.

Fig. 3. Raspberry Pi 5

B. ESP32 Microcontroller

The ESP32 Microcontroller is a powerful Wi-Fi and Bluetooth-enabled development board used in IoT sys-tems.It controls sensors and motors, collects data, and communicates with the Raspberry Pi 5.

Fig. 4. ESP32

C. Nema 17 Stepper Motor

The NEMA 17 stepper motor is a precise motor that moves in fixed steps for accurate positioning.It rotates to direct waste into the correct compartment based on classification.

Fig. 5. NEMA 17 Stepper Motor

D. 180° Servo Motor(SG90/MG995)

The 180° servo motor is a motor that provides precise an-gular movement using PWM signals.It opens and closes the bin lid automatically after user authentication.

Fig. 6. 180° Servo Motor

E. ESP32-CAM Module

The ESP32-CAM captures im-ages and sends them wirelessly. It takes waste images and sends them to the Raspberry Pi 5 for classification.

Fig. 7. ESP32 CAM Module

F. HC-SR04 Ultrasonic Sensor

The HC-SR04 ultrasonic sensor measures distance using sound waves.It detects the bin fill level and triggers alerts when the bin is full.

Fig. 8. Ultrasonic Sensor

G. 5 KG Load Cell

The 5kg load cell measures weight by converting force into an electrical signal.It calculates waste weight to assign user rewards.

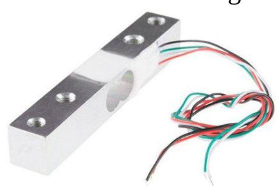

Fig. 9. Loadcell

VI. DATASET INFORMATION

Class Label	Waste Categories			
	Food	Plastic	Metal	Miscellaneous
No. of Images	997	1984	1020	2627
Total Images				**6628**

The dataset used in this study is based on the publicly available *Garbage Dataset* obtained from Kaggle, which was further enhanced by incorporating additional images collected by the authors. The final dataset consists of 6628 images categorized into four classes: food, plastic, metal, and miscellaneous waste. This combination of publicly available and self-collected data helps improve the diversity and robustness of the dataset, enabling the model to generalize better under real-world conditions. The distribution of images across different categories is presented in Table.

VII. EXPERIMENTAL SETUP & EVALUATION

To evaluate the effectiveness of the proposed Reward Based Smart Waste Segregation System, a series of experiments were conducted focusing on classification performance, system re-sponse time, and overall operational efficiency. The evaluation was performed using real-time waste samples under controlled conditions.

A. Experimental Setup

The system prototype was developed by integrating both hardware and software components. The hardware setup in-cludes an ESP32 microcontroller, ESP32-CAM module for image capture, ultrasonic sensor for bin level detection, load cell with HX711 module for weight measurement, and servo and stepper motors for automated segregation. A Raspberry Pi was used as the processing unit to execute the Convolutional Neural Network (CNN) model for waste classification.

The CNN model was trained and tested using a dataset con-sisting of multiple waste categories such as food, metal,plastic, and miscellaneous. The backend system was implemented using Node.js and Express.js, while MongoDB/Firebase was used for data storage. A web-based interface developed using React.js was used for monitoring system performance and user interaction.

B. Classification Performance

The performance of the CNN model was evaluated using standard metrics such as precision, recall, and F1-score. The model achieved an overall accuracy of 95.37%, demonstrating its effectiveness in correctly classifying different types of waste.

TABLE I
CLASSIFICATION PERFORMANCE METRICS

Class	Precision	Recall	F1-Score	Support
Food	0.8696	0.9091	0.8889	22
Metal	0.9342	0.9467	0.9404	75
Miscellaneous	0.9825	0.9655	0.9739	116
Plastic	0.9550	0.9550	0.9550	111
Overall Accuracy	0.9537 (95.37%)			

It can be observed that the model performs exceptionally well in classifying paper and plastic waste, achieving high precision and recall values. The classification performance for metal waste is also satisfactory, while slightly lower accuracy is observed in food waste classification due to visual similarities with other categories.

C. Confusion Matrix Analysis

The confusion matrix was used to further analyze the classification results.

TABLE II
CONFUSION MATRIX OF WASTE CLASSIFICATION

Actual / Predicted	Food	Metal	Miscellaneous	Plastic
Food	20	0	1	1
Metal	0	71	0	4
Miscellaneous	2	2	112	0
Plastic	1	3	1	106

The dataset consists of 6628 images categorized into four classes. Out of these, 324 images were used for validation to evaluate model performance. Most values are concentrated along the diagonal, indicating correct classification. A small number of misclassifications occur between visually similar waste categories such as food and Miscellaneous, and plastic and metal.

D. System Response Time

The total response time of the system was measured from the moment waste is inserted into the bin until it is successfully segregated.

TABLE III
SYSTEM RESPONSE TIME ANALYSIS

Process Stage	Time (seconds)
Image Capture	1.2
CNN Classification	2.0
Segregation Mechanism	1.5
Data Storage & Reward Update	0.8
Total Time	5.5 seconds

The results show that the system operates within an average time of 5 to 6 seconds, making it suitable for real-time applications.

