ECE 445

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Waste Segregation System

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1. Introduction

1.1 Problem and Background

Inefficient waste segregation represents a critical environmental challenge. While the U.S. recycling rate has increased from less than 7% in 1960 to the current rate of 32%, we are far from optimal recycling efficiency. The EPA estimates that nearly 75% of all waste is recyclable, yet between 70% and 90% of all items that could be recycled in the United States end up in landfills. This gap between potential and actual recycling rates is particularly striking when compared to countries like Sweden, which achieves 99% of its waste not ending up in a landfill.

The scale of this problem is massive. Of the 8.3 billion metric tons of plastic created globally, almost 6.3 billion metric tons have ended up in the trash. In the United States alone, the production of major appliances consumed about 5.3 million tons of ferrous metals, while only about 3.1 million tons were recycled. Currently, there are over 2,600 MSW landfills in the United States, with the largest spanning 2,200 acres. [1]

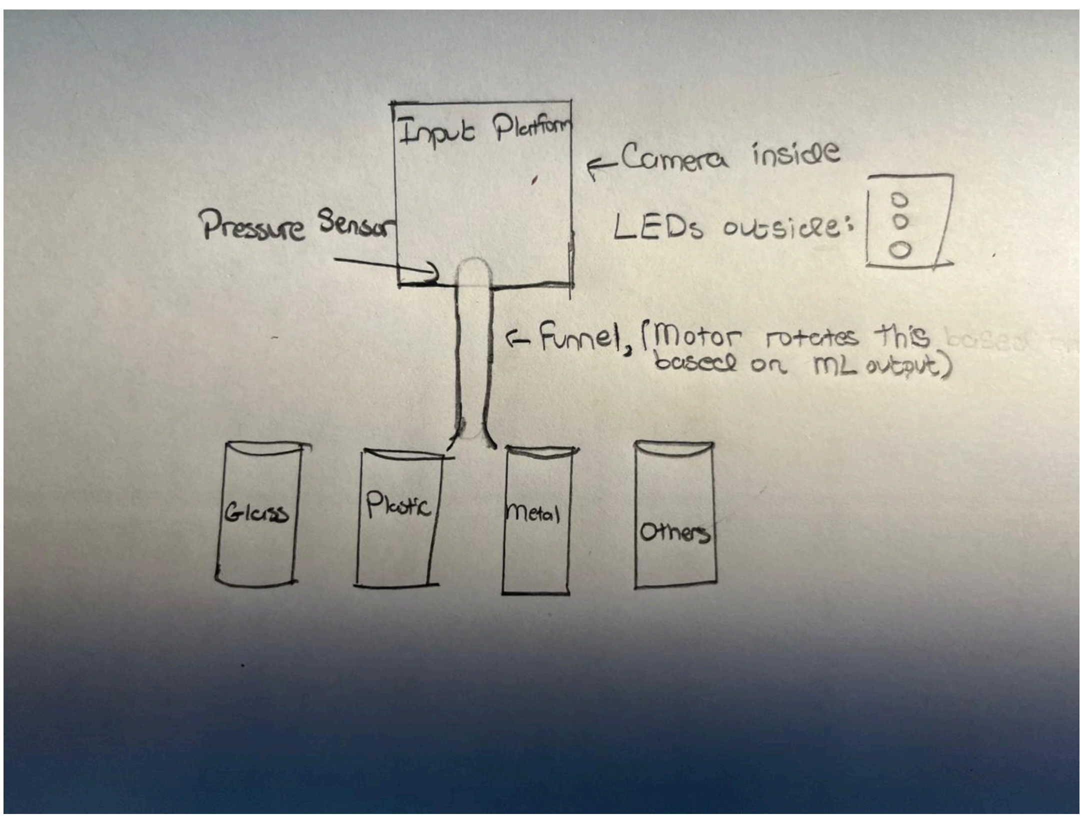
The current market offers two main approaches to waste sorting:

1. Large-scale automated sorting machines:
    - Limited to large recycling facilities
    - Not feasible for small businesses or local implementation
    - Require significant maintenance
    - High initial investment costs
2. Basic multi-bin recycling systems:
    - Depends entirely on user knowledge
    - Lack of any verification capability
    - No way to ensure proper sorting

This creates a clear need for an affordable, automated waste segregation system that can operate at the point of disposal, bridging the gap between expensive industrial solutions and error-prone manual sorting.

