Tracking Recyclables Automated Sorting Hand

(T.R.A.S.H.)

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Motivation and Background

Recycling is essential to reducing waste and protecting the environment, but traditional sorting methods are often manual and time-consuming. With the growing waste problem around the world, there is a need for more efficient and automated solutions. Robotic sorting systems have already begun addressing this issue in the waste management industry, but these systems are often expensive, very large, and complex to operate. Our project aims to solve this problem by creating a compact, cost-effective, scalable robotic sorting system. By utilizing optics and computer vision technology, we plan to provide a solution that improves the efficiency of sorting recyclable materials while also being accessible and affordable for small and local waste management companies.

Objectives and Goals

The objective of the T.R.A.S.H. project is to design and implement a cost-effective, compact, and self-contained robotic sorting system that efficiently identifies and separates recyclable materials from mixed waste using computer vision, optics, and Artificial Intelligence. The system aims to improve waste sorting efficiency for small-scale recycling operations by providing high detection accuracy, precise pick-and-place capabilities, and an automated classification process while ensuring scalability, energy efficiency, and ease of use.

a. **Basic Goals -** These goals define the fundamental capabilities required for the project to meet its minimum success criteria by the conclusion of Senior Design.

b. **Basic Objectives Optics** - Design and implement a spectrometer to read spectral information of sample. The sample for the basic goal is a soda can. Samples will get taken of the can to build a reference.

- **Computer Vision**
    - Achieve detection of 12 oz. aluminum cans with a minimum of 80% accuracy using computer vision algorithms and Artificial Intelligence.
    - Precisely identify the location of a 12 oz can within a ±5 mm margin and transmit positional data to the robotic arm for retrieval.
    - Efficiently scan and classify recyclables from mixed waste within a workspace containing 4-5 items.
    - Complete the detection and scanning process for all items within a 30-second timeframe.
- **Robotic Arm**
    - Ensure the robotic arm initializes from a designated home position prior to operation, to allow the computer vision to see the workspace.

    - Execute the grasping of items with an accuracy within a 5 mm tolerance and relocate item into their designated locations.
    - Complete the entire sequence of scanning, positioning, and picking tasks within one minute.
  - **Optics**
    - Utilize a spectrometer to identify 12 oz aluminum Coke cans within a maximum of 30 seconds.
    - spectrometer detection 80% accuracy.
  - **Hardware**
    - Integrate ESP32 and Raspberry Pi systems to manage processing, control functions, and system integration.
    - Ensure the power supply unit (PSU) reliably delivers 12V output, able to distribute into 12V, 5V, and 3.3V for other peripherals.
    - Design a PCB that is able to run the whole system.

c. **Advanced Goals -** These goals reflect the ideal outcome for the project, demonstrating enhanced functionality and performance.

d. **Advanced Objectives Optics -** Expand the library of reference spectrums to be able to identify more recyclables. In addition to optimizing performance to reduce identification times.
  - **Computer Vision**
    - Improve object detection accuracy to 90% or higher.
    - Identify plastic water bottles and mini cardboard boxes using advanced computer vision algorithms.
    - Detect and classify mixed recyclables in a workspace with more than 5 items.
    - Reduce total scanning and detection time to under 20 seconds.
  - **Robot Arm**
    - Develop a robotic arm capable of returning to a home position after each task.
    - Improve arm precision to within 3 mm accuracy for item pickup.
    - Complete scanning, positioning, and pickup tasks in under 45 seconds.
  - **Optics**
    - Create a library of spectrums used to identify 3 common recyclables (e.g. Plastic water bottle, cardboard, and aluminum)
    - Reduce spectrometer identification time to under 20 seconds per item.
    - Increase the spectrum resolution of the spectrometer by increasing accuracy by 20%.
  - **Hardware**

- Ensure all hardware components are optimized for energy efficiency, maintaining power consumption below 150W.
- Enhance modularity by being able to support adding extra peripherals and motors for customized automation functions.

- **User Interface**
  - Develop an application to display the real-time camera feed from the robot.
  - Incorporate an on/off switch within the application for system control.

e. **Stretch Goals -** These goals represent additional features and innovations that can be achieved if the project surpasses the advanced goals.

f. **Stretch Objectives Optics –** Instead of having the light be coupled into spectrometer via a lens it will be fiber coupled. Continue Expand the library of reference spectrums to be able to identify more recyclables.

