

Tracking Recyclables Automated Sorting Hand (T.R.A.S.H.)

Group 7 Authors:

Dylan Bowers

Sayed
Almousawi

Jayden
Lumas

Tristan
Koopman

*Photonics
Engineering*

*Electrical
Engineering*

*Computer
Engineering*

*Mechanical
Engineering*

Advisors:

Dr. Lei Wei

Dr. Chung
Yong Chan

Dr. Arthur
Weeks

Dr. Aravinda
Kar

Committee Members:

Dr. Behal

ECE

Professor

Dr. Delfyett

CREOL

Professor



UNIVERSITY OF
CENTRAL FLORIDA

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1.0 Executive Summary

A common fear among United States of America citizens is that the rise in robotics technology spells the end of the common laborer. The speculation among most is that with industrial robots fulfilling menial tasks, many hard-working citizens will be left without jobs. However, the more significant threat to the United States is not labor shortage, but rather laborer shortage. Since 1963, the world's births per woman have steadily declined from 5.32 to 2.27 in 2022. In the United States specifically, the birth per woman has gone from 3.32 to 1.66 [1]. This is concerning because to sustain a stable population, the total fertility rate needs to be 2.1 births per woman [2].

With severe laborer shortages and an aging population expected to hit the United States, automation is needed to avoid an economic disaster. One area that stands to benefit greatly from automation is the waste management industry. Historically, plastic waste needed to be sorted by hand from a conveyor line into designated recycling bins, requiring significant manual labor, which is becoming difficult to sustain. With the advancements in industrial robotics, the industry has seen some integration of automated sorting systems. However, these systems are generally large and hazardous machinery, moving in areas that are not safe for human workers and can be quite expensive. The TRASH project aims to provide a safe, affordable, and efficient automated solution for identifying, acquiring, and sorting recyclable waste products from other than recyclable waste.

The TRASH project focuses on the development of a robotic arm capable of sorting recyclable waste. The 6-degree-of-freedom (6DOF) robotic arm will be integrated with a system that utilizes computer vision and optical sensors to identify and acquire recyclable materials from waste. This innovation will provide a safer alternative to traditional sorting methods, reducing the need for manual labor and increasing the efficiency of waste processing at an affordable price, available to local waste management companies.

The integration of computer vision and spectroscopy systems will contribute to making our robot fully automated by adding the ability to detect the material and obtain its location without any human interaction needed. This will be in addition to a touch display user interface used to force any commands wanted or check the status of the machine.

2.0 Project Description

In this section, the motivation and background of the project are discussed.

2.1 Project Motivation and Background

The primary motivation behind the TRASH project is the growing laborer shortage and the efficiency of waste management. As the American population steadily decreases with a fertility rate that is unable to sustain its population size, robotics are needed more than ever. With the implementation of robotics, human resources can be allocated more efficiently as fewer workers are needed to take care of a larger population unable to work. While there are many advances in the realm of home care robotics, there are a slew of safety concerns, and more advancements are needed before implementation can even be considered a widespread practice. However, the industrial environment requires little to no human interaction and much less complicated environments, with many industrial robotics systems using fixed programmed systems.

Additionally, as America has become sustainment-oriented, the waste industry requires more workers in order to maintain the green initiative. Therefore, there exists an increased number of workers whose only purpose is to pick up and sort recyclables from garbage. These simple tasks can and have begun to be automated in order to free up human resources for more complex tasks that require human engagement.

2.2 Project Goals

TRASH aims to address these challenges by developing a 6DOF pick and place robot arm capable of identifying, acquiring, and sorting recyclables from non-recyclable waste. TRASH will be as lightweight as possible in order to decrease the cost of materials and actuators. It will utilize a combination of computer vision and optical systems for onboard material identification, allowing ease of integration for the robot into an already-existent system and item positioning.

2.2.1 Basic Goals

For our robotic arm, we have a set of basic goals that our project will achieve. As a group, we have determined these goals to be fundamental capabilities required for TRASH. At its most basic level, TRASH will be able to detect the positional data of a plastic bottle among trash using optical and computer vision techniques. After identifying the position and material data, the robot arm will be able to grab and relocate the recyclable item to its respective bin.

Base Goals		
Identification		
Identify 12oz Green Glass Bottle	Yes	Y/N

Detect Item Position Accuracy	80	%
Detect 5 Items Presented to Robot	Yes	Y/N
Material Identification Accuracy	80	%
Identification Time	30	sec
Motion		
Minimum Payload	100	grams
End Effector Target Positioning Tolerance	5	mm
Motion Time	1	min
Voltage Input	120	VAC

Table 1: Basic Goals

2.2.2 Advanced Goals

Our Advanced Goals reflect the ideal outcome for TRASH, demonstrating enhanced functionality and performance. For our advanced goals, TRASH has better performance criteria and a larger library of identifiable materials, not limited to just plastic bottles, which is achieved by increasing spectrometer spectrum resolution. Additionally, TRASH will incorporate an interface to give users a real-time camera feed.

Advanced Goals		
Identification		
Identify Cardboard and Aluminum	Yes	Y/N
Detect Plastic Bottle Position	90	%
Detect 6+ Items Presented to Robot	Yes	Y/N
Material Identification Accuracy	90	%
Identification Time	20	sec
Motion		
Minimum Payload	500	grams
End Effector Target Positioning Tolerance	3	mm
Motion Time	45	sec
Max Power Consumption	150	W
Added Functionality		
UI with Real-Time Camera Feed	Yes	Y/N

Table 2: Advanced Goals

2.2.3 Stretch Goals

For TRASH to exceed all expectations, it will achieve its stretch goals. The stretch goals are best-case scenario circumstances that we will try to achieve. For our stretch goals, we aim to improve upon some criteria related to time and accuracy. We also look to integrate systems that improve the efficiency and overall package of the robotic arm. Include the optical fiber integrated into the end effector, allowing for quick material identification without the need to move an item to the spectrometer only to return nonrecyclables back to where they were picked.

Stretch Goals		
Identification		
Identify 4+ Recyclable Items	Yes	Y/N
Detect Item Position Accuracy	80	%
Inventory Items into Database	Yes	Y/N
Material Identification Accuracy	80	%
Identification Time	10	sec
Motion		
Minimum Payload	1	kg
Motion Time	30	sec
PCB Layout Footprint	432	in ³
Added Functionality		
UI Displays Number of Recyclables	Yes	Y/N
Conveyor Belt System	Yes	Y/N
Integrated Optical Fiber	Yes	Y/N

Table 3: Stretch Goals

2.3 Project Objectives

The objective of the TRASH 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. The main objectives of the TRASH project include

1. **Development of a Robotic Arm:** Design and build a lightweight, cost-effective robotic arm that can accurately perform waste sorting tasks with high precision.
2. **Integration of Computer Vision and Optical Systems:** Use computer vision and optical sensors to allow the robot to identify recyclable materials based on their light reflectance characteristics and machine learning, ensuring accurate sorting.
3. **Increased Efficiency:** Improve the efficiency of waste management by automating a process that is typically labor-intensive, freeing human workers for more complex tasks.
4. **Cost-Effective Solution:** Minimize costs by using lightweight materials for the robot's construction and choosing efficient actuators and components.
5. **Seamless Integration:** Ensure the TRASH robot can be easily integrated into current waste management workflows and systems without requiring major infrastructure changes.

2.4 Specifications and Engineering Requirements

As a part of our design requirements, we have presented below in Table 4 and Table 5 our deliverable specifications.