1.2 Solution

Our team proposes an intelligent waste segregation system that automatically identifies and sorts waste into appropriate recycling categories using computer vision and mechanical automation. The system consists of a main intake chamber equipped with an HD camera that captures images of disposed items. These images are processed by a TensorFlow Lite model running on a Raspberry Pi 4, which classifies materials into four categories: glass, plastic, metal, and non-recyclable waste. Once classified, a motorized tilting platform directs items into their designated collection bins. The system includes status indicators, jam detection, and emergency stops to ensure reliable operation. Custom-designed PCB and microcontroller components manage the sensor inputs and motor control for precise and reliable sorting operations. By automating the sorting process at the point of disposal, our solution bridges the gap between expensive industrial systems and error-prone manual sorting, making accurate waste segregation accessible for small businesses and institutions. The complete system fits within a compact footprint suitable for indoor spaces, operates on standard power outlets, and requires minimal maintenance for sustained operation. Here is a rough visual of what this will look like:

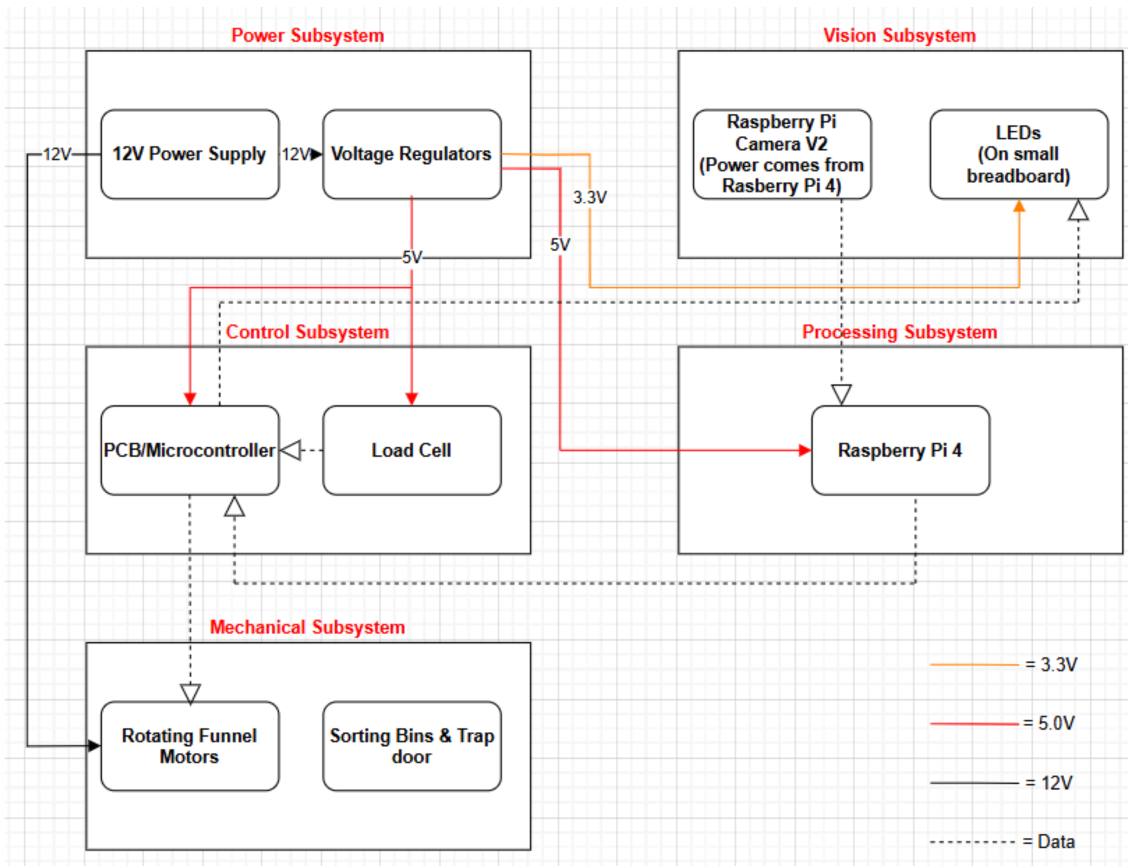


1.3 High-Level Requirements

- The machine learning model must correctly classify waste materials into their proper categories (plastic, metal, glass, or non-recyclable) with at least 70% accuracy under standard indoor lighting conditions.
- The mechanical sorting system must successfully route classified items to their designated bins within 20 seconds per item, maintaining this performance for objects weighing up to 500g.
- The anti-jamming system must detect blockages within 2 seconds and automatically halt system operation when a jam is detected, keeping the overall system jam rate below 20% during continuous operation.

2. Design

2.1 Block Diagram



2.2 Subsystem Descriptions

2.2.1 Vision Subsystem

The Vision Subsystem consists of the camera and LEDs which are used to capture the 720p resolution (1280x720 pixels) images for the MobileNetV2 SSD Model. This camera will be connected to the Raspberry Pi 4 as the image data collected by the camera will be sent to the MobileNetV2 SSD Model hosted on the Raspberry Pi 4 for classification. The LEDs are connected to the Raspberry Pi along with the custom PCB & microcontroller which is used to indicate whether there are any jams or other errors. We use 3 LEDs (green, yellow, and red) to indicate the current status of the system (green to indicate the funnel is clear, yellow to indicate there is an object currently being disposed of, and red to indicate a jam).