- **Sorting & Material Expansion**
  - Enable the spectrometer to detect at least four different recyclable materials.
  - Add a motor-powered conveyor belt system for continuous sorting.
- **Data Tracking & Optimization**
  - Create an inventory database to count and log the number of recyclable items detected and their material.
- **Innovative Enhancements**
  - Integrate a laser-based analysis system inside the robotic arm for improved material classification.
  - Enhance computer vision capabilities to perform complete scans within 10 seconds.
  - Optimize robotic arm movements to complete tasks within 30 seconds.
  - Extend the user interface to identify and display the number of recyclables detected.
  - Implement sorting and categorization of items by material type within the application.
  - Redesign PCB Layout to be compact enough to fit in 12”x6”x6” Box
- **Optics**
  - Integrate a fiber-coupled spectrometer for enhanced classification.
  - Create a library of spectrums used to identify 5 common recyclables (e.g. Plastic water bottle, cardboard, aluminum, steel and copper)

Description of Features/Functionalities

a. Core Features:

- Computer Vision System and detection system:
    - Use Artificial Intelligence for detecting recyclable items.
    - Gather item position data to send to the robotic arm.

- Robotic Arm:
    - Pick and place items in their respective bins with precision.
    - Ability to pick irregularly shaped items.
- Power System:
    - Operates using standard wall AC power.

b. Additional Functionalities:

- Wireless Control App:
    - Use a mobile app to monitor and control the system.
- Self-Contained Design:
    - Compact and portable structure.
- Modular design
    - Customer's ability to add additional motors and peripherals as needed.

State of Technology

There are multiple examples of recycling robots that exist in the world. Companies like ZenRobotics [1], EverestLabs [2], and Recorra [3] are just a few of the sorting arm robots out in waste management. However, just because these products exist and are currently out in the market does not mean they cannot be improved upon.

There are currently a couple of issues that are facing modern recycling solutions. Firstly, many of these robots can be very expensive coupled with the fact that these robots have a hard time dealing with variation in waste size, shape, and material, throws the question of practical effectiveness into question. Additionally, integrating these solutions is not always practical as they often require specific infrastructure that is not practical or within budget.

Mechanical Structure and Controls

Structure

When it comes to robotics there are soft and rigid robotics. Soft robotics are used for integrating multiple functions into one material, such as actuation, sensing, adaptivity, and locomotion. At this point in time there does not appear to be a specific need to utilize soft robotics in our design. There is a possibility of needing to integrate soft robotics for the manipulator do to the complex and inconsistent nature of the materials being acquired by the robot. However, our robot will be primarily rigid and common rigid robotics are made of steel, aluminum, hard, plastic, alloys and composite. [4]

For our robotic arm we will need be manipulating heavy objects, therefore the amount of internal loading within the robotic arm are minimal. For this reason our robot will use plastic 3D printed materials, as it is cheaply made, highly customizable, and contains adequate material properties. However, do to the complexities of modern day controls, weight of the robot may need to be increased in order to account for overshoot.

Controls

Control systems have pervaded the technological world today, allowing for more complex and more autonomous systems to be used in the natural environment. However, as controls systems get increasingly more complicated (as we see within the field of robotics) feedback control systems face several challenges, including response delays, errors in sensor data interpretation, and the complexity of managing intricate, non-linear systems.[5]

Firstly, when analyzing the current state of response delays, we see a discrepancy. This issue is not immediately prevalent to our project, as it is unlikely our robot will need to make reactionary based decisions. However, current robotic systems that try to follow in the legacy of robotics behaviorism (reactionary actions) tend to have contradictory results that deal with optimal timing of feedback. There seems to be conflicting results that indicate delayed feedback provides more accurate information acquisition, while other researchers are claiming that immediate feedback provides better results compared to delayed feedback.[6]

An additional point of investigation relates to errors in sensor data interpretation. Regardless of the system in question disturbances and sensor errors will always appear. It is for this reason that much research has been conducting in accounting for disturbances and sensor error. However, with the amount of complexity in real world environments it can be extremely challenging and case specific when designing controllers relating to disturbances and errors.[7]

Lastly, when it comes to non-linear systems, the most commonly used design methodology is to estimate the physical model parameters through means of identification which employs a set of input-output measurements collected from the system. However, in many applications it is challenging to derive a simple and accurate model of the physical system. For this reason there is research being conducted to develop direct and indirect data-driven inverse control techniques. [8]

Electrical

In robotic sorting systems, a lot of prior work has focused on improving image processing and object detection to make sorting more accurate and efficient. For our project, looking at it from an electrical perspective, we aim to create a system that's not only precise but also scalable, energy-efficient, and compact. Most industrial robotic arms use stepper motors and servo motors due to their great accurate positioning and precise movements, which make them perfect for repetitive tasks like sorting. A lot of existing projects we have seen rely on external computers for heavy tasks like image processing and calculating position. However, we want our system to be self-contained, without needing to connect to an external computer. That's why we're planning to use a Raspberry Pi to act as the brains of our automation system and to handle all the calculations and programs. At the same time, Arduino microcontrollers are well-known for being reliable when it comes to controlling motors and managing movement commands. In this section, we will take a closer look at the current technologies out there and explain the options we are researching and comparing to use in our project and achieve our goals.