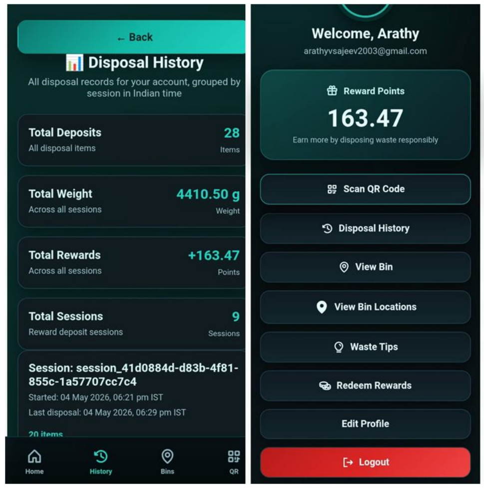

Fig. 10. Disposal History and User Dashboard

Fig. 11. Waste Bin

VIII. CONCLUSION AND FUTURE WORK

The proposed Reward-Based Smart Waste Segregation Sys-tem provides an effective and intelligent solution for modern waste management by integrating automated waste classification with a user incentive mechanism. The system utilizes a Convolutional Neural Network (CNN) model to improve segregation accuracy while reducing manual intervention. In addition, the real-time reward update mechanism encourages active user participation and promotes responsible waste dis-posal behavior. The modular architecture ensures reliable performance, efficient data processing, and seamless interaction between hardware and software components. Overall, the system enhances waste segregation efficiency, improves user engagement, and supports sustainable environmental practices, making it suitable for deployment in smart environments.

Future work will focus on improving the system's accuracy, scalability, and overall performance. The classification model can be enhanced using larger and more diverse datasets to handle real-world variations more effectively. The system can be extended to support multiple waste inputs simultaneously and include additional waste categories. Further optimization of processing speed and hardware efficiency can reduce response time. The reward mechanism can also be expanded with advanced features such as digital redemption, gamification, and user ranking systems to increase user participation. Emerging technologies such as blockchain and smart system optimization can further enhance waste management efficiency and scalability [15]. Additionally, integration with mobile applications and smart city infrastructure will improve accessibility, scalability, and real-time monitoring capabilities.

IX. ACKNOWLEDGMENT

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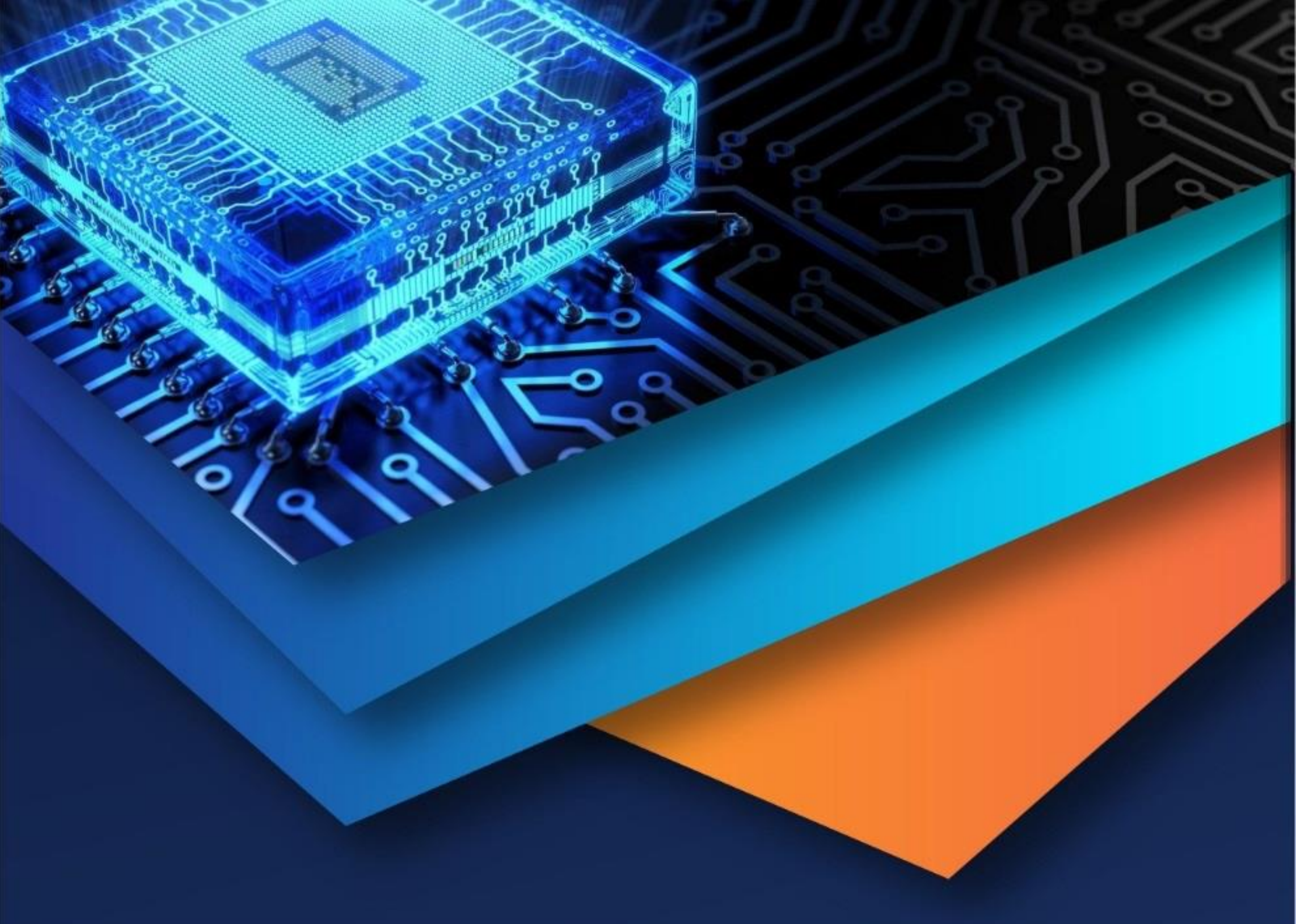

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