2.2.2 Power Subsystem

The Power Subsystem is responsible for regulating the power going to all components of the waste segregator system. The components that will receive an active power supply include the Raspberry Pi 4, pressure sensor, motor, LEDs, load cells and the PCB. The system is powered by a simple 12 V battery, which will then be regulated using DC-DC buck converters to step down input source voltage and provide the appropriate voltages required for each component. The voltage values are showcased in the block diagram.

2.2.3 Processing Subsystem

The Processing Subsystem is responsible for receiving image data from the camera and performing the necessary object detection and classification on the Raspberry Pi 4 using the MobileNetV2 SSD Model. The goal of this subsystem is to identify and classify the nature of the item thrown to determine which of the Plastic, Metal, Glass, or Non-Recyclable categories the item belongs to. The model is a pre-trained model that will be adapted for this use case to ensure that we meet the requirements of classifying objects with a minimum of 70% accuracy.

The process starts with the Raspberry Pi 4 processing the images captured at 720p resolution (1280x720 pixels) by the camera, before using the MobileNetV2 SSD Model to determine the object category. The model inference is estimated to take less than 10 seconds. Once the object has been classified, the results are sent to the Control Subsystem for sorting.

2.2.4 Control Subsystem

The Control Subsystem is responsible for interpreting the classification results retrieved from the Processing Subsystem to execute the relevant mechanical actions to put the objects in the appropriate waste bin. To achieve this, we use our custom PCB with a microcontroller and load cells to account. When the signal is received from the Processing Subsystem, the microcontroller sends the appropriate PWM signals to maneuver the funnel toward the correct bin. We use load cells during this process to detect the objects and their movement to ensure that the object is successfully dispatched and that there are no jams. The microcontroller is also linked to the LEDs as part of the Vision Subsystem to indicate any jams or other processes that block functionality.

