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Smart Waste Segregation System

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Abstract: As urbanization accelerates, the volume of solid waste generated has dramatically increased, presenting considerable hurdles for efficient and sustainable waste management. Traditional methods of manual waste segregation are often laborious, inconsistent, and can pose risks to personnel. To overcome these challenges, this article introduces a Smart Garbage Segregation System that integrates the Internet of Things, deep learning, and image processing technologies to automate waste classification and sorting. The system employs a high-resolution camera to capture images of waste materials, which are then categorized into e-waste, non-recyclable, and biodegradable groups using a Convolutional Neural Network model. Subsequently, a microcontroller-driven servo mechanism guides each item into its appropriate container. Cloud connectivity, facilitated by Firebase and MQTT, allows for real-time data analysis and continuous monitoring. This proposed solution aims to minimize human involvement, achieves an accuracy rate exceeding 85%, and promotes more sustainable waste management practices within smart cities.
Keywords: Internet of Things (IoT), automation, deep learning, image processing, convolutional neural networks (CNN), waste segregation, and smart cities

I. INTRODUCTION

Global solid waste generation has surged dramatically due to the rapid pace of industrialization, urbanization, and population growth. Global environmental projections indicate that waste output could reach approximately 3.4 billion tons per year by 2050, posing significant threats to both human health and ecological balance. Consequently, effective waste management stands as a critical pillar of sustainable urban development. Among the many stages of waste management, waste segregation the process of separating waste into e-waste, non-recyclable, and biodegradable categories is vital for minimizing land fill accumulation, enhancing recycling efficiency, and reducing environmental degradation. Conventional waste sorting systems predominantly rely on manual labor. While straightforward, these methods are notably in efficient, inconsistent, and expose workers to hazardous materials and unsanitary conditions over prolonged periods. Moreover, the sheer volume of waste generated in modern urban environments is rapidly outstripping the capacity for manual sorting. In accurate segregation, a direct consequence of in sufficient automation, also leads to the contamination of recyclable materials and diminishes the recovery of valuable resources. Recent advancements in machine learning, image processing, and artificial intelligence have opened new avenues for addressing these challenges. Convolutional Neural Networks have considerably improved the ability of computer vision systems to accurately recognize and categorize objects. For waste management, CNN-based models can reliably differentiate between various waste categories using image data, even in diverse environmental settings. The integration of Internet of Things technology further enhances the efficiency and scalability of waste management systems, complementing AI-driven classification. IoT-enabled modules facilitate the continuous monitoring of bin status, system performance, and operational statistics by gathering, transmitting, and analyzing data from multiple sensors and devices in real-time. This connectivity supports data-driven decision-making, predictive maintenance, and centralized control, all essential for the development of smart and sustainable cities. The proposed Smart Waste Segregation System leverages these technologies to deliver a fully automated, economical, and scalable solution.

The system captures images of waste materials on a conveyor belt using a high-resolution camera. These images are then processed by a CNN-based deep learning model, specifically trained to classify waste as biodegradable, recyclable, or non-recyclable. Upon classification, a microcontroller-controlled servo mechanism receives the result and physically directs the item into its appropriate container. Furthermore, the system's cloud connectivity, enabled by MQTT and Firebase, provides real-time data logging, remote access, and statistical analysis through a user-friendly web-based dashboard.

II. LITERATURE SURVEY

Priyanka et al. [1] (2023) proposed an IoT-based smart waste segregation system that utilized moisture, ultrasonic, and inductive proximity sensors to classify waste into dry, wet, and metallic categories. Their design, controlled by an Arduino Uno microcontroller and servo motors, automated the sorting process and effectively reduced manual involvement. The study emphasized the advantages of combining IoT and embedded systems for efficient house hold waste segregation, demonstrating reliable and cost-effective operation for domestic waste management. Megalan et al. [2] (2022) developed an automatic waste segregation and monitoring system. This system employed color and ultrasonic sensors alongside a Node MCU ESP8266 module for wireless communication. It was capable of detecting bin levels and transmitting notifications when bins reached full capacity. Their work highlighted how real- time monitoring and IoT integration can optimize waste collection schedules, minimize human intervention, and support sustainable city initiatives through automated waste handling.