Specification	Target Value	Units
Object Detection Time	20	sec
Total Pickup Time	30	sec
Pickup Accuracy	± 5	mm
Min. Payload	100	g
Arm Degrees of Freedom	6	DOF
Power Consumption	≤ 350	W
Power Supply	120	VAC
Computer Vision	1	camera
Material Identification	At least 2	Materials

Table 4: Engineering Requirements

Specification	Target Value	Units
Slit Width	$8 \leq x \leq 40$	μm
Spectral Resolution	< 20	nm
Lens Focal Distance	100	mm

Table 5: Optics Specifications

2.5 Function of Project

TRASH will be able to orientate its position on the initial startup. From there, TRASH will locate all available items. It will then identify what the material of the items seen are and classify the items as recyclable or not recyclable. If an item is recyclable, the item will be placed in a designated bin. All other items will be left for waste disposal. TRASH will use 6 degrees of freedom in order to allow full manipulation of all items regardless of orientation.

2.6 Illustration

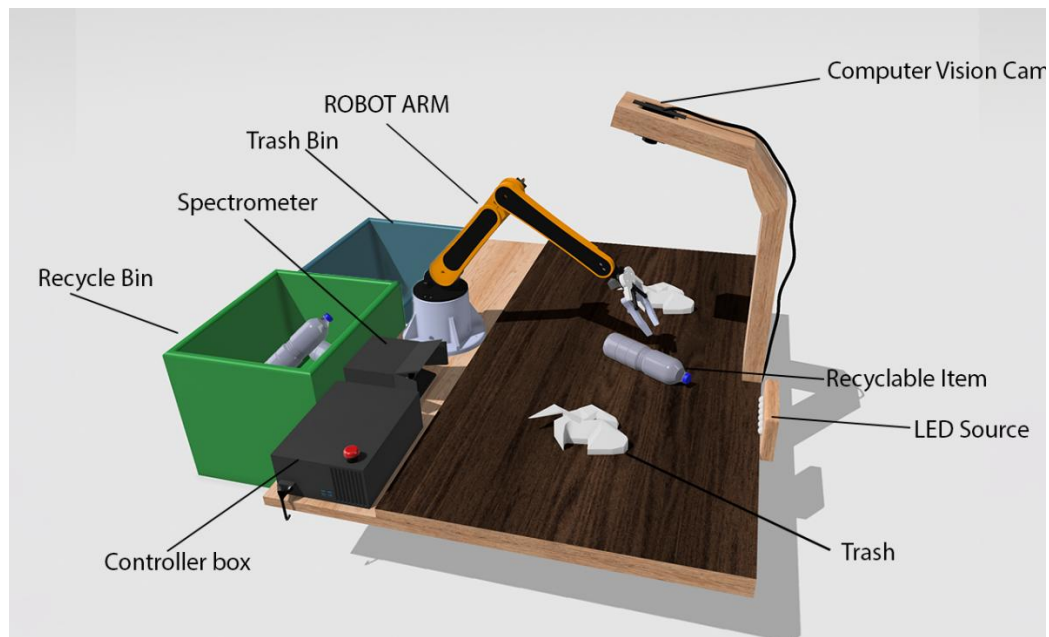


Figure 1: TRASH Concept Illustration

Figure 1 represents a simple 3D illustration of the TRASH concept design we would like to have by the end of this project. The design is not finalized or accurate at this point. The robot arm used in this illustration does not represent the actual design of the arm. This was just a simple free robot arm design downloaded from the internet to support our illustration. The spectrometer system shown is the basic idea of what it would be like. A spectrometer box is mounted next to the arm while a bunch of LED lights are shined on its lens from the opposing side of the base. The robot arm would then place an item in between the LED lights and the box to determine the item's material.

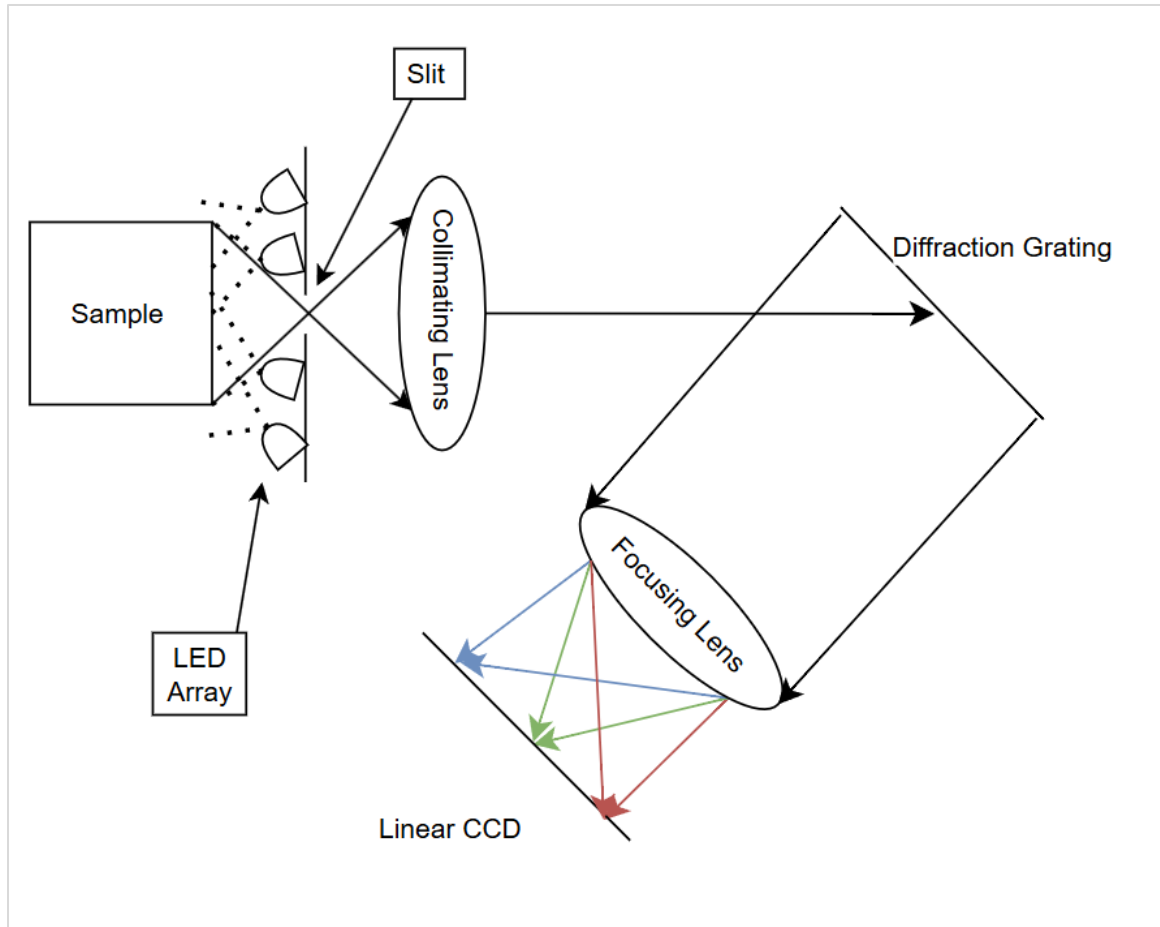


Figure 2: Spectrometer Diagram

Figure 2 serves as a simple reduction of the final design. The samples is illuminated by a array of LEDs which can be a combination of WLEDs and IR LEDs to ensure to illuminate the spectral range from 400nm to 1100nm. A reflection-based diffraction grating will be used with a blazed wavelength of 1000nm to compensate for the drop of responsivity of the silica-based detector. The samples that are going to be tested are discussed in length in the recycled material portion of the paper; however, sample can include, glass bottles, aluminum cans, and plastic materials.