2.2.5 Mechanical Subsystem

The Mechanical Subsystem is responsible for the channeling of the waste, acting as a bridge between the inlet and outlet of the waste. We think that the most optimum solution to transfer the waste is to design a funnel. Ensuring efficient waste classification and disposal. It consists of the input platform, funnel rotation mechanism, waste sorting chutes, and supporting frame.

The subsystem integrates a motor-driven pivot system to rotate the funnel, aligning it with the correct bin based on classification. A stepper motor ensures precise movement, with encoders that provide position feedback to the Raspberry Pi. The waste sorting chutes are designed to prevent clogging, ensuring smooth disposal, while a sturdy frame supports all components, protecting electronics from debris. Safety mechanisms like jam detection pressure sensors and emergency stops enhance reliability, ensuring efficient and automated waste segregation.

2.3 Subsystem Requirements

2.3.1 Vision Subsystem

- Camera Requirements
  - Must capture and transmit images at **720p resolution (1280x720 pixels)** at **30 frames per second**.
  - Must achieve focus on objects placed on the **30cm** × **30cm** platform within **500ms**.
  - Must maintain proper exposure for reflective materials within **±10%** of optimal brightness levels.
- LED Requirements
  - Must provide uniform illumination of **500 lux (±10%)** across the entire **30cm** × **30cm** platform
  - Must turn on within 100ms when the item is detected in the platform area
  - Must maintain constant brightness at **5V** DC input without flickering
  - Need a small breadboard with a certain calculated resistance that can help mount the LEDs

2.3.2 Power Subsystem:

- Power Supply Requirements
  - Use a battery, let's say a 12V source that could potentially power a 12V motor, a standard voltage rating used for motors.
- Varying voltage requirement
  - We will require our PCB to include a power board of a 12 to 5V buck converter to power the low-voltage components like the Raspberry Pi, pressure sensor, LEDs and load cells. .
  - An LM2596 pre-built module could be used to step down the voltage and all that would need to be done to get 5V is to adjust the potentiometer. This will be a very cost-effective method over building a custom built power board with a transformer, inductor, capacitor and Schottky diode.
- Wiring Considerations

    - Thick gauge wires (AWG 14-16) should be used for high current 12V lines, while AWG 20-22 is sufficient for low-power 5V components.

2.3.3 Processing Subsystem

- Raspberry Pi 4 Requirements
    - Must accept **720p images (1280x720 pixels)** from the **camera**.
    - Must normalize pixel values to **0–1** for TensorFlow Lite compatibility.
    - Must handle **single-item images** placed within a **30x30cm platform**.
- MobileNetV2 SSD Model Requirements
    - A **TensorFlow Lite (TFLite)** implementation of the **MobileNetV2 SSD model must be used**.
    - Must achieve **≥70% classification accuracy** under **standard indoor lighting conditions**.
    - Must perform **model inference** within **10 seconds** for each captured image.
    - Must classify waste items into one of the following categories:
        - **Plastic**
        - **Metal**
        - **Glass**
        - **Non-Recyclable**
    - Must provide an **output confidence score** between **0 and 100%** along with the classification label.
    - Must reject predictions with a **confidence score below 50%** and request **reclassification**.
    - Must be capable of detecting **single items of ≥10g weight**.
    - Must ignore **background elements** to prevent false positives.
    - Must handle images with **standard indoor lighting** and **reflective materials** with minimal performance degradation.

2.3.4 Control Subsystem

- PCB/Microcontroller Requirements
  - Must control **servo and DC motors** via **PWM signals** with a response time of **≤300ms**.
  - Must use **GPIO pins** to interface with:
    - **LED indicators** for sorting status.
    - **Emergency stop button** for user safety.
    - **Input signals** from Raspberry Pi 4 and load cells
  - Must support **I2C/SPI communication** for **sensors and peripherals**.
- Load Cells Requirements
  - Must register a **successful item drop** into the bin with a sensitivity of **≥10g**.
  - Must trigger an **error condition** if an item remains undetected for **> 5 seconds**.