Motors

a. Stepper motors:
   - Widely used in robotic systems like 3D printers (e.g., Prusa i3 MK3)
   - Provide precise control of the robotic arm's movement with micro stepping option.
   - Best for accurate positioning tasks, such as picking and placing objects.
   - Provide high torque and no feedback required for positioning.
   - Since there is no feedback, a homing mechanism maybe required to reset position after restart.
   - An example of a stepper motor is the NEMA 17, which is known for its reliability and precision.

b. Servo motors:
   - Widely used in robotic/educational projects due to accurate rotational movement.
   - Provide smooth rotational movement with feedback for precise angle control and receiving data.
   - Ideal for controlling robotic arm claws.
   - Have built-in encoders which make them easy to integrate and ensure high accuracy
   - Might be a better option since feedback would avoid the need for a homing mechanism.

Microcontrollers and Microprocessors

a. Arduino:
   - Arduino has been successfully used in numerous robotic arm projects.
   - Great for prototyping and testing.
   - Excellent for managing peripherals and tasks such as controlling motor movements and reading sensor data.
   - Cost-efficient and easy to program.
   - Supports many communication protocols such as UART and I2C, making it suitable for integration with other devices.
   - Example: The uArm Swift Pro robot uses Arduino MEGA as its motherboard for controlling motors and managing sensors.

b. ESP32:
   - Similar to the Arduino in many ways.
   - Great for controlling motors and peripherals.
   - Has built-in Wi-Fi/wireless functionality.
   - Processor is much faster when compared to an Arduino.
   - Smaller in size compared to other microcontroller options that have similar functionality and performance.
   - Many development kit options available for prototyping.
   - Easily integrate it into a PCB and get most functionality.
   - Can be coded with Arduino IDE.

c. Raspberry pi:
   - A common choice in image processing and object detection applications
   - Higher computation capabilities compared to an Arduino, making it ideal for running image processing tasks.
   - Support wireless communication, which can be used for integration with a mobile app.

Communication protocols

a. UART:
   - Used for simple communication tasks, mainly integrated in a microcontroller.
   - Can only have up to two devices. Communicating directly with one another.
   - Have a low speed compared to other protocols.

b. I2C:
   - Commonly used in systems where a microcontroller and microprocessor need to communicate.
   - Simple, two-wire protocol with multiple slaves and masters.

- Faster than UART.
- Can connect up to 128 devices on a single bus.
- Supported by many peripherals and sensors.

Optics

A key function of the robot is to identify objects and place them in the appropriate receptacle. To achieve our main objective, we must solve two main problems. Problem one, successfully identifying objects as trash or recycling in addition to separating the recycling into paper, plastic, and metal. Problem two being able to find the position of the object in 3D space based on a 2D image. Problem 2 it's an optics problem; however, the imaging system that is designed must be able to provide the information necessary to solve for object location. Both the PSE and CE student will work in collaboration to achieve a solution. My current method is using a laser and a diffraction grating to project grid to allow the camera system to find location [10].

To Identify objects as trash or recyclables a spectrometer will be used. There is a project currently, a CEC Senior design project with one PSE student working on a similar project called ALiCE. They use a spectrometer to identify objects by using the robot arm it picks up trash and holds it up to a lens that focuses light into the spectrometer. Aa a stretch goal, I would like to imbed a fiber into the hand of the robot arm to channel the light into the spectrometer. Careful consideration of the type of fiber is essential to ensure that there is enough light, so the senser can detect.

The purpose of the image system is to capture imaging for computer vision. It was my original intention to design my lens systems; however, the purchase of a CMOS sensor costs $500 on Thor Labs and an achromatic doublet lens can cost $100. Meanwhile a similar camera system pi cam can be bought for less than $25 in addition to its ease of integration with Raspberry Pi. Going with a Raspberry Pi also allows for the EE and CPE to start testing the system sooner to have a working prototype at the end of the semester. In, conclusion there is no real advantage to designing a camera system unless it fulfills the design requirements for the PSE part of the senior design.

LIBS system Laser-Induced Breakdown Spectroscopy. LIBS is an emission spectroscopy technology that detects the elemental spectrum of a sample [9]. I am in favor of this method because it is robust. It is not affected by the ambient environment, the samples orientation, shape, and color. In addition, a Machine learning aspect will use a library to store data we will have to collect to collect our staples. An alternative to LIBS is reflective spectroscopy, which would be more suitable. However, when using reflective spectroscopy, we will have to have a white light lamp and control the ambient environment to reliable results.

