



Smart AI-Based Waste Segregation System

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ABSTRACT :

The Smart AI-Based Waste Segregation System is an intelligent waste management solution designed to automatically identify and segregate different types of waste using Artificial Intelligence (AI) and image processing technology. The proposed system uses an ESP32-CAM module to capture an image of the waste item placed in front of the camera. The captured image is transmitted through Wi-Fi to an AI-based image analysis system integrated with OpenAI for intelligent waste classification. Based on the visual characteristics of the captured waste, the system categorizes it into predefined classes such as wet waste, dry waste and metal waste. After classification, the control unit activates the appropriate segregation mechanism to direct the waste into the corresponding collection bin. This automated approach reduces the need for manual waste sorting and improves the efficiency and accuracy of waste segregation. The system combines IoT, embedded systems, computer vision and Generative AI to provide a smart and scalable solution for modern waste management, and can be implemented in smart cities, educational institutions, industries, public places and residential environments.

Keywords: waste segregation; artificial intelligence; image classification; ESP32-CAM; OpenAI; Internet of Things; servo motor

Introduction

Waste management is one of the major environmental challenges faced by modern cities, industries, institutions and residential areas. The increasing generation of municipal waste has created a need for efficient collection, segregation, recycling and disposal methods. Proper segregation at the source is important because mixing wet, dry and recyclable waste reduces recycling efficiency and increases the difficulty of waste processing. Traditional segregation mainly depends on manual sorting, which is time consuming, labour intensive and prone to human error.

Recent developments in Artificial Intelligence (AI), computer vision, Internet of Things (IoT) and embedded systems have enabled intelligent waste management solutions. AI-based image processing can analyze the visual characteristics of waste items and classify them into different categories. By combining an ESP32-CAM module with an AI-based image analysis system, waste items can be captured and identified automatically. The ESP32-CAM provides image acquisition and wireless communication, while the AI system analyzes the captured image and determines the waste category.

This paper presents a Smart AI-Based Waste Segregation System that uses an ESP32-CAM to capture images of waste placed in front of the camera and classifies it into predefined categories such as wet waste, dry waste and metal waste. Based on the classification result, the controller activates the segregation mechanism that directs the waste into the corresponding bin. The system reduces human involvement in the initial waste-sorting process and can be extended with bin-level monitoring, data logging and remote supervision. It can be applied in smart cities, educational institutions, industries, public places, offices and residential environments.

1.1. Problem definition

In conventional waste management, different types of waste such as wet, dry and metal waste are often mixed together, making further processing and recycling difficult. Manual segregation requires considerable human effort, and improper classification can lead to contamination and reduced recycling efficiency. The absence of an automated system capable of identifying waste from its visual characteristics creates a need for an intelligent segregation solution. This work therefore aims to develop a system that uses an ESP32-CAM, Wi-Fi communication, image processing and AI-based classification to identify different waste categories automatically.

Literature survey

Several researchers have investigated AI-assisted and IoT-enabled waste management. Kumar et al. [1] presented an AI-assisted waste sorting framework in which image processing identifies waste objects and determines their category, combining image acquisition, AI-based classification and automated sorting for smart cities, industries, educational institutions and residential environments. Hossain et al. [2] proposed an IoT-enabled waste

management system that combines sensors, wireless communication and machine learning to monitor waste conditions and improve collection and segregation, giving real-time information to support automated decision-making.

Computer vision and deep learning have been widely used for waste identification. Yang et al. [3] trained a deep learning model on waste images to recognize categories from their visual characteristics, and the work in [4] used Convolutional Neural Network (CNN) techniques to extract visual features, showing that automated image-based classification supports faster and more consistent segregation than manual sorting. Prasad et al. [5] categorized waste images into organic, recyclable and non-recyclable classes, and Kang et al. [6] developed an automatic garbage classification system based on deep learning for environmental protection and resource recycling. Sidharth et al. [7] proposed a CNN-based smart garbage classifier trained on labelled images of plastic, paper, cardboard and metals, and obtained a testing accuracy of 76 %.

Recent studies continue to improve classification accuracy with advanced deep learning models [8] – [11], [13] – [21], [25], while IoT-enabled and smart-bin systems combine deep learning with wireless communication, mobile applications and monitoring [12], [22] – [24], [26], [27]. The present work combines ESP32-CAM image capture, OpenAI-based image analysis and a servo-driven sorting mechanism in a single low-cost embedded system.