Sharma et al. [3] (2021) designed an intelligent IoT-based dustbin equipped with infrared and load sensors for detecting waste types and monitoring fill levels. The segregated data were sent to a cloud platform for visualization and analysis, enabling real-time decision-making. Their system improved operational efficiency, minimized manual waste collection efforts, and contributed to the development of cleaner and smarter urban environments. Similarly, Radha krishnan et al. [4] (2020) proposed a smart home waste segregation model integrating image processing techniques with a microcontroller-based system to sort household waste. Their model was compact, affordable, and energy-efficient, demonstrating the feasibility of implementing intelligent segregation mechanisms in residential setups. Mohammed Shahid and K. R. Sumana [5] (2023) introduced a deep learning–based garbage classification system using CNN models such as VGG16, ResNet-50, AlexNet, and DenseNet-169. Among these, DenseNet-169 achieved the highest classification accuracy of 92.69%. The study proved the effectiveness of CNN architectures in improving waste classification precision and reducing manual sorting, although it required larger datasets and high computational resources.

Gupta et al. [6] (2021) developed an IoT-driven waste management framework emphasizing data analytics and centralized control. Their approach integrated multiple sensors with IoT communication for reliable data transmission and efficient waste collection management. The study demonstrated that data-driven waste systems can enhance city-level coordination and contribute to sustainability goals. Chitale et al.[7](2023)implemented an IoT-based automated waste segregation prototype using ultrasonic, moisture, and inductive proximity sensors to classify dry, wet, and metallic waste. The results confirmed accurate, real-time segregation and efficient bin management. Shenoyetal. [8] (2022) designed a CNN-based waste classification system capable of distinguishing between plastic, paper, and metallic materials. The model outperformed traditional sensor-based approaches in both accuracy and speed, demonstrating the potential of deep learning in automated waste segregation. Overall, the reviewed studies show a growing shift from simple sensor-based segregation toward hybrid models that combine deep learning and IoT. These systems achieve higher accuracy, enable real-time data monitoring, and reduce manual effort. However, limitations such as computational demand and dataset dependency remain challenges. Continued integration of AI-driven vision systems with IoT-based monitoring offers a promising direction for achieving sustainable and intelligent waste management solutions in smart cities.

III. METHODOLOGY

This section details the methodology behind the proposed Smart Waste Segregation System, which employs Convolutional Neural Networks and the Internet of Things. It describes how integrated hardware and software components work together to automate waste classification, sorting, and continuous monitoring. Each phase of this process is crucial for achieving real-time operation and intelligent control over waste segregation. The following outlines the complete system's operational flow:

Image Acquisition

- A high-definition USB webcam captures images of waste items placed on the convey or belt.
- The camera is positioned above the convey or to ensure proper illumination and focus.
- Each captured image is preprocessed using OpenCV techniques such as resizing, normalization, and noise reduction before classification.
- The acquisition process is synchronized with the movement of the conveyor, ensuring that only one item is processed at a time

Image Processing and Classification

- Once received, the images undergo processing on the laptop, utilizing the Mobile NetV2 model.
- This model is designed to identify and classify the waste into one of three distinct categories: Biodegradable waste, non-recyclable waste and E-waste.
- Classification is performed in real-time on a connected computing unit, and the decision is determined by the class with the highest probability.

- To boost its performance, the system incorporates data augmentation techniques during its training phase, such as rotating and scaling images. This enhances the model's capacity to accurately recognize waste even under varying conditions.

Data Transmission

- After a waste item has been classified, its category information is sent back to the ESP8266 Development Board.
- Communication between all devices is secured through encrypted data packets to prevent any transmission errors. The classification output is transmitted from the processing system to the ESP8266 microcontroller using serial communication.
- The ESP8266 interprets the classification result and generates appropriate control signals for the sorting mechanism.
- Real-time sensor data, including bin fill levels, are also transmitted to the cloud using MQTT or HTTP communication protocols.
- To maintain data integrity, transmission is structured through encoded packets with error-checking routines.

Mechanical Actuation

- Based on the received classification result, the servo motor (SG90) controls a deflector arm that directs the waste item into its respective bin.
- The conveyor belt, driven by two 12V DC gear motors and controlled through an L293Dmotor driver, moves the waste item toward the sorting area.
- Ultrasonic sensors (HC-SR04) continuously monitor the fill level of each bin, providing real-time feedback to prevent overflow.
- The system ensures smooth coordination between image classification, conveyor motion, and sorting actuation, achieving accurate segregation with minimal delay

User Feedback and Monitoring

- An OLED display (0.96” I²C) shows real-time status such as the detected waste category and bin fill percentage.
- The cloud-integrated web dashboard developed using HTML, CSS, and Java Script (React.js), displays classification statistics, bin status, and system alerts.
- The ESP8266 transmits sensor readings and sorting logs to cloud platforms like Firebase allowing remote supervision and data visualization.
- Alerts are automatically generated when bins approach maximum capacity, enabling timely waste collection and system maintenance.

