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DEEP LEARNING BASED MULTI-CLASS WASTE SEGREGATION SYSTEM USING CONVEYOR BELT AND SERVO MECHANISMS

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Abstract: Rapid urbanization and population growth have intensified the global solid waste management challenge. Manual segregation is labor-intensive, error-prone, and hazardous. This paper presents an automated multi-class waste segregation system that integrates deep learning-based object detection with embedded hardware automation. The system employs a Raspberry Pi 4 as the central controller, a YOLOv6-based classification model, infrared proximity sensors, servo-motor-driven diverter arms, and a DC motor-driven conveyor belt. Waste items placed on the conveyor are detected by a proximity sensor, halting the belt for image capture. The captured image is classified into one of four categories—plastic, paper, glass, or biodegradable—and the appropriate servo mechanism routes the waste to the correct collection bin. Experimental results demonstrate reliable real-time detection and sorting with minimal human intervention, offering a scalable solution for smart waste management applications.

Index Terms — Waste Segregation, YOLOv6, Raspberry Pi, Object Detection, Conveyor Belt, Servo Motor, Deep Learning, Embedded Systems.

I. INTRODUCTION

In recent years, rapid urbanization, industrial growth, and population increase have led to a significant rise in the generation of solid waste. Managing this waste efficiently has become one of the major challenges faced by modern society. Improper waste disposal not only leads to environmental pollution but also poses serious health hazards to humans and animals. One of the most critical steps in waste management is waste segregation, which involves separating waste into distinct categories such as plastic, paper, glass, and biodegradable. Proper segregation ensures effective recycling, reduces landfill burden, and promotes sustainable environmental practices.

Traditionally, waste segregation is carried out manually by workers. However, manual segregation is time-consuming, labor-intensive, and prone to human error. It also exposes workers to harmful and hazardous materials. With advancements in Artificial Intelligence (AI), Machine Learning (ML), and Embedded Systems, it has become possible to design smart systems capable of identifying and classifying objects in real time. One such powerful technique is YOLO (You Only Look Once), a deep learning-based object detection algorithm that can detect and classify multiple objects quickly and accurately.

This paper presents an automated waste segregation system using Raspberry Pi, computer vision, proximity sensors, and servo motor-based mechanisms. A conveyor belt mechanism transports waste items for continuous and efficient processing. The system detects, classifies, and physically diverts waste into appropriate bins without manual intervention. The integration of YOLOv6, embedded sensing, and mechanical actuation demonstrates a practical, scalable solution for smart urban waste management.

II. LITERATURE SURVEY

Several studies have addressed automated waste classification using deep learning and robotics. Narayanswamy, Rajak & Hasan compared YOLO, CNN, and Faster-RCNN for waste classification, finding that YOLO is best suited for real-time embedded deployment due to its speed and low computational cost, while Faster-RCNN achieves higher accuracy at the expense of significantly greater processing requirements.

Zhou et al. (2021) developed a dual-arm robotic waste sorting system using an improved YOLOv4 model combined with GhostNet for lightweight feature extraction, demonstrating high-speed and accurate pick-and-place operations on a custom four-class dataset. Padalkar, Pathak & Sthynes (2021) benchmarked Scaled-YOLOv4-CSP and EfficientDet, with the former achieving up to 97% accuracy, highlighting its suitability for industrial-scale smart waste management.

Sai Sushanth, Jenila & Agnel Livingston (2021) applied CNNs to web-scraped data and identified significant misclassification of glass waste, emphasizing the need for high-quality training datasets. Sheth et al. (2010) demonstrated a color-based robotic arm for waste sorting, showing high speed and repeatability in controlled environments. Thanawala, Sarin & Verma (2020) integrated Google Speech API, YOLOv3, and ROS MoveIt for a voice-controlled medical waste segregation robot, showcasing multi-modal automation. Chinnathurai et al. (2019) developed RecycleBot, a GUI-driven MATLAB-based robotic platform for waste classification and control.

The literature collectively confirms that YOLO-family models offer the best trade-off between accuracy and real-time performance for embedded waste classification systems. However, most prior works rely on robotic arms for physical sorting; the present work proposes a simpler, cost-effective conveyor-and-servo mechanism that is easier to scale and maintain.

III. SYSTEM ARCHITECTURE

The proposed system is built around a Raspberry Pi 4 that serves as the central processing and control unit. It interfaces with all peripheral components, executes the embedded control logic, and runs the YOLOv6-based object detection model. Based on sensor inputs and classification results, the Raspberry Pi coordinates the operation of the conveyor belt motor and the servo-driven segregation mechanisms.