System analysis

1.2. Existing system

In the existing waste management practice, segregation is carried out mainly through manual sorting or basic mechanical separation. Different types of waste such as wet waste, dry waste, plastic, paper, glass and metal are collected either together or in separate bins based on user identification.

1.3. Limitations of the existing system

- Requires significant manual effort for waste segregation.
- Manual sorting is time-consuming and inconsistent.
- Improper segregation may contaminate recyclable materials.
- Conventional systems have limited ability to identify different waste types automatically.
- Basic sensor-based systems may require different sensors for different materials.
- Integration of AI and computer vision for visual waste recognition is limited.
- Real-time intelligent classification is generally not available.

Proposed system

1.4. System overview

The proposed Smart AI-Based Waste Segregation System identifies and separates different types of waste using AI, computer vision, IoT and embedded technology. An ESP32-CAM captures an image of the waste item placed in front of the camera and transmits it through Wi-Fi to an AI-based image analysis system integrated with OpenAI. The AI system analyzes the visual characteristics of the image and identifies the waste category, such as wet waste, dry waste or metal waste. The result is communicated to the control unit, which activates the corresponding motorized segregation mechanism to direct the waste into its collection bin. The combination of ESP32-CAM, Wi-Fi communication, AI-based image analysis and automated mechanical sorting minimizes manual intervention and enables real-time classification and segregation.

1.5. Advantages of the proposed system

- Automatic waste segregation into appropriate categories.
- AI-based classification of waste from its visual characteristics.
- Reduced manual effort in the waste-sorting process.
- Improved and consistent classification accuracy.
- Real-time capture and analysis of waste images.
- IoT connectivity through Wi-Fi for transferring images and system information.
- Contactless handling that reduces direct human contact with harmful waste.
- Multiple waste categories such as wet, dry and metal waste.
- Automated sorting mechanism that directs waste into the corresponding bin.

1.6. Block diagram

The block diagram of the proposed system is shown in Fig. 1. The ESP32 acts as the main controller; it receives power from the power supply and works with the ESP32-CAM, and drives the LCD display and the motor driver, which operates the segregation mechanism to direct the waste into the respective bins.

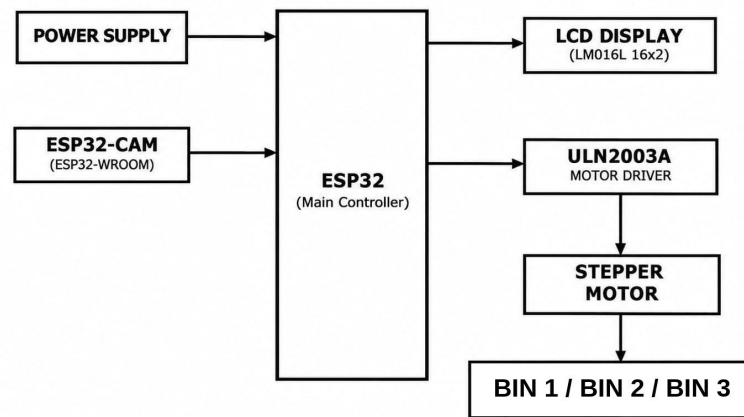


Fig. 1 - Block diagram of the Smart AI-Based Waste Segregation System.

1.7. Working principle

The waste item is first placed in front of the ESP32-CAM module. The camera captures an image, and the ESP32-CAM establishes a Wi-Fi connection to transmit the captured image to the AI-based analysis system. The image is analyzed using OpenAI-based image recognition, which examines the visual characteristics of the waste and determines its category, such as wet waste, dry waste or metal waste. The classification result is sent back to the control unit, which determines the direction of segregation. Based on the received category, the controller activates the corresponding servo motor or mechanical actuator, which moves or directs the waste into the appropriate collection bin. After segregation, the mechanism returns to its initial position and waits for the next waste item.

Components details

1.8. Hardware and software requirements

The hardware consists of an ESP32 controller, ultrasonic sensor, gas sensor, ESP32-CAM, Wi-Fi connectivity, LCD display and buzzer, together with the motor drive, servo motor and DC motor of the segregation mechanism. The software requirements are the Arduino IDE for the ESP32 firmware, a cloud database, OpenAI for image analysis and a web dashboard.