2.7 Hardware Diagram

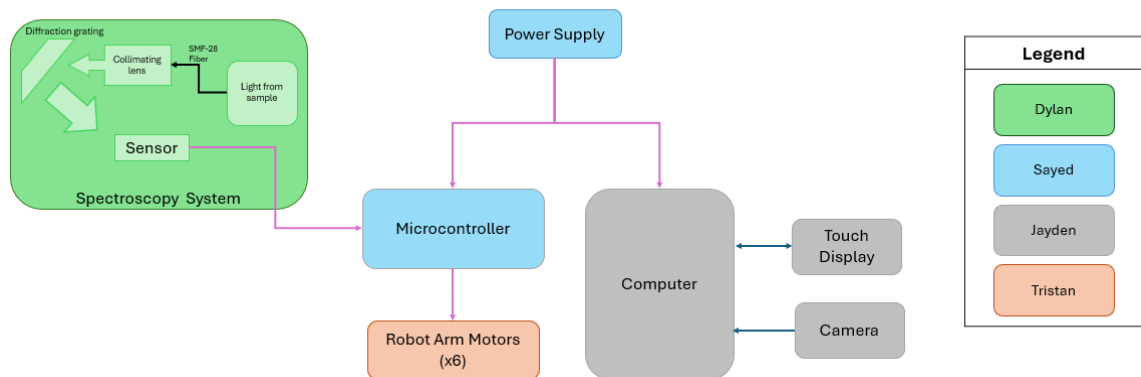


Figure 3: Hardware Block Diagram

Status of each block:

- Power Supply: Researched and designed
- Microcontroller: Researched and acquired
- Computer: Researched and acquired
- Motors and drivers: Researched, to be acquired
- Touchscreen Display: Researched and acquired
- Camera: Researched, to be acquired
- Spectrometer: Researched and designed (sensor acquired)

2.8 Software Diagram

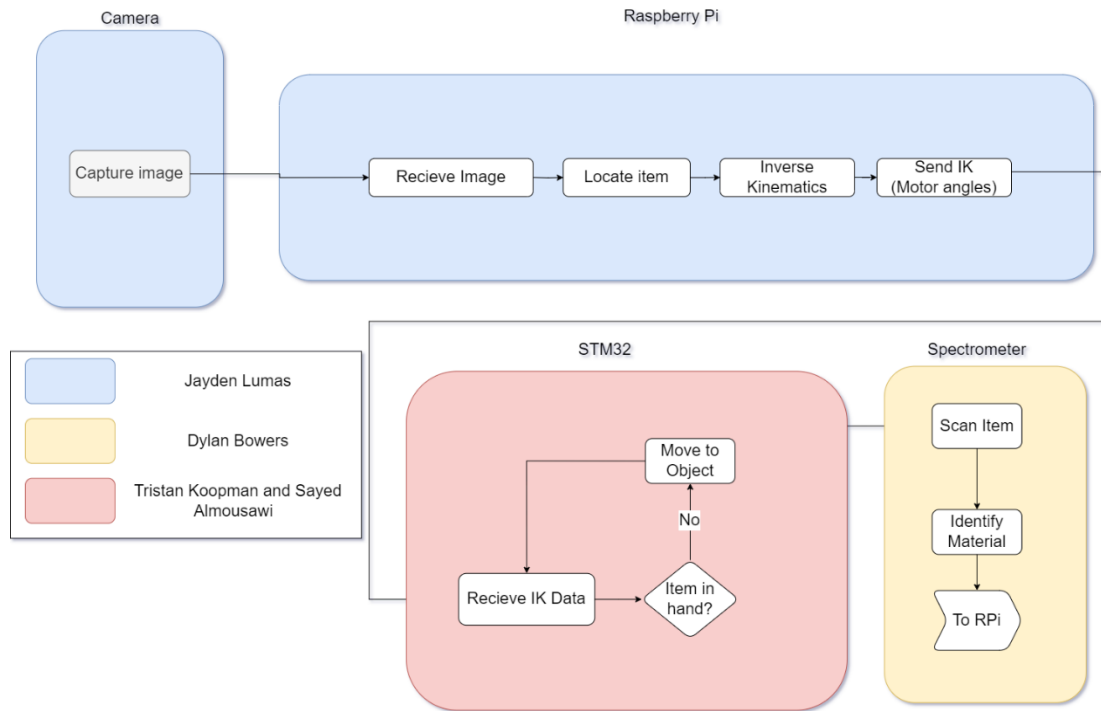


Figure 4. High-Level Software Block Diagram

2.9 House of Quality

This section explains the technical design elements and customer expectations, showing how the House of Quality (HoQ) shown in Figure 5: House of Quality can be a helpful tool for teams to communicate better. The HoQ acts as a central point, making it clear how design features connect with customer needs

, which makes decision-making more effective. By ensuring the final product or service meets customer expectations, the HoQ is important for keeping time and resources are focused on areas of importance.

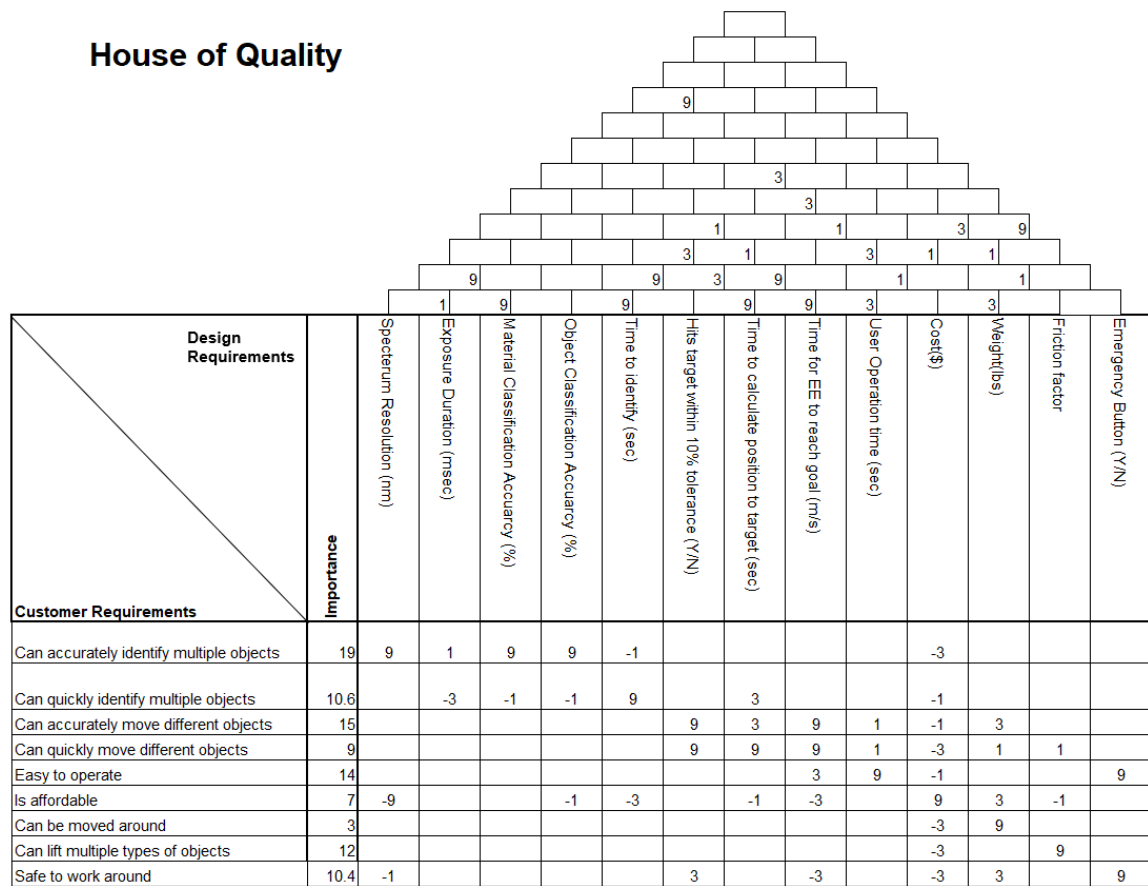


Figure 5: House of Quality

2.10 Existing Products and Past Projects

Descriptions to be written...