2.3.5 Mechanical Subsystem

A **stepper motor** can rotate 360 on a low-torque application. With it being a DC brushless motor, it fits the criteria of converting the digital signal sent from the Raspberry Pi directing it where the waste should be let out.

- **Input Platform:**
  - This platform where the user will throw in their waste will be designed with a smooth, non-stick surface to prevent waste from getting stuck before classification.
- **Funnel Rotation Mechanism:**
  - Once the waste is classified, the funnel rotates to align with the correct waste bin using a motor-driven pivot system.
  - A stepper motor like NEMA 17/23 could be used for controlled rotation, ensuring accurate positioning for waste disposal.
- **Waste Sorting Chutes**

        - The funnel directs waste into one of four bins (Glass, Plastic, Metal, and Others).
        - The chute design prevents clogging, ensuring smooth waste flow into the designated bins.
        - Each bin is placed at an optimal angle to minimize impact and prevent cross-contamination of different waste types.
    - **Structural Framework**
        - The entire system is mounted on a sturdy frame made of reinforced plastic to ensure durability.
        - The frame includes a protective casing around electrical and mechanical components to prevent damage from debris.
        - The design allows for easy maintenance, with access panels to the motor, sensors, and electronic components for troubleshooting or repairs.

2.4 Tolerance Analysis

The most critical aspect of our waste segregation system is ensuring that the entire process from image detection to item sorting is done within 20 seconds. This timing chain involves multiple sequential operations that must each meet specific deadlines. Let's analyze each subprocess and make sure it fits within a timely window:

1. **Image Capture/Processing:**
    a. Camera Focus Time: 1/30 seconds (33.3ms)
    b. Image Transfer to Raspberry Pi: ~100ms
    c. Total: ~633.3ms
2. **ML Model Interference:**
    a. Image Pre-processing: ~200ms
    b. MobileNetV2 SSD Model Inference: ≤ 10,000ms
    c. Total: ~10,200ms
3. **Mechanical Response:**
    a. Motor Response Time: ≤ 1000ms
    b. Item Travel Time (gravity-assisted): ~1000ms
    c. Total: ~ 2000ms

4. **Error Detection:**
    a. Jam Detection Requirement: 2,000ms
    b. Weight Confirmation: 500ms
    c. Total: 2500ms

This analysis shows us that our total time should theoretically be 633 + 10,200 + 2000 + 2500 ~ 15.3 seconds. This provides us with a 4.7-second margin.

3. Ethics & Safety

3.1 Ethics

The goal of this project is to build a device that encourages sustainability and is environmentally friendly. We aim to promote the use of waste segregation bins and want to enhance the already environmentally conscious approach taken by the University of Illinois to conserve the planet. This purpose falls in line with Section 3.1 of the ACM Code of Ethics which states that this work must be done to ensure public good, which we aim to do by promoting eco-friendly practices to contribute to broader environmental conservation efforts (ACM, 2018, Section 3.1) [(2)].

3.2 Safety

As part of this project, we must take a cautious approach to building our solution due to the nature of the product and the exposure to people. Adhering to Section 1.2 of the ACM Code of Ethics, we will ensure that all the components required for this project will be thoroughly tested and any work done will be completed while adhering to the necessary safety protocols established by the University of Illinois Lab Requirements. Our goal is to create a sustainable product that prioritizes the safety of all users (ACM, 2018, Section 1.2) [(2)].

4. Citations and References

(1) **Book Clean Go.** (n.d.). *Recycling statistics: The truth about recycling in the U.S.* [Blog post]. Retrieved February 13, 2025, from https://www.bookcleango.com/blog/recycling-statistics

(2) Association for Computing Machinery (ACM). (2018). *ACM Code of Ethics and Professional Conduct*. Retrieved from https://www.acm.org/code-of-ethics