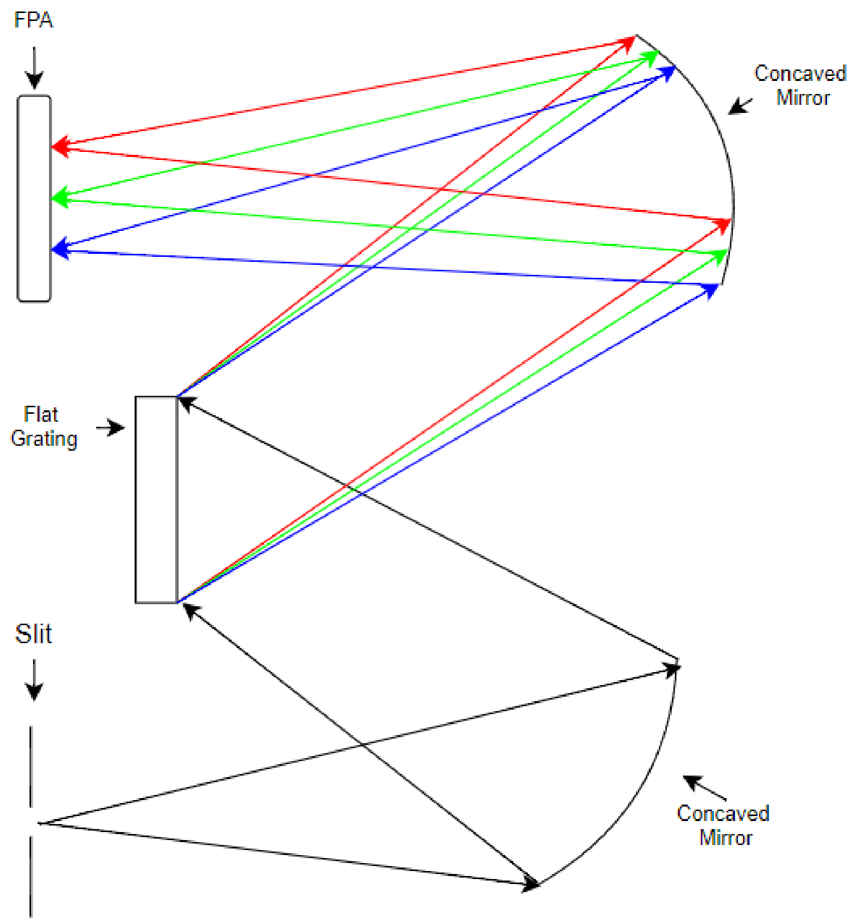


Figure 1, Sketch of a spectrometer with a reflective grating and optics. The FPA stands for Focal Plane Array, a grid of sensors arranged at the focal plane of an imaging system.

Software and Integration

For the T.R.A.S.H. project, we are leveraging modern software technologies to enhance system efficiency and performance. Our approach integrates powerful AI and machine learning tools to optimize the detection and sorting of recyclables.

Microsoft Azure AI Integration

We will utilize Microsoft Azure's AI services for object detection and classification in the workspace. Azure's cloud-based AI capabilities offer robust machine learning models, allowing for precise identification of various recyclable materials. This integration enhances real-time detection accuracy and scalability of the system.

Computer Vision and Image Processing

The system employs OpenCV for processing images captured by the robot's camera. This enables the identification of object positions, shapes, and materials with high accuracy. The combination of OpenCV and Azure AI ensures that the detection process is both fast and reliable.

System Architecture

A Raspberry Pi running Linux Ubuntu will manage all automation tasks. The Raspberry Pi will process data from the camera and control the robotic arm's movements. For precise motor control, an Arduino will handle the servo and stepper motors, receiving commands from the Raspberry Pi.

User Interface

A user-friendly application will be developed to display real-time camera feeds and provide control options, including an on/off switch. Future enhancements will include item count displays and material-based sorting visualization.

This integration of Microsoft Azure AI, OpenCV, and modern hardware control systems positions the T.R.A.S.H. project at the forefront of automated waste sorting technology.

Specifications

Table 1. Engineering Specifications of the System

Specification	**Value**
CV Object Detection time	< 20 sec per item
Pickup time of Identified Object	< 30 seconds per item
Pickup location Accuracy	+- 5 mm
Min Payload	> 30 grams
Power Consumption	< 150W

Table 2. Optical Specification

Spectrometer	
Specification	**Value**
Wavelength Range	400nm to 800nm
Spectral Resolution	< 20 nm
Slit Width	50 to 500 µm
Objective lens focal distance	100 mm

Note: The specifications highlighted in blue are chosen for demonstration.