2.10.1 Compact Automated Waste Sorter – UCF Fall2021 G1

Descriptions to be written...

2.10.2 Annin Robotics AR4 6DOF Robot Arm

Descriptions to be written...

3.0 Research

In the following sections we will discuss the foundational research developed that influenced our final designs.

3.1 Torque Estimations

By providing the Torque Estimations for the TRASH robot we are able to get a better understanding of the requirements and limitations of the robot. From these baseline estimations, we are able to provide a holistic understanding of the cost breakdown required for the robot and insight into the weight requirements needed throughout the robot arm. These estimations are directly used in 3.7 Motors and 3.2 Linkage Structure.

3.1.1 Procedure

Determining a preliminary estimate of the torque requirements, firstly, involves making a slew of assumptions. The purpose of these assumptions are to provide a baseline for which we can calculate torque requirements. These assumptions are designed to be an over-exaggeration of what the real prototype design will be. This is done to simplify calculations and to allow room for design. Additionally, by creating these assumptions with outstanding values, we are able to make practical purchasing decisions that require us to assume and investigate more expensive and robust technologies. However, after our prototype designs are finalized and we revisit the necessary torque requirements for the robot arm, we will either be on track with our initial estimates or we will be well below our margins and in a situation where we are under budget rather than over budget.

The assumptions that were made take the loadings in the worst-case scenario. (1) We assume that the arm is purely horizontal, creating the largest moments at the base of each linkage. In practice, the arm will rarely be fully extended. (2) To account for the linkage weight, we assume that the support structure is a solid aluminum rod with a $\frac{1}{2}$ inch diameter and lengths of 7 inches. In actuality, an aluminum rod is an overkill for accounting for the internal loadings flowing through the support structure, and if an aluminum rod is being used, it will likely be hollowed out. (3) To account for the connection mechanism connecting the linkages to each other, we assume the connector is a solid cube of 2 inches at 100% infill PETG at each end of the 2 linkages. In actuality, the connector will be far more complicated than a cube and will likely span a larger surface area than 2x2x2. However, the connector will be at most 20% infill and will comprise of mechanisms that have spacings between them. (4) To account for possible gears to adjust gear ratios, we assume a singular cylinder of 1in diameter, $\frac{1}{2}$ in thickness, and 100% infill PETG. In actuality, the gears in use, if used, will be at most 30% infill and will likely be much smaller. (5) In order to account for the weight of the end effector at the end of the robot, we assume the End Effector (EE) is 3 linkages of 2in x $\frac{1}{2}$ in x 1in at 100% infill PETG. In actuality, the EE will be much more complicated than 3 rectangular linkages and has the possibility of spanning a larger workspace, however, the EE will have at most a 20% infill. (6) In order to account for the weight of the motors, we assume that each motor is placed at the

intersection of the linkages and weighs 0.2 lbs. In actuality, the weight of the motors will decrease further from the base we travel. (7) to account for the workspace of the wrist, we assume that the length of the wrist is $\frac{1}{2}$ in. However, the size of the wrist is unknown. (8) The final assumption is that the arm is holding 2 lbs at the end of the EE. In actuality, we are only required to hold 1 lb of weight with the EE. Additionally, it would be poor practice for the robot to grab items with the tips of the EE rather than at the center of the gripper. This excess weight serves to round off the numbers, providing an additional Factor of Safety (FS), and allows the option of including other, more complicated means of acquiring objects.

Name	Accounting	Assumption	Reality
(1) Arm Position	Worst Case position	Worst-case position is horizontal & fully extended	Arm will rarely be at this position.
(2) Support Structure	Weight of the Support Structure	Solid aluminum rod $\frac{1}{2}$ in $\varnothing$ x 7in. for 2 linkages	Lighter material; if else: rod will be hollow
(3) Connectors	Weight of connection mechanism of linkages	2in x 2in x 2in 100% infill PETG at each end of 2 linkages	Larger area, more spacing, $\leq 20\%$ infill
(4) Gears	Weight of gear trains	1in $\varnothing$ x $\frac{1}{2}$ in 100% infill PETG at each joint	May not be used, if used, likely smaller, $\leq 30\%$ infill
(5) End Effector	Weight of EE	3 linkages of 2in x $\frac{1}{2}$ in x 1in 100% infill PETG	More complicated, larger workspace, $\leq 20\%$ infill
(6) Motors	Weight of motors	Placed at each joint, weighs 0.2lbs	Weight of motors will decrease further from base
(7) Wrist	Size of the wrist workspace	Length is $\frac{1}{2}$ in	Length is unknown
(8) Object	Weight of item being acquired	Object weighs 2lbs	Only required to lift a 1lb object, not at tip of EE

Table 6 Robot Arm Weight Assumptions

Linkage Lengths	
x1	7 in
x2	7 in
x3	0.5 in
x4	2 in

Table 7: Prototype Arm
Dimensions: Length of linkages

Linkage Connectors	
l	2 in
w	2 in
h	2 in

Table 8: Prototype Arm
Dimensions: Connector

Motor Weights	
M1	0.2 lb
M2	0.2 lb
M3	0.2 lb
M4	0.2 lb
M5	0.2 lb
M6	0.2 lb

Table 9: Prototype Arm
Dimensions: Weight of Motors

Rods	
Radius1	0.25 in
Radius2	0.25 in

Table 10: Prototype Arm
Dimensions: Rod

End Effector Dimensions	
l	2 in
w	0.5 in
t	1 in

Table 11: Prototype Arm
Dimensions: EE

Gear	
Radius	0.5 in
Depth	0.5 in

Table 12: Prototype Arm
Dimensions: Gear

3.1.2 Calculations

Step 1: Calculate the different loads being acted upon the robot arm.

For calculating the weight of the rod, first we need to calculate the volume of the rods. The formula for calculating the volume of a rod is given in (3.1).

$$V_r = \pi r^2 h \quad (3.1)$$

Substituting the values of the linkage from Table 10: Prototype Arm Dimensions: Rod into (3.1) gives

$$V_{r1} = V_{r2} = \pi(0.25in)^2(7in) = 1.37in^3$$

The aluminum rod being used is an Everbilt 1/2 in. x 3 ft. Aluminum Solid Round Rod Extruded with aluminum alloy 6063-T5. Aluminum alloy 6063-T5 has a material density of $\rho = 0.0975 \text{ lb/in}^3$ [3].