1.9. ESP32 controller and ESP32-CAM

The ESP32 has a powerful 32-bit dual-core processor running at 240 MHz, 520 KB of on-chip SRAM and 4 MB of flash memory, and provides several GPIO pins for connecting sensors, motors and cameras. It supports UART, SPI and I²C, has PWM output, and offers Wi-Fi 802.11 b/g/n and Bluetooth, along with low-power operating modes. In this work it controls the connected components and processes the required data.

The ESP32-CAM board is built around the ESP32-S module with Wi-Fi and Bluetooth, an OV2640 camera with flash, a TF card slot supporting up to 4 GB for data storage, 32 Mbit of built-in flash and 4 MB of external PSRAM in addition to 512 KB of internal RAM. The camera interface enables image capture for computer vision and AI-based applications, and the board is shown in Fig. 2.

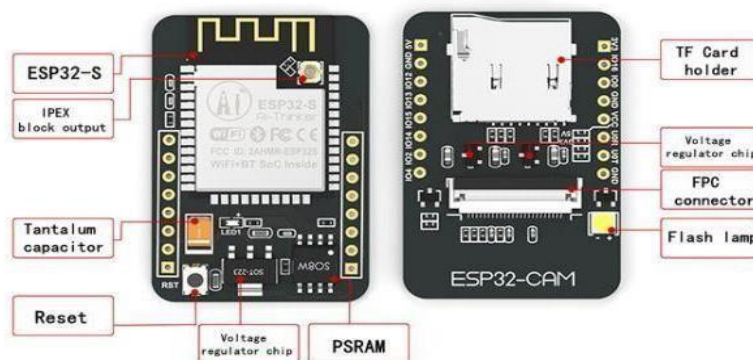


Fig. 2 - ESP32-CAM board.

1.10. Sensors

The HC-SR04 ultrasonic module provides ranging from 2 cm to 40 cm with an accuracy of up to 3 mm and operates at 5 V DC with a working current of 15 mA. A trigger pulse of at least 10 μ s makes the module send eight 40 kHz pulses, and the distance to the obstacle is calculated from the time of the echo output, so that the presence of waste can be detected. An MQ-6 gas sensor, which is highly sensitive to LPG, iso-butane and propane and has low sensitivity to alcohol and smoke, detects gas released from the waste at concentrations up to 10,000 ppm.

1.11. Motor drive, servo motor and DC motor

The L293D motor driver IC receives control signals from the microcontroller and supplies the voltage and current required by the motors, allowing DC motors to rotate in either direction. It supports a motor supply of up to 36 V and a maximum current of 600 mA per channel. The servo motor consists of a motor, a potentiometer, a gear assembly and a control circuit, and is controlled by PWM with a pulse repetition period of 20 ms: a 1 ms pulse sets the shaft to 0°, 1.5 ms to 90° and 2 ms to 180°. In this project different servo angles are programmed to direct different types of waste into their collection compartments. A 12 V, 60 RPM DC motor is used for moving and handling the waste.

1.12. Display, alert and power supply

A 16×2 LCD displays the sensor readings and system status, and a buzzer (5 V DC, 9 mA maximum, 85 dB minimum) provides an audible alert when required. The 12 V and 5 V DC supplies are obtained from a step-down transformer (230 V to 12 V), a bridge rectifier and filter, and 7812 and 7805 voltage regulators.

Experimental setup

1.13. Prototype implementation

The hardware prototype is shown in Fig. 3. Fig. 3(a) shows the mechanical segregation unit with the collection bins, and Fig. 3(b) shows the controller board that carries the ESP32 and its interface circuitry.