Hardware Block Diagram

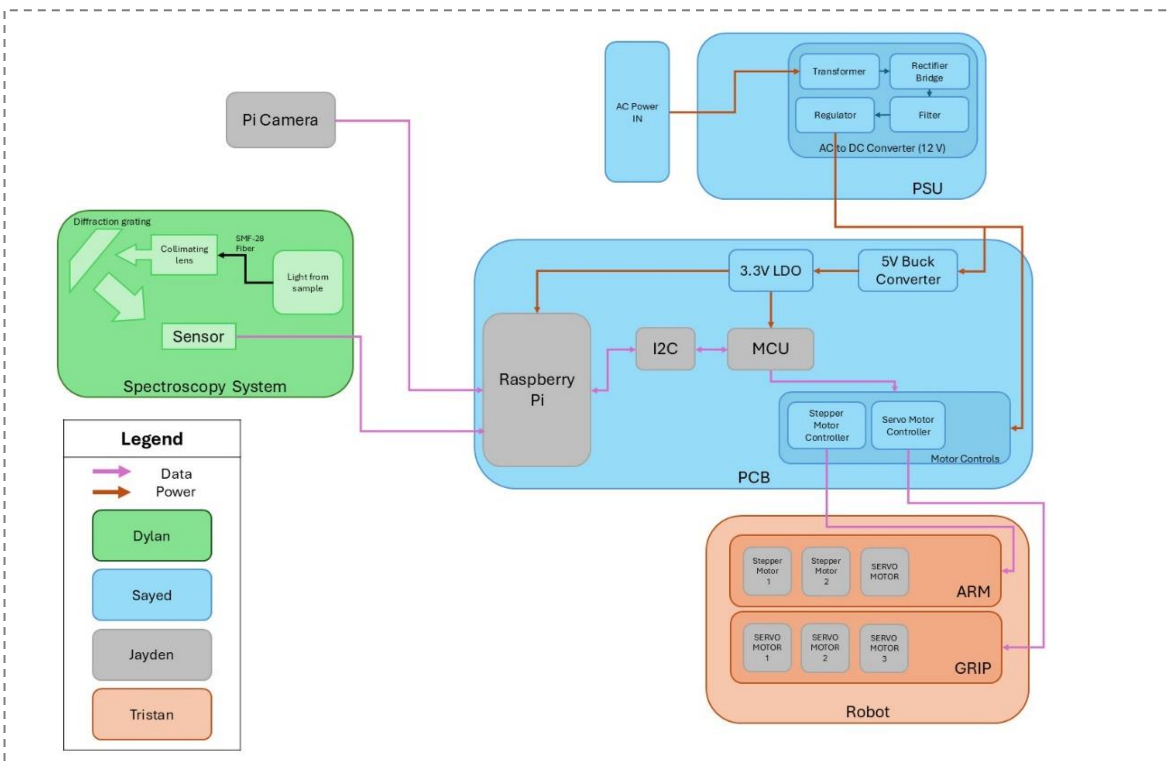


Figure 2. Hardware Diagram

Note: Everything is still in the designing phase, none of the blocks have been acquired yet.