Using the calculated volume and the provided density, we calculate the weight of each rod using (3.2).

$$W_r = V_r \rho_A \quad (3.2)$$

$$W_r = (1.37in^3) \left(0.0975 \frac{\text{lb}}{\text{in}^3} \right) = 0.134\text{lb}$$

By repeating these steps and using Table 12: Prototype Arm Dimensions: Gear we are able to calculate the volume and weight of the gear.

$$V_G = \pi r^2 h \quad (3.1)$$

$$V_G = \pi(0.5)^2(0.5) = 0.393in^3$$

PETG is used as it has a higher density compared to PLA, providing an additional increase in FS. The density for Overture PETG (a common and reliable brand) is given as $\rho = 1.25 \text{ g/cm}^3$, which converts to 0.04516 lb/in^3 [4].

$$W_G = V_G \rho_{PETG} \quad (3.2)$$

$$W_G = (0.393in^3) \left(0.04516 \frac{lb}{in^3} \right) = 0.0177lb$$

Next, using Table 8: Prototype Arm Dimensions: Connector we will calculate the connectors that will be located at the end of each linkage using Overture PETG,

$$V_C = lwh \quad (3.3)$$

$$V_C = (2)(2)(2) = 8in^3$$

$$W_C = V_C \rho_{PETG} \quad (3.2)$$

$$W_C = (8in^3) \left(0.04516 \frac{lb}{in^3} \right) = 0.361lb$$

Repeating the same steps with Table 11: Prototype Arm Dimensions: EE and the same material, we are able to calculate the weight of the EE;

$$V_{EE} = lwh \quad (3.3)$$

$$V_{EE} = (2)(0.5)(1) = 1in^3$$

$$W_{EE} = V_{EE} \rho_{PETG} \quad (3.2)$$

$$W_{EE} = (1in^3) \left(0.04516 \frac{lb}{in^3} \right) = 0.04516lb$$

After calculating the applied loads, we can now apply the calculated loadings along the arm. Because the weight of each segment is a uniformly distributed loading applied equally across the surface area, we are able to take the resulting load and calculate it at the centroid of the segment. Thus simplifying our calculations.

Step 2: Calculate Moments

In order to calculate the standing torque required of the motors, we must calculate the moments created at the motor positions by the applied loadings. To do this, we will apply the sum of moments **Error! Reference source not found.** at each motor location to calculate the resulting moment acted upon by the motor by the various loadings starting from the motor furthest from the base.

$$\sum M = 0 = Fx \quad (3.4)$$

There are 6 motors in this design. One providing rotational movement of the entire arm assembly, one motor providing motion to each of the two linkages, and 3 motors comprising the wrist and gripper motion. For the purposes of determining static torque, only motors 2-6 need to be considered. It is important to note that for simplicity of calculations, Motors 5&6 are coincident with each other at the centroid of the wrist mechanism.

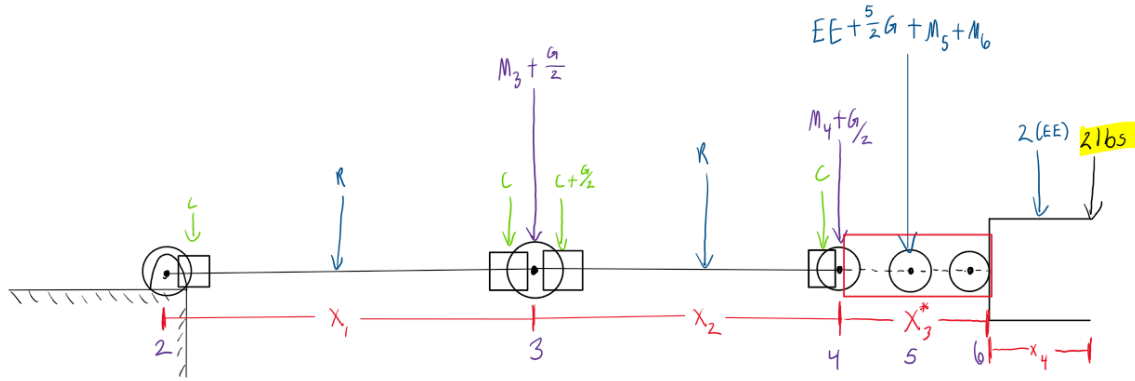


Figure 6 Free Body Diagram

For Motors 5&6, these motors must support the weight of the object being held, along with the two pincers of the EE. Thus, the Moment equation is as follows:

$$\sum M_{5,6} = 0 = -(2lb)\left(\frac{x_3}{2} + x_4\right) - 2(W_{EE})\left(\frac{x_4}{2} + \frac{x_3}{2}\right) \quad (3.5)$$

Motor 4 includes the same loadings as Motors 5&6 with increased offset distance, along with the inclusion of the full wrist mechanism.

$$\begin{aligned} \sum M_4 = 0 = & -(2lb)(x_3 + x_4) - 2(W_{EE})\left(x_3 + \frac{x_4}{2}\right) \\ & - (W_{EE} + \frac{5}{2}W_G + W_{m_5} + W_{m_6})\left(\frac{x_3}{2}\right) \end{aligned} \quad (3.6)$$

Motor 3 includes all of motors 4-6, along with the second rod and respective connectors.

$$\begin{aligned}
\sum M_3 = 0 = & -(2lb)(x_2 + x_3 + x_4) \\
& - 2(W_{EE})\left(x_2 + x_3 + \frac{x_4}{2}\right) \\
& - \left(W_{EE} + \frac{5}{2}W_G + W_{m_5} + W_{m_6}\right)\left(x_2 + \frac{x_3}{2}\right) \\
& - \left(W_{m_4} + \frac{W_G}{2}\right)(x_2) - (W_C)\left(x_2 - \frac{C_l}{2}\right) \\
& - (W_R)\left(\frac{x_2}{2}\right) - (W_C + \frac{W_G}{2})\left(\frac{C_l}{2}\right)
\end{aligned} \tag{3.7}$$

Motor 2 includes all of motors 3-6, along with the first rod and respective connectors.

$$\begin{aligned}
\sum M_3 = 0 = & -(2lb)(x_1 + x_2 + x_3 + x_4) \\
& - 2(W_{EE})\left(x_1 + x_2 + x_3 + \frac{x_4}{2}\right) \\
& - \left(W_{EE} + \frac{5}{2}W_G + W_{m_5} + W_{m_6}\right)\left(x_1 + x_2 + \frac{x_3}{2}\right) \\
& - \left(W_{m_4} + \frac{W_G}{2}\right)(x_1 + x_2) \\
& - (W_C)\left(x_1 + x_2 - \frac{C_l}{2}\right) - (W_R)\left(x_1 + \frac{x_2}{2}\right) \\
& - \left(W_C + \frac{W_G}{2}\right)\left(x_1 + \frac{C_l}{2}\right) \\
& - \left(W_{m_3} + \frac{W_G}{2}\right)(x_1) - (W_C)\left(x_1 - \frac{C_l}{2}\right) \\
& - (W_R)\left(\frac{x_1}{2}\right) - (W_C)\left(\frac{C_l}{2}\right)
\end{aligned} \tag{3.8}$$

Plugging in values to equations **Error! Reference source not found.**, (3.6), (3.7) and (3.8) from Table 7, Table 9, and Table 11 along with the weights calculated previously, we get the following minimum static torque requirements:

$$T_6 = T_5 = 52.12 \text{ Ncm}$$

$$T_4 = 59.41 \text{ Ncm}$$

$$T_3 = 313.93 \text{ Ncm}$$

$$T_2 = 653.32 \text{ Ncm}$$

3.2 Linkage Structure

In order to optimize the weight efficiency of the robot arm, special attention and research is conducted into the linkage structure.

3.2.1 Material Selection

A critical factor in the design of a robot arm structure is the material. For any robot weight is a limiting factor directly affecting the resulting success or failure of the robot. In the case of a robot arm, this fact is painfully obvious. After calculating the Torque Estimations in Calculations we see that any weight acted at the end of a moment arm. For this reason, it is critical that we choose a material that is extremely lightweight. Additionally, when analyzing the force acting on our robot arm, we realize that the only stress acting upon the linkages is bending, as there are rare instances when the robot's arms will experience compression, tension, or torsional stress. However, by analyzing Figure 6 Free Body Diagram, we see that bending stress is a crucial case we need to consider. Cost is the final consideration, as seen in Table 13: Concept Alternatives – Material Selection.