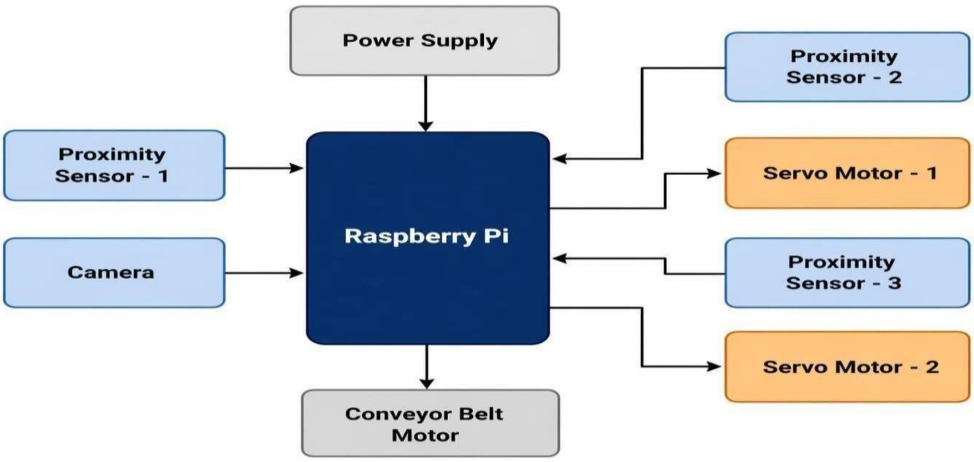

Fig. 1: Block Diagram of the Automated Waste Segregation System

A. Sensing and Detection Mechanism

Three infrared proximity sensors are strategically positioned along the conveyor belt to facilitate sequential detection and control:

1. Object Detection Sensor (Entry Point): The first proximity sensor detects the presence of incoming waste material on the conveyor belt. Upon detection, it signals the Raspberry Pi to halt the conveyor belt, ensuring the object remains stationary for accurate image capture and classification.
2. Segregation Point Sensor – Stage 1 (Proximity Sensor 2): Located at the first segregation point, this sensor confirms the arrival of the object and triggers precise actuation of Servo Motor 1.
3. Segregation Point Sensor – Stage 2 (Proximity Sensor 3): Located at the second segregation point, this sensor triggers Servo Motor 2 for handling the remaining waste categories.

B. Image Acquisition and Classification

Once the object is detected at the first sensor and the conveyor belt is stopped, an overhead 50MP camera captures a clear image of the waste item. This image is processed by the YOLOv6-based object detection model running on the Raspberry Pi. The model classifies the waste into one of four predefined categories: Plastic, Paper, Glass, or Biodegradable. This classification result determines the subsequent actuation strategy for segregation.

C. Actuation and Segregation Mechanism

Two servo motor-driven diverter arms are positioned at two segregation points along the conveyor:

- Servo Motor 1 (First Segregation Stage): Responsible for directing Waste Type 1 (Plastic) or Waste Type 2 (Paper) into the corresponding bins (Bin 1 or Bin 2) by rotating left or right.
- Servo Motor 2 (Second Segregation Stage): Handles Waste Type 3 (Glass) or Waste Type 4 (Biodegradable), enabling segregation into Bin 3 or Bin 4.

After classification, the conveyor belt resumes motion, the object travels to the designated segregation point, the corresponding proximity sensor triggers a belt stop, and the servo motor physically diverts the object into the appropriate bin.

IV. SYSTEM FLOWCHART AND WORKING PROCESS

The flowchart in Fig. 2 illustrates the complete operational sequence. The system starts by initializing all components and activating the conveyor belt. Proximity Sensor 1 continuously monitors the entry point. Upon object detection, the conveyor halts and the camera captures the waste image. The YOLO model classifies the waste, after which the appropriate servo (Servo Motor 1 for Types 1/2, Servo Motor 2 for Types 3/4) is pre-positioned. The belt resumes and the object travels to the corresponding segregation point, where the respective proximity sensor triggers the belt stop and servo actuation to push the waste into the correct bin. The conveyor then resumes for the next item, creating a continuous processing loop.