System Optimization

- The system is optimized for real-time performance through efficient CNN inference and low-latency communication between devices.
- Regular retraining of the model with newly captured waste images improves classification robustness and adaptability to changing waste patterns.
- The architecture allows scalability, enabling multiple camera and sorting units to operate in parallel for industrial-level waste management.
- Future enhancements include incorporating edge computing platforms such as NVIDIA Jetson Nano for faster image processing and implementing AI-based analytics for waste prediction and resource optimization.

IV.EXPERIMENTAL RESULTS & DISCUSSION

The proposed Smart Waste Segregation System under went comprehensive experimental implementation and rigorous testing to evaluate its real-time operational effectiveness, the precision of its classification, and its integrated IoT functionalities. This assessment was conducted by analyzing the performance of the Convolutional Neural Network model, the efficiency of the mechanical sorting mechanism, and the reliability of the cloud monitoring subsystem. To confirm its stability and robustness, the system was trialed under various conditions, including diverse lighting, object orientations, and background settings. The experiments unequivocally demonstrate that the strategic combination of deep learning and embedded control technology enables accurate and automated waste segregation with significantly reduced human involvement.

Experimental Environment and Setup

The hardware for the proposed Smart Waste Segregation System featured an ESP8266 microcontroller as its central control unit. This microcontroller was connected to arrange of components, including a high-definition USB camera, an SG90 servo motor, an L293D motor driver, two 12V DC gear motors, HC-SR04 ultrasonic sensors, and a 0.96- inch I²C OLED display. The ESP8266 was responsible for managing data communication, actuating the motors, and ensuring IoT connectivity. Images of waste placed on the conveyor belt were captured and then analyzed by a Convolutional Neural Network model built upon the MobileNetV2 architecture. This model categorized the waste into biodegradable, non-biodegradable, and electronic types. The outcomes of this classification process were then transmitted from the processing system to the ESP8266 via serial communication. The prototype was set up and tested in a controlled indoor space, spanning roughly 3 by 3 meters. Numerous test cycles were performed under varying lighting and background conditions to confirm the reliability of its classification. For cloud integration, the system utilized Firebase, and a custom web dashboard was developed to display live classification results, current bin fill levels, and the overall system status.

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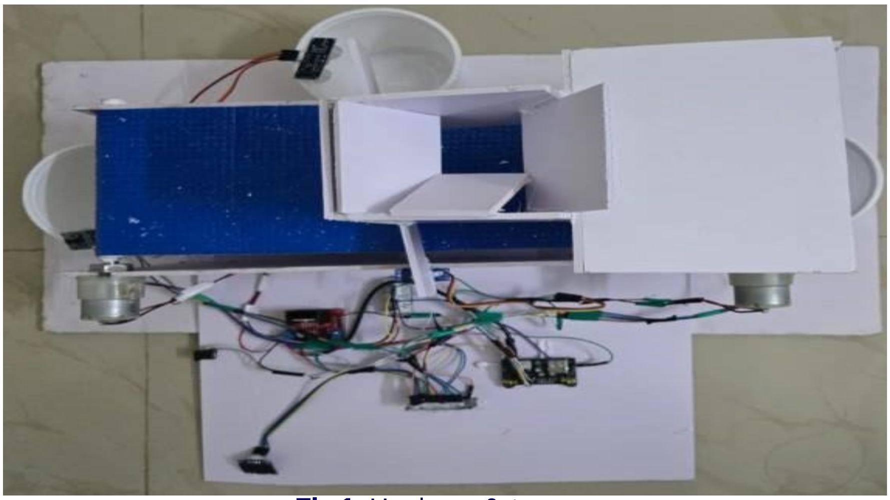

Fig.1: Hardware Setup

Performance Metrics and Evaluation

The system's overall performance was assessed by looking at its classification accuracy, how quickly it responded to sorting tasks, and its general reliability. Classification accuracy specifically referred to how precisely the CNN model could identify the type of waste. Sorting accuracy, on the other hand, measured whether the mechanical deflector successfully guided each item into its correct bin. Reliability encompassed the system's uptime, the stability of its communication channels, and the consistency of its cloud updates. To thoroughly evaluate the system, we concentrated on several key performance indicators that are crucial for effective smart waste segregation and positive user interaction