The material being compared will be investigated based on the criteria from Table 13: Concept Alternatives – Material Selection. Weight will be evaluated based on density (g/cm^3) as it is not dependent on the volume of the material. This is important because for materials with higher Bending Stiffness and Strength the volume will decrease. Bending stiffness will be determined based on Young's Modulus, which is "The ratio of stress to strain when deformation is totally elastic; also a measure of the stiffness of a material" [3]. Bending Strength can be represented as either Tensile Strength or Yield Strength. Tensile Stress involves plastic deformation, whereas Yield Strength is the highest point before deformation [3] we will use Yield Strength for our application. The cost will be represented in US Dollars.

		Concept Alternatives							
		Aluminum		Carbon Fiber		Steel		PETG	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Light Weight	35%	2	0.70	4	1.40	2	0.70	4	1.40
Low cost	25%	4	1.00	1	0.25	3	0.75	4	1.00
High Bending Stiffness	20%	2	0.40	3	0.60	4	0.80	1	0.20
High Bending Strength	20%	2	0.40	4	0.80	3	0.60	1	0.20
Totals	100%		2.50		3.05		2.85		2.80
Rating	Value								
Unsatisfactory	0								
Just Tolerable	1								
Adequate	2								
Good	3								
Very Good	4								

1. Importance weights assigned
2. Team rates each concept 0 to 4
3. Multiply rating X importance
4. Sum weighted ratings

Table 13: Concept Alternatives – Material Selection

As seen from the Table above, based on the Importance Weight given the previously mentioned criteria, Carbon Fiber material will be used for the robot arm linkages.

3.2.1.1 Aluminum

Aluminum is an obvious candidate for the material of the support structure as it is an abundant resource commonly used in engineering for its light weight and adequate material properties. There are multiple types of Aluminum Alloys used in manufacturing. However, we will be comparing them with Annealed 6063-T5 as it is common and readily available.

Aluminum is one of the lighter metals that is commonly used in manufacturing, with a density of only around 2.70 (g/cm³) [3]. Aluminum also has decent strength with a Modulus of Elasticity of 69 GPa and a Yield Strength of 55 MPa [3]. It is due to its lightweight properties, decent strength, and simple manufacturing that it is commonly used in transportation.

3.2.1.2 Carbon Fiber

Carbon fiber has become a trend in the materials industry. It is rare to find college and home projects alike that do not use some form of carbon fiber element. Carbon fiber has become a buzzword in the same way Artificial Intelligence has, and for good reason. Carbon fiber is an extremely challenging material to quantify and measure. Therefore, for simplicity, we will be using “Materials Science and Engineering” by Callister and Rethwisch [3] analysis of “Standard Carbon Fiber”.

Carbon Fiber is composed of layers of interwoven strands of carbon filament cured in resin prepreg creating a rigid structure from molds or casts. Carbon fiber is relatively light weight with a density of $1.6 \text{ (g/cm}^3\text{)}$. However, with a strength comparable to steel, much less material is needed to perform engineering applications. In comparison, steel, with a Modulus of Elasticity of 207 GPa has a density of $7.85 \text{ (g/cm}^3\text{)}$. Standard Carbon Fiber has a Modulus of Elasticity of 145GPa, meaning Carbon Fiber has more than a 3 times strength to weight ratio. Carbon fiber is a brittle material and therefore does not have a yield strength. However, its Tensile Strength is 1240 MPa making it an extremely effective and weight efficient material. However, with so many benefits there comes a cost, and that cost is monetary. While manufacturing practices for carbon fiber have improved drastically, it still costs more for less material.

3.2.1.3 Steel

Steel is a common material used in engineering applications for its pure strength. Very common material for robotics, still can be seen in most industrial robotic arms, a field with which our project is looking to enter. For simplicity we will be making our comparison with Hot-rolled Steel alloy A36 [3].

For industrial robot arms that are doing precise motion, a common issue arises in the realm of controls. In order to simply fix this issue, roboticists increased the weight of the robot arms in order to decrease the overshoot without compromising rise time. Therefore, most industrial robot arms use titanium and steel which are both heavily and costly to make. However, for our robot arm we are not aiming to solve any controls problems. Steel has a density of $7.85 \text{ (g/cm}^3\text{)}$, a Modulus of Elasticity of 207 GPa, and a yield strength of 220-250 MPa. Due to its high weight-to-strength ratio, Steel is not an option for our robot.

3.2.1.4 PETG

PETG, or Polyethylene Terephthalate, is a common filament used for FDM printing for most hobbyists. Compared to other filaments used, PETG has a higher Yield and Tensile strength with a slightly increased weight. For purposes of comparing to the other materials, we will be referencing Overture PETG [4] as it is a well-known and used brand.

PETG is a lightweight material with a density of $1.25 \text{ (g/cm}^3\text{)}$. FDM manufacturing is also an extremely easy and efficient method for manufacturing custom and complex pieces. However, with a Young's Modulus of 1986 MPa and Tensile strength of 44.3 MPa, it is orders of magnitude weaker than other materials. It is also a very unreliable material as slight alterations to nozzle temperature, bed temperature, humidity, and speed can all affect the quality of the material. Meaning the material can likely fail at a much lower loading.

3.2.2 Linkage Cross-Section

Now that we have determined Carbon Fiber is the best choice for material, the next question is what cross-section will be best for our robot arm. Because carbon fiber is very costly to

get custom-shaped, the only options being considered are cross sections that are most commonly produced. These cross-sections are rods, tubes, and plates/brackets.

		Concept Alternatives					
		Rod		Plates		Tube	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Hardware	30%	4	1.20	2	0.60	3	0.90
Volume	25%	2	0.50	4	1.00	4	1.00
Modularity	25%	4	1.00	2	0.50	4	1.00
Joint Interface	20%	3	0.60	4	0.80	3	0.60
Totals	100%		3.30		2.90		3.50
Rating	Value						
Unsatisfactory	0						
Just Tolerable	1						
Adequate	2						
Good	3						
Very Good	4						

1. Importance weights assigned
2. Team rates each concept 0 to 4
3. Multiply rating X importance
4. Sum weighted ratings

Table 14: Concept Alternatives – Linkage Cross-Section

3.2.2.1 Rod

Rods are very commonly manufactured; however, because of their manufacturing method and increased volume, they are much more expensive compared to other cross-sections like plates or tubes. The circular design does allow for cusps to be screwed onto the outside of the rod. Because these cusps are friction fit, it also allows for easy swapping of different modules. The joint interface of the linkage is not ideal. The adhesive would be the best method for securing the linkage to the joint adaptor. However, this would be permanent and would not allow for a redesign without the need to purchase more rods. Therefore, friction-fit adaptors will be needed in order to allow retrofits.

3.2.2.2 Plates and Brackets

Plates are much easier to manufacture and, therefore, much cheaper. They can also be manufactured very thin and, therefore, have a much lower volume compared to rods. The commonly manufactured brackets also provide a very simple and replaceable method for connecting to the joint interface. However, for modularity, in order to add mounts for cables or motors, adaptors will need to be bolted in the plates. This not only degrades the overall strength of the linkage but requires hardware, adding additional weight to the robot arm. Additional hardware is to be avoided.

3.2.2.3 Tubes

Tubes provide the same benefits as rods with the reduced volume. Tubes are another very commonly manufactured structure and have a much more customizable surface area

without additional weight or unneeded strength. It is for these reasons that the linkages will be made using Carbon Fiber tubes as the base structure.