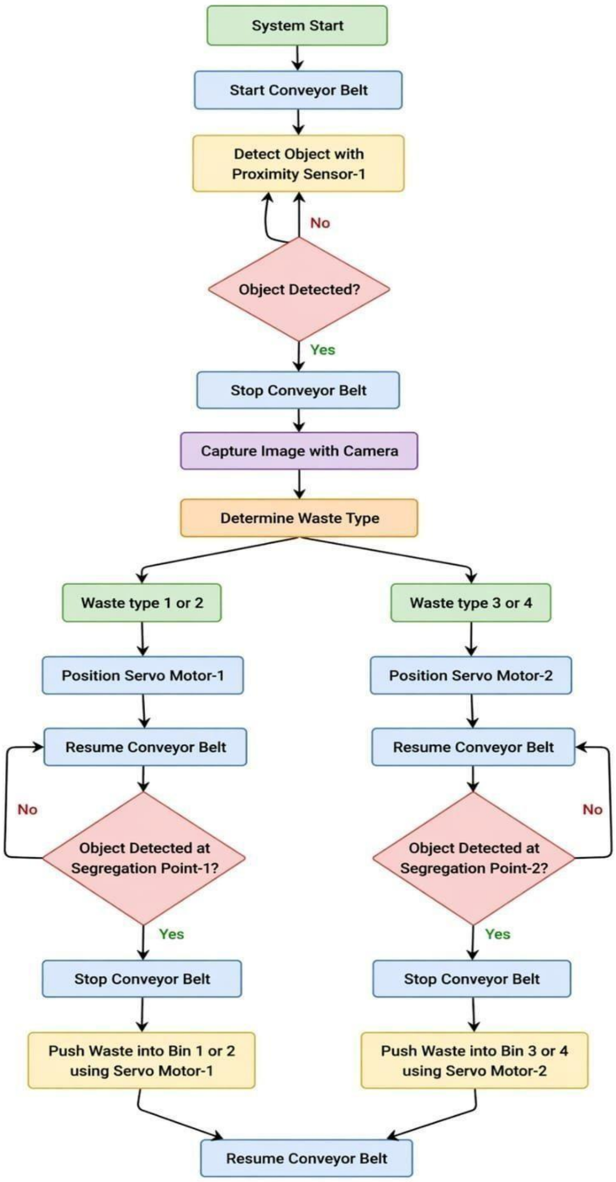

Fig. 2: Flowchart of the Multi-Class Waste Segregation System

V. HARDWARE COMPONENTS

The system integrates the following key components, selected for reliability, availability, and compatibility with the Raspberry Pi ecosystem:

Table I: Bill of Materials

Component	Specification	Qty	Role	Interface
Raspberry Pi 4	4GB RAM, 1.8GHz	1	Central Controller	GPIO/USB
Proximity Sensor	IR-based, 5V	3	Object Detection	GPIO Digital
Servo Motor	MG996R, 180°	2	Waste Diversion	PWM Signal
DC Motor	12V, 60 RPM	1	Conveyor Drive	Motor Driver
Camera Module	50MP, USB	1	Image Capture	USB/CSI
Buck Converter	LM2596, 12V→5V	1	Power Regulation	Power Line
Conveyor Belt	60cm length	1	Waste Transport	Mechanical

A. Raspberry Pi 4

The Raspberry Pi 4 (4GB RAM, Broadcom BCM2711 quad-core Cortex-A72 at 1.8GHz) serves as the primary computing platform. It runs Raspberry Pi OS with Python, OpenCV, and the YOLOv6 inference runtime. Its GPIO pins interface directly with proximity sensors and servo motors via PWM, while USB hosts the camera and motor driver board.

B. Proximity Sensors (IR)

Three infrared proximity sensors provide non-contact object detection. Each sensor emits IR radiation; when an object reflects the IR beam back to the detector, the digital output pin transitions to indicate object presence. The sensors are powered at 5V and connected to Raspberry Pi GPIO input pins.

C. Servo Motors (MG996R)

The MG996R 180° servo motors provide precise angular control for the diverter arms. They receive PWM signals from the Raspberry Pi, rotating to pre-programmed angles (typically ±45° from center) to push waste into the left or right collection bin. Their metal gear construction ensures durability under repeated actuation.

D. DC Motor and Conveyor Belt

A 12V DC motor drives the conveyor belt, controlled via a motor driver circuit interfaced with the Raspberry Pi. The conveyor belt (approximately 60cm in length) provides a stable platform for transporting waste items sequentially through detection and segregation zones.

E. 50MP Camera Module

A high-resolution 50MP USB camera is mounted overhead at the detection zone. The high pixel density ensures detailed image capture, which directly improves the classification accuracy of the YOLO model by providing clear texture and shape features for each waste item.