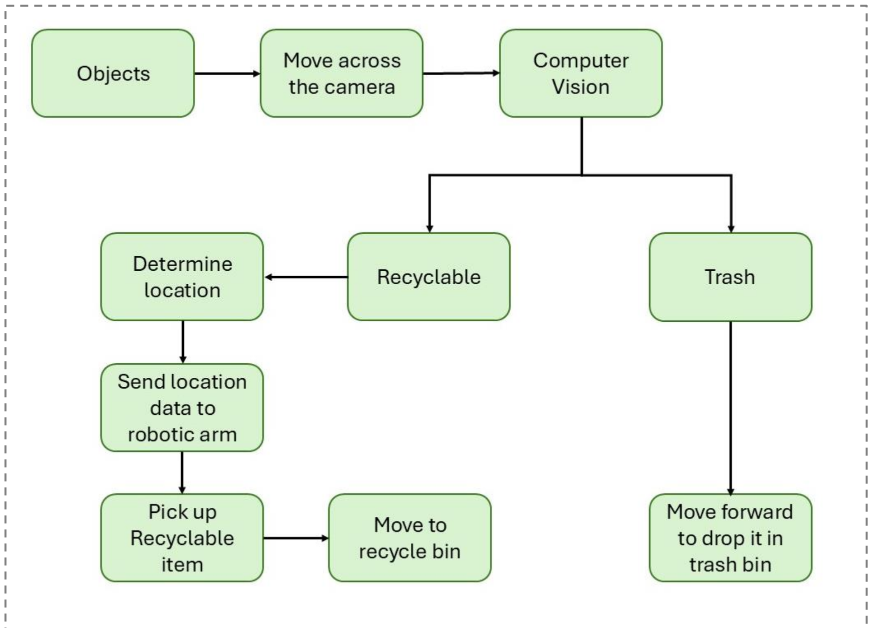


Figure 3. High-Level Flow Chart

Software Diagram

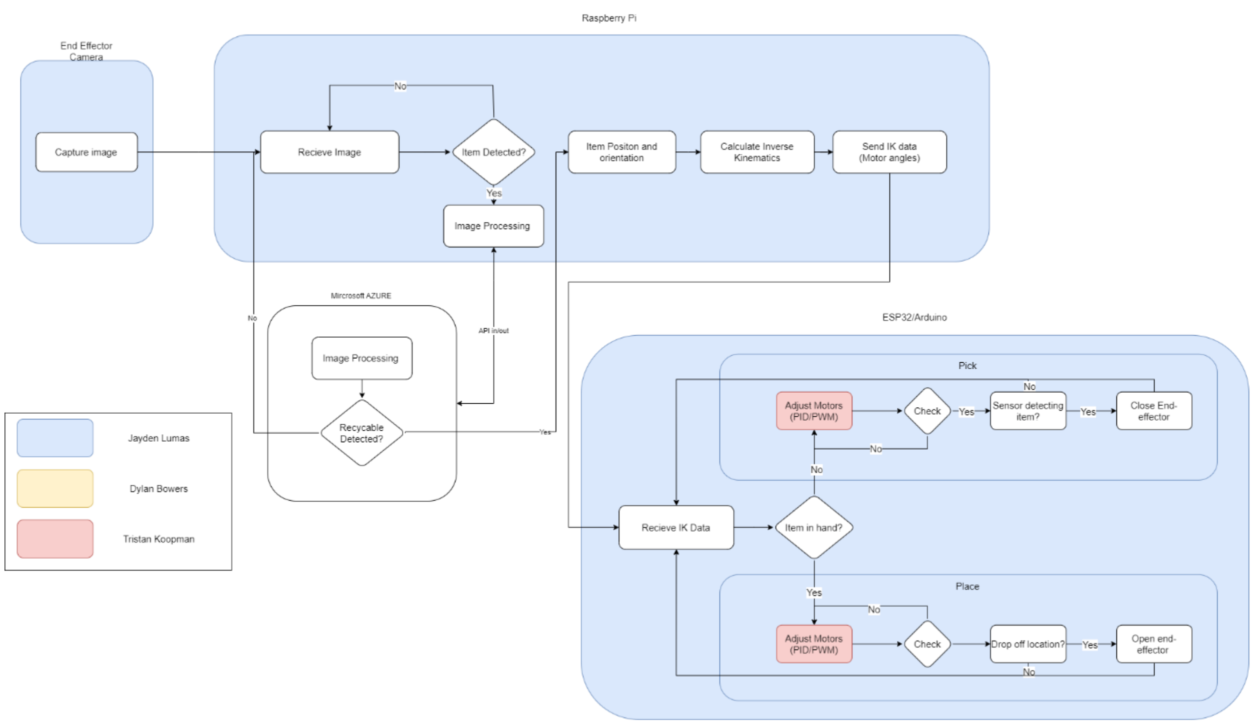