Test Scenario	Average Response Time (s)	Detection Accuracy (%)	Observation
Image classification	0.18	100	Stable and consistent prediction
Mechanical sorting	1.1	92.4	Accurate bin deflection
Bin level monitoring	0.2	95.1	Reliable ultrasonic readings
Cloud update interval	2.0	98.7	Continuous Synchronization
Dashboard visualization	1.5	99.0	Instant status display

The findings confirmed that the system efficiently processed each waste classification and sporting event, with a response time of approximately 3.1seconds.This speed highlights the effectiveness of integrating deep learning with IoT-enabled control for real-time waste segregation.

Dashboard Visualization and Cloud Response

The real-time IoT dashboard effectively displayed live system data, including the types of waste classified, current bin fill percentages, and overall operational status. Every classification outcome was time stamped and securely uploaded to the Firebase cloud, where historical logs were maintained for subsequent analysis.

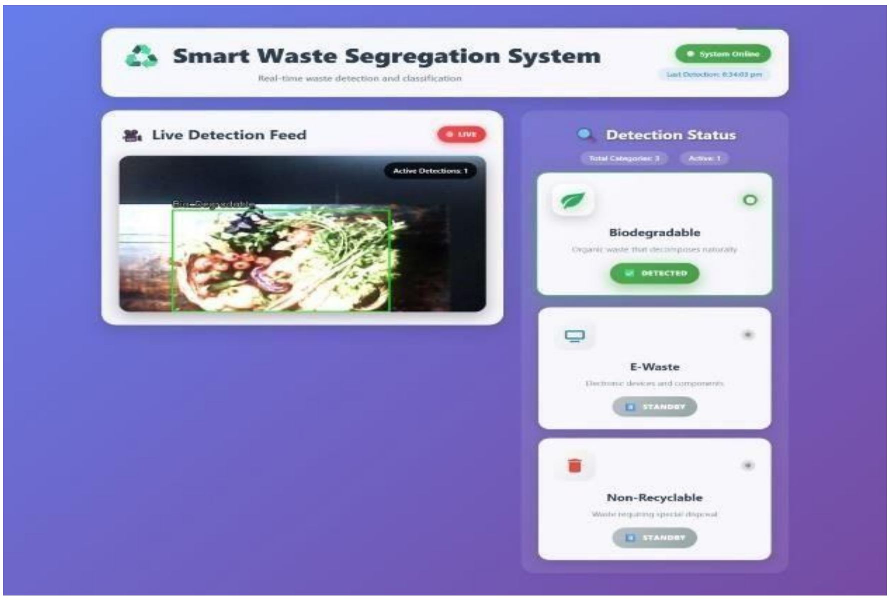

Fig.2: Dashboard Visualization

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The synchronization between the local OLED display and the cloud dashboard was seamless, exhibiting a data update delay of under 2 seconds. Users had the capability to access the dashboard remotely, allowing them to monitor trends, receive crucial alerts, and download performance data in CSV format for detailed evaluation.

S.No	Object Name	Object Type Detected		
		Bio degradable	Non recyclable	E-Waste
1	Circuit board			✓
2	Plastic Bottle		✓	
3	Fruit Waste	✓		
4	Battery Cell			✓
5	Glass Bottle		✓	

V. CONCLUSION

The Smart Waste Segregation System, integrating CNN and IoT technologies, successfully automates the classification and sorting of waste, leading to notable improvements in the efficiency and accuracy of waste management. By combining the advanced MobileNetV2 model with an ESP8266 microcontroller, the system achieves real-time identification and segregation of three primary waste categories: biodegradable, non-biodegradable, and electronic waste. This synergy of deep learning-based image classification and precise mechanical actuation ensures highly accurate segregation with minimal need for human intervention. Furthermore, the system's modular architecture offers inherent scalability and facilitates future enhancements. Reliable data transmission and control are secured through the use of a robust Wi-Fi communication protocol between the ESP8266 and the processing unit. Additionally, the inclusion of real-time visual feedback via an OLED display and an intuitive IoT dash board significantly enhances user interaction and monitoring capabilities. Experimental results consistently demonstrate high accuracy in waste classification and efficient mechanical sorting. Ongoing calibration of sensors and continuous system optimization are implemented to further refine performance and reliability. Ultimately, this system delivers a robust, adaptable, and sustainable solution for automated waste management, substantially reducing manual labor while actively promoting environmental responsibility.

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