3.3 Computer Vision (CV)

Computer Vision is an essential component of modern robotic systems, enabling machines to perceive and interpret visual information for enhanced automation and efficiency. By utilizing advanced image processing techniques, computer vision allows robots to detect, classify, and interact with their environment with high precision. In waste recycling, this capability is crucial for accurately identifying and sorting materials, reducing reliance on manual labor, and improving overall system sustainability.

For the T.R.A.S.H. project, computer vision serves as the foundation for workspace visualization and object detection. Traditional sorting methods are often limited by the need for physical contact or constrained sensing mechanisms. In contrast, a computer vision system provides a holistic view of the sorting environment, allowing the robot to identify, track, and categorize objects before they reach the end effector. This proactive approach streamlines the sorting process and enhances the overall efficiency of our system.

3.6.1 Comparison with Alternative Detection Methods

3.6.1.1 Ultrasound Sensors

Ultrasound sensors operate by emitting high-frequency sound waves and measuring the time delay of the echo after bouncing off an object. These sensors are widely used for distance measurement and obstacle detection due to their low cost and robustness in different lighting conditions. However, despite these benefits, ultrasound sensors present major challenges when applied to our sorting system:

Limited Field of View & Continuous Scanning Requirement: Since ultrasound sensors can only detect objects directly in front of them, the robotic arm would need to continuously scan the entire workspace to locate objects. This is problematic because the arm must actively sweep across the workspace to search for height and distance discrepancies. Additionally, if multiple objects are present, the system may accidentally knock over previously scanned and unscanned items, forcing re-scans and making object tracking unreliable.

Edge Detection and Object Centering Requirement: One of the key limitations of using an ultrasonic sensor is the lack of shape and edge detection. To accurately grasp an object, especially when the end effector and the target object have precise dimensions, the robot would need to scan around the object to determine its edges and overall size. Since ultrasonic sensors only provide single-point distance measurements rather than a full

outline, the system would require additional movement to estimate the center of the object. This adds complexity and reduces the efficiency of the sorting process.

Environmental Interference: Ultrasonic sensors are highly sensitive to environmental conditions that can affect the speed and reliability of sound wave propagation. Variables such as temperature, humidity, and air pressure directly influence the velocity of sound in air, leading to drift in distance measurements over time. When operating over longer periods, these fluctuations can compound, causing the sensor to deliver inconsistent readings across the same workspace. This creates challenges in maintaining accuracy, especially when precision is required for repetitive sorting tasks.

Material Absorption and False Readings: The performance of ultrasonic sensors also depends on how well sound waves reflect off surfaces. Certain materials, such as rubber, foam, and fabric, can absorb sound energy rather than reflect it. When this happens, the sensor may receive weakened or no echo at all, resulting in false, delayed, or entirely missed readings. This poses a serious issue for object detection and sizing, particularly when dealing with mixed-material waste streams where surface properties vary significantly.

Surface Geometry and Precision Limitations: Curved or irregular surfaces, like cylindrical cans or plastic bottles, present another obstacle. Sound waves can be deflected away from the sensor at unpredictable angles, which causes errors in calculating the object's position or shape. Combined with the sensor's inherently low spatial resolution, this limits the robot's ability to reliably identify object boundaries or centers. In applications where precise alignment between the end effector and the object is necessary, these inconsistencies can lead to frequent pickup failures or misclassifications.

Due to these limitations, ultrasound sensors are not ideal for our workspace, as they restrict flexibility, require continuous movement, and struggle with complex object geometries.

3.6.1.2 LiDAR Sensors

LiDAR (Light Detection and Ranging) is a sensing technology that uses laser pulses to measure the distance to objects and generate detailed 3D point cloud maps of the environment. It is commonly used in autonomous vehicles, surveying, industrial automation, and robotic mapping because of its ability to deliver high-resolution spatial data with accuracy. However, despite these capabilities, LiDAR presents several limitations for the T.R.A.S.H. system:

High Cost: LiDAR units are significantly more expensive than other sensing solutions. Even entry-level LiDAR systems often cost hundreds to thousands of dollars, which

exceeds the budget constraints of this project. Since cost-efficiency is a major requirement for T.R.A.S.H., LiDAR is not a financially practical option.

Memory and Processing Demands: LiDAR systems generate dense 3D point clouds that require substantial memory and processing power to analyze. This presents a major issue for T.R.A.S.H., which is designed to operate on lightweight, embedded processing platforms. Attempting to run real-time detection and classification from LiDAR data would result in delays, inefficiencies, or system overload.

Limited Material Identification: While LiDAR excels at identifying object shape and spatial position, it does not detect color, texture, or material composition. For a sorting system where material type is the defining sorting parameter, this makes LiDAR unsuitable without pairing it with additional hardware such as spectrometers or vision systems.

Environmental Sensitivity: Although LiDAR is less affected by lighting than traditional cameras, it can still struggle in certain indoor conditions. In our case, the system will operate indoors, where reflective surfaces such as aluminum cans or glossy plastics, as well as translucent materials like plastic bags or clear bottles, may be present. These materials can scatter or absorb the laser pulses, leading to incomplete point clouds, false readings, or missing object data. These challenges reduce the reliability of LiDAR in accurately detecting recyclable items within the T.R.A.S.H. workspace.

Overhead in Multi-Object Environments: LiDAR systems are often optimized for mapping or vehicle-scale environments rather than small, cluttered workspaces with many overlapping or touching objects. Distinguishing individual recyclables in a dense pile using point cloud data alone is computationally complex and would require additional algorithms to parse object boundaries and determine grasp points.

While LiDAR provides excellent 3D spatial awareness, its high cost, processing demands, and inability to detect material properties make it an inefficient choice for T.R.A.S.H. Given the nature of our indoor sorting environment, where reflective and translucent materials are common, the reliability of LiDAR further decreases. For a system that prioritizes cost-effectiveness, accuracy, and material classification, LiDAR does not meet the practical or technical requirements of our design.

3.6.2 Advantages of Computer Vision

To overcome the limitations of ultrasound and LiDAR, we propose using a computer vision camera for object detection. This method offers a balanced combination of accuracy, adaptability, and affordability, making it the most suitable option for the T.R.A.S.H. system.

Affordability: Computer vision cameras are significantly more cost-effective than LiDAR systems while still providing dependable object detection. This makes them ideal for budget-conscious applications without sacrificing essential functionality.

Consistent and Wide-Area Coverage: Unlike ultrasound sensors that require constant movement to scan the workspace, a single camera can capture a broad and stable view of the entire area in one frame. This reduces the need for mechanical scanning and allows the system to track multiple objects efficiently.

Flexible Object Identification: Computer vision excels in identifying a wide range of objects based on shape, color, texture, and material appearance. Unlike ultrasound, which struggles with curved or soft surfaces, and LiDAR, which only maps shape and distance, computer vision provides meaningful visual context. This is essential for distinguishing between different types of recyclables, such as plastic bottles, aluminum cans, and paper products.

Adaptability with Machine Learning: Computer vision systems can be enhanced through integration with machine learning and AI models, allowing the system to continuously improve in recognizing and classifying objects. Over time, as more data is gathered, these models can be retrained to increase accuracy and adapt to changes in object appearance, orientation, or environmental conditions. Additionally, there is a wide range of existing cloud-based solutions and frameworks that can accelerate development and improve detection performance. Services such as Amazon Web Services (AWS) Rekognition and Microsoft Azure Computer Vision provide robust, pre-trained models that can be adapted or integrated into our system. These platforms offer tools for object detection, image classification, and anomaly recognition, reducing the development time and increasing reliability through proven architectures.