Figure 4. Software Diagram

Illustration

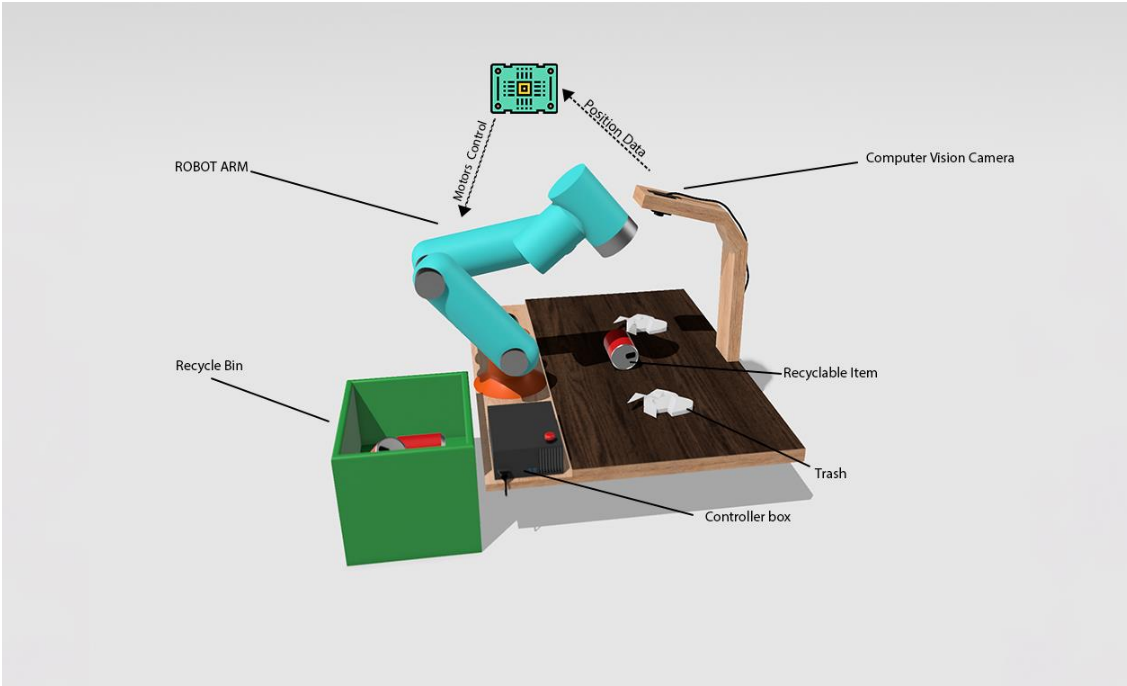
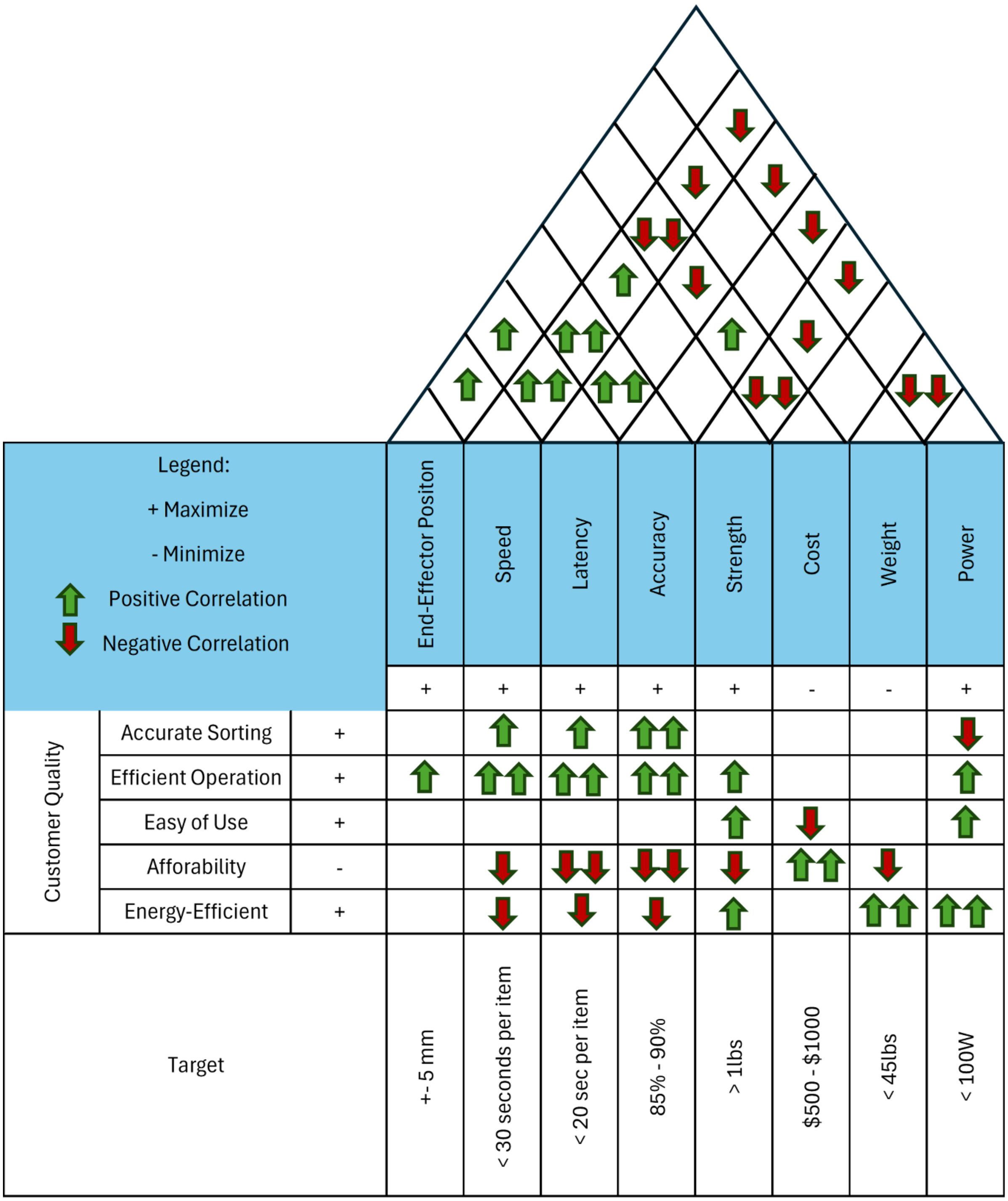