F. Buck Converter (LM2596)

The LM2596 step-down DC-DC converter regulates the 12V supply from the external adapter down to a stable 5V output for the Raspberry Pi, sensors, and camera. This single regulated supply simplifies the power architecture and protects sensitive components from voltage fluctuations.

VI. IMPLEMENTATION AND HARDWARE PROTOTYPE

The physical prototype was constructed on a rigid black-anodized aluminum frame approximately 70cm in length. The conveyor belt runs along the center of the frame, driven by the DC motor at one end. Two servo motor-arm assemblies are mounted at two points along the frame length, each with a triangular diverter plate to redirect waste into the bins below.

The Raspberry Pi 4 and associated circuitry (motor driver, power distribution) are mounted on a raised platform at one end of the frame. Three IR proximity sensors are fixed along the conveyor sides at the entry point and the two segregation points. Four labeled collection bins (Glass, Biodegradable, Plastic, Biodegradable) are positioned below the conveyor at the segregation locations.

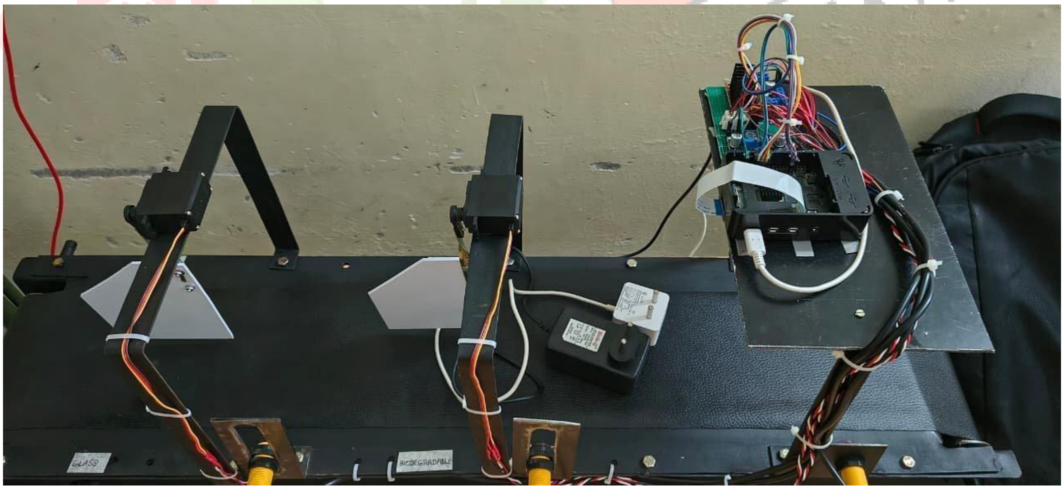

Fig. 3: Top view of the hardware prototype showing servo arms and Raspberry Pi module

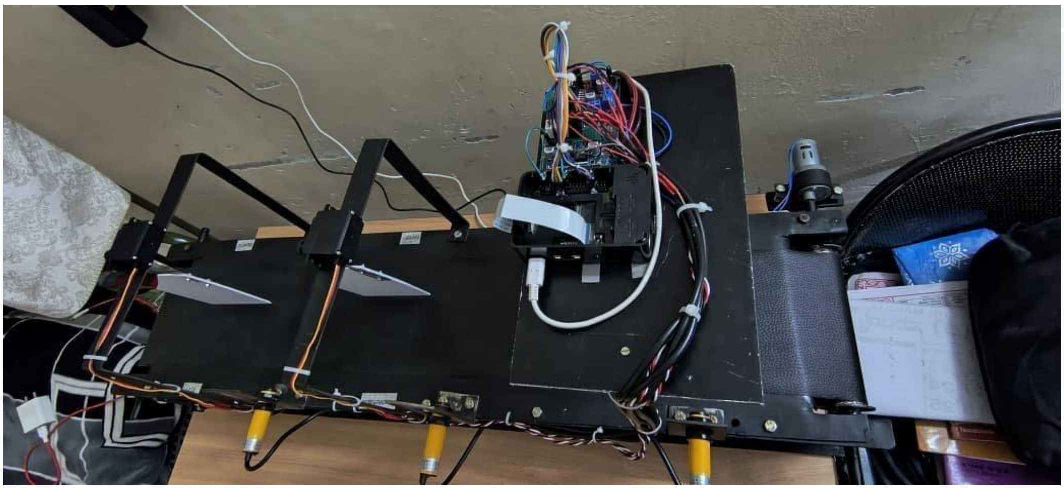

Fig. 4: Alternate top view showing conveyor belt and servo diverter arms in position