3.6.4 Conclusion

In summary, this section evaluated three object detection technologies: ultrasound sensors, LiDAR, and computer vision, to determine the most suitable solution for the T.R.A.S.H. system. Ultrasound sensors, while low-cost and reliable in certain environments, were ruled out due to their limited scanning capabilities, environmental sensitivity, low precision, and poor performance with curved or sound-absorbing surfaces. LiDAR sensors offer high spatial accuracy but were dismissed because of their high cost, large processing requirements, difficulty operating with translucent or reflective indoor materials, and inability to classify materials.

Computer vision emerged as the most effective and scalable solution. It provides broad workspace coverage, real-time classification, and the flexibility to detect recyclables based on shape, color, texture, and material appearance. When paired with machine learning, computer vision enables continuous improvement in object recognition accuracy. The

availability of cloud-based AI tools such as AWS Recognition and Microsoft Azure Computer Vision further enhances development efficiency and detection reliability.

By integrating computer vision into the T.R.A.S.H. system, we achieve a solution that is cost-effective, precise, and well-suited for handling dynamic recycling environments. This technology supports our goal of building an automated sorting system that can accurately identify, classify, and process recyclables with minimal hardware overhead and maximum adaptability.

3.4 Microcontroller

Microcontrollers (MCUs) are essential components in embedded systems and robotics. They manage all of the hardware components, process sensor data, and execute control tasks. An MCU has a central processing unit (CPU), memory, and I/O peripherals on a single chip, designed for efficient embedded applications.

For our project, the MCU is responsible for automating various tasks, including processing sensor data, controlling the robotic arm motors, and managing system communication. Given the need for precise real-time control of the robotic arm, the selected MCU must offer sufficient computational power, peripheral support, and energy efficiency.

Additionally, the spectroscopy system in our design uses a Linear CCD sensor which requires an MCU to generate very specific and complex clock signals, acquire sensor output signals, and transmit data to other subsystems. These tasks require efficient resource management to ensure accuracy and reliability. The Linear CCD Sensor requirements are discussed in more detail in section 6.15 but basically, it requires 4 timers (at least one 32-bit timer), ADC, DMA, and a fast serial communication protocol.

To meet these requirements, we will evaluate whether a single high-performance MCU is sufficient or if multiple MCUs operating in parallel would provide better efficiency. If multiple MCUs are used, they must communicate effectively using a reliable communication protocol to facilitate seamless data exchange. Since MCUs are generally cost-effective, this approach could optimize performance without significantly increasing manufacturing costs.

The choice of an MCU depends on several critical specifications. Computational power is determined by the CPU architecture and clock speed, which affects the ability to process data in real-time. Memory resources, including RAM and Flash storage, must be sufficient to handle real-time data processing and program execution. Peripheral support is another crucial factor, as the MCU needs to include essential features such as GPIO pins, analog-to-digital converters (ADC), pulse-width modulation (PWM), direct memory access (DMA), and communication interfaces like I²C, SPI, and UART for integration with sensors and actuators. Power consumption must also be optimized for efficiency,

particularly for continuous operation. Additionally, the development ecosystem is another critical consideration. An ideal MCU should be well-documented, have strong community support, and offer robust development tools and software libraries.

Another key consideration is the data size, as the architecture of an MCU varies between 8-bit, 16-bit, and 32-bit designs. An 8-bit MCU is suitable for basic control tasks with minimal processing demands, while a 32-bit MCU provides higher data throughput and better computational capabilities and is ideal for applications requiring real-time processing. Considering these criteria, the following sections will provide a detailed analysis of each MCU we are considering before concluding with our final selection based on our project requirements.

3.4.1 ATmega328P

The first MCU under consideration is the ATmega328P, an 8-bit AVR RISC-based microcontroller developed by Atmel. It is widely used in Arduino platforms due to its low cost, simplicity, and power efficiency. The ATmega328P has a maximum CPU frequency of 20 MHz, 32 KB of Flash memory, 2 KB of SRAM, and 1 KB of EEPROM. It features 23 GPIO pins and supports communication interfaces such as UART, I²C, and SPI. It also includes three timers: two 8-bit and one 16-bit, along with six PWM channels.

While the ATmega328P is a reliable MCU for basic embedded applications, it presents several limitations for our project. The 8-bit architecture and 20 MHz clock speed are insufficient for handling the complex real-time control tasks required by the robotic arm and spectroscopy system. Additionally, its limited peripheral support, particularly the availability of only three timers, may not be adequate for generating motor control signals and meeting the precise timing requirements of the spectroscopy system, which requires at least one high-resolution 32-bit timer and multiple PWM outputs. The microcontroller also features only one UART/USART port, which could become a bottleneck when interfacing with multiple serial devices simultaneously. Another significant limitation is the lack of a DMA controller, which is essential for efficient data acquisition from the spectroscopy sensor. Without DMA, the CPU would need to handle data transfers manually, leading to processing delays and inefficiencies.

Due to these constraints, the ATmega328P is most likely not enough to meet our project's requirements. While it remains a viable option for simpler control tasks, our project demands a more capable MCU with better peripherals support and development features. Further comparison with other microcontrollers will help determine the best choice for our specific needs.

3.4.2 ESP32-S3-WROOM-1-N8

Our next consideration is the ESP32-S3-WROOM-1-N8, it is a powerful 32-bit microcontroller designed by Espressif, featuring a dual-core Xtensa LX7 processor with a

maximum clock speed of 240 MHz. It is becoming a popular microcontroller due to its built-in Wi-Fi and Bluetooth capability. It includes 8 MB of Flash memory, 384 KB of ROM, and 512 KB of SRAM. It has 36 GPIO pins and supports various communication protocols, including three UART interfaces, two I²C interfaces, and four SPI interfaces. The microcontroller features four timers, all with 54-bit resolution based on a 16-bit prescaler. For pulse-width modulation (PWM), it provides eight LED PWM channels and two motor control pulse-width modulation (MCPWM) channels. It consists of two 10-channel 12-bit SAR ADCs, supporting up to 20 channels in total.

While the ESP32-S3 is capable of the tasks for this project and despite its high processing power and integrated Wi-Fi/Bluetooth capabilities, it is not the best option for our project due to a lack of sufficient timer configurations needed for the spectroscopy system. Additionally, we found that its ADC performance is very poor according to the reviews of people who tried it. While the ESP32-S3 does support direct memory access (DMA), its timing precision and peripheral integration are less suited to the high-speed, real-time operations required in our system. Due to these limitations, we have decided to look for an alternative microcontroller that is more suitable with our project requirements.

3.4.3 STM32F401

After evaluating multiple options, we have selected the STM32F401 as the microcontroller for our project. This MCU, part of the STM32F4 series developed by STMicroelectronics, features a 32-bit ARM Cortex-M4 core running at a maximum clock speed of 84 MHz. It has 256 KB of Flash memory, 512 bytes of one-time programmable (OTP) memory, and 64 KB of RAM. It includes 36 GPIO pins and supports a variety of communication protocols, including three UART interfaces, three I²C interfaces, and three SPI interfaces.

The STM32F401 is particularly well-suited for our application due to its extensive timer support. It features two 32-bit timers and six 16-bit timers, providing more than enough timing resources for both the robotic arm control and spectroscopy system. The STM32 series also offers clear and detailed documentation, particularly regarding the timer trigger registers, enabling precise synchronization and advanced control using the STM32CubeIDE development environment. Additionally, its ADC system consists of 10 channels with 12-bit resolution and a much faster sampling rate compared to the ESP32-S3.

Another advantage of the