Figure 5. System Illustration

House of Quality



Budget

Table 2. Budget allocation for various parts of the project

Sub-System	Budget
PCB and Electricals	$100
Motors and Mechanical Parts	$125
Frame/Robotic Arm Build Materials	$150
Optics and Sensors	$500
Total	$875

Work Distribution and Milestones

Table 3. Senior Design 1: Component Breakdown

SD1 Requirements		
Milestones		Due Date
Midterm Report		3/24/25
Midterm Report Meeting		3/26/25
Revised Report		4/4/25
Final Report Draft / Demo Video		4/14/25
Final Report		4/22/25
Software System		
Component	Assigned to	Time Worked On
Motor Positional data	Tristan	10 days
Motor Home Positions	Tristan, Jayden	7 days
Inverse Kinematics	Tristan	3 days
Data Transfer	Sayed, Tristan	3 days
Computer Vision	Jayden	21 days
Optics Software		
Machine Learning/Artificial Intelligence	Dylan, Jayden	7 days
Position Data	Tristan, Jayden	14 days
Ros	Jayden	14 days
Linear CCD Sensor integration	Dylan	14 days
Library of Spectrum Data	Dylan	10 days

Hardware System		
Component	Assigned to	Time Worked On
Power Supply/Voltage regulators/ Power Requirements	Sayed	2 Weeks
Stepper / Servo Motor Controllers	Sayed	4 Days
Microcontroller	Sayed	1 Week
Raspberry Pi	Sayed	1 Week
Communication system	Sayed	3 days
Breadboard prototype	Sayed	2 Weeks
Linear CCD Sensor Driver -> Rasbery pi	Dylan, Sayed	3 days
PCB Schematic		3 Weeks

Mechanical System		
Component	Assigned to	Time Worked On
Base	Tristan	5 Days
Hardware Storage	Tristan	3 Days
Linkages	Tristan	14 Days
End Effector	Tristan	10 Days
Support Structure	Tristan	7 Days
Wire Housing	Tristan	5 Days
Optics Housing	Tristan	7 Days
Simulations		
FEA: Stress Analysis	Tristan	14 Days
MATLAB Motion Simulation	Tristan	10 Days

Optical System		
Component	Assigned to	Time Worked On
ZEMAX Design	Dylan	21 days
Objective Lens	Dylan	2 days
Pin hole	Dylan	2 days
Concaved Mirrors 1	Dylan	2 days
Concaved Mirrors 2	Dylan	2 days
Grating diffraction	Dylan	5 days
Linear CCD Sensor	Dylan	10 days
System Alignment	Dylan	14 days
Collection of Sample Data	Dylan	10 days

** Design Complete, Manufacturing Incomplete*

Table 4. Senior Design 2: Component Breakdown with work Distribution

SD2 Requirements		
Milestones		Due Date
Subsystems integration		TBD
PCB Assembly		TBD
Testing and Adjustments		TBD
Final Testing		TBD
Final Presentation/Demo		TBD
Final Paper		TBD
Software System		
Component	Assigned to	Time Worked On
Motor Positional data	Tristan	5 days
Motor Home Positions	Tristan, Jayden	10 days
Computer Vision	Jayden	14 days
Optics Software		
Machine Learning/Artificial Intelligence	Dylan, Jayden	7 days
Position Data	Tristan, Jayden	14 days
Ros	Jayden	7 days
Library of Spectrum Data	Dylan	21 days
Hardware System		
Component	Assigned to	Time Worked On
Design PCB Layout	Sayed	1 Week
Finalize PCB Layout	Sayed	2 Weeks
PCB Assembly	Sayed	1 Week
PCB Testing & Redesign	Sayed	3 Weeks
Final Testing and assembly	Sayed	3 Weeks
Mechanical System		
Component	Assigned to	Time Worked On
Base	Tristan	7 Days
Hardware Storage	Tristan	5 Days
Linkages	Tristan	14 Days
End Effector	Tristan	21 Days
Support Structure	Tristan	7 Days
Wire Housing	Tristan	5 Days
Optics Housing	Tristan	12 Days
Simulations		
FEA: Stress Analysis	Tristan	5 Days
Optical System		
Component	Assigned to	Time Worked On

Linear CCD Sensor Optimization	Dylan	5 days
Improve system alignment	Dylan	7 days
Pin Hole Optimization	Dylan	10 days
Collection of Sample Data	Dylan	14 days

* *Optimization*

Appendix A – References

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