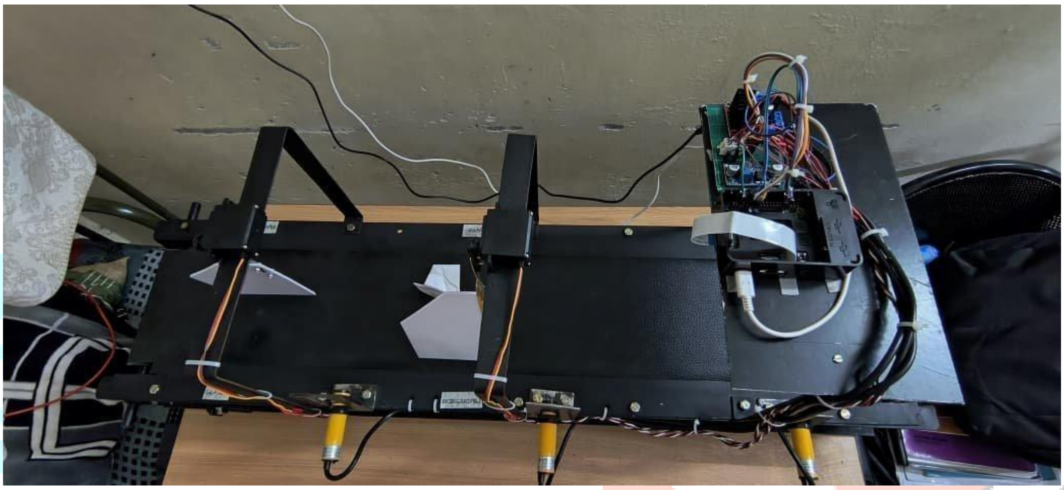

Fig. 5: Top view showing complete assembly with wiring and collection bins below

A. Software Stack

The software stack runs on Raspberry Pi OS (64-bit). YOLOv6 is deployed using PyTorch with an ONNX-exported model for faster inference on the ARM architecture. OpenCV is used for image capture and preprocessing. GPIO control for sensors and PWM for servo motors is implemented using the RPi.GPIO and pigpio libraries. The overall control loop is implemented in Python 3.

B. YOLO Model Training

The YOLOv6 model was fine-tuned on a custom dataset of waste images comprising four categories: plastic, paper, glass, and biodegradable. The dataset was augmented with rotation, flipping, brightness variation, and scale jitter to improve generalization. Training was conducted on a GPU-equipped workstation and the resulting weights were deployed on the Raspberry Pi for edge inference.

VII. RESULTS AND DISCUSSION

The prototype was tested with multiple samples of each waste category. The system demonstrated consistent detection and correct physical segregation across trials. Key observations include:

- Proximity Sensor 1 reliably halted the conveyor belt within 50ms of object detection, ensuring blur-free image capture in all test cases.
- The YOLOv6 model achieved high classification accuracy across all four categories under normal indoor lighting conditions, with occasional confusion between crumpled paper and plastic bags.
- Servo motor actuation was precise and repeatable, with waste items correctly diverted in the majority of trials.
- The overall cycle time from detection at Sensor 1 to bin deposit averaged approximately 4–6 seconds per item, which is suitable for low-to-medium throughput applications such as office or institutional waste points.

The controlled start-stop mechanism of the conveyor belt proved critical: attempts to classify while the belt was moving resulted in motion-blurred images and reduced model accuracy. The stationary capture protocol completely eliminated this issue in tested scenarios.

The two-stage servo segregation architecture efficiently handles four waste categories with only two actuators, reducing hardware cost and complexity compared to systems requiring one actuator per category. The design is also readily extensible: additional segregation stages can be added downstream for more categories.

VIII. CONCLUSION

This paper presented a deep learning-based automated multi-class waste segregation system integrating YOLOv6 object detection with a Raspberry Pi-controlled conveyor and servo mechanism. The system successfully classifies waste into four categories—plastic, paper, glass, and biodegradable—and physically routes each item to the correct collection bin without human intervention. The design demonstrates that cost-effective embedded hardware, when combined with state-of-the-art deep learning, can deliver practical and reliable automation for waste management applications.

Future work includes expanding the model to cover additional waste categories such as electronic waste and organic matter, improving inference speed through model quantization, integrating fill-level sensors in the bins, and connecting the system to a cloud dashboard for remote monitoring and analytics. The proposed system forms a strong foundation for intelligent waste management infrastructure in smart cities and industrial facilities.

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