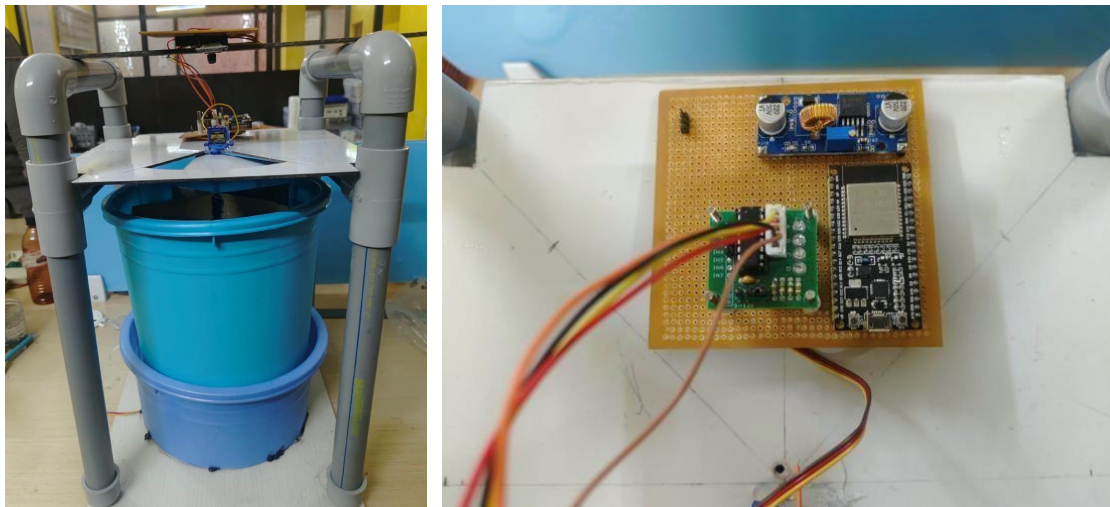


Fig. 3 - Hardware prototype of the system: (a) mechanical segregation unit; (b) controller board.

1.14. Software implementation

The firmware was developed in the Arduino IDE. One program runs on the ESP32-CAM, which initializes the camera, captures the image and sends the classification result to the control unit using the ESP-NOW protocol. A second program on the control unit receives the classification and drives the sorting servo motor to the preset angle of the identified waste category. The operational process of the system is summarized in Table 1.

Results and discussion

The Smart AI-Based Waste Segregation System was developed to identify and separate waste automatically using an ESP32-CAM, Wi-Fi communication, AI-based image analysis and an automated segregation mechanism. During testing, the ESP32-CAM successfully captured images of the waste items placed in front of the camera and transmitted them to the AI-based classification system, which classified the items into predefined

categories such as wet waste, dry waste and metal waste. Based on the classification result, the controller activated the corresponding servo motor or mechanical actuator to direct the waste into the appropriate collection bin.

Table 1 - Operational process of the Smart AI-Based Waste Segregation System.

Step	Operation	Description
1	Waste detection	Ultrasonic sensor detects the presence of waste.
2	Image capture	ESP32-CAM captures the image of the waste.
3	AI classification	AI processes the image and identifies the waste category.
4	Waste separation	Servo motor operates the mechanism based on the identified category.
5	Waste collection	DC motor helps in moving/handling the waste.
6	Gas detection	Gas sensor detects the presence of gas from the waste.
7	Status display	LCD displays the system status/information.
8	Alert	Buzzer provides an alert when required.

The results indicate that the system can provide real-time waste identification and automated sorting under suitable lighting and camera conditions, and that AI-based image classification can reduce the need for manual waste identification. Wi-Fi communication enabled image transmission between the embedded system and the AI analysis platform. However, classification performance may vary with the appearance, size, orientation and lighting conditions of the waste and with the similarity between different waste materials. Overall, the system demonstrates the feasibility of combining AI, computer vision, IoT and embedded technology to develop an intelligent waste management solution.

Conclusion

The Smart AI-Based Waste Segregation System provides an intelligent, automated and efficient approach to waste management by integrating AI, computer vision, IoT and embedded technologies. The ESP32-CAM captures images of the waste, an AI-based image classification system identifies the waste category, and a motor and servo-based mechanism directs the waste towards the corresponding collection bin, reducing direct human involvement and the exposure of workers to harmful or contaminated waste. The ESP32-based control unit coordinates the camera, sensors, motors and servo, and its Wi-Fi capability makes it possible to connect the system to IoT-based monitoring platforms. Because the AI model can be trained with additional images, the system can recognize a wider variety of waste materials as the dataset grows. The system has potential applications in smart cities, industries, educational institutions, hospitals, offices, shopping centers, public places and residential environments, and provides a strong foundation for smarter, cleaner and more automated waste management.

Future scope

The system can be enhanced by increasing the number of waste categories, for example plastic, paper, glass, e-waste, organic and hazardous waste, and by using advanced deep learning and computer vision models, trained on larger and more diverse datasets, to improve recognition accuracy. Object detection can identify multiple waste items simultaneously, and lightweight or edge AI models can reduce dependence on external processing and improve response time. Ultrasonic or other level sensors can monitor the filling level of each bin, with a mobile application or cloud dashboard for remote monitoring, notifications and analysis of waste-generation data. Solar panels and rechargeable batteries can provide energy-efficient operation, and multiple units can be deployed across public places and connected to a centralized waste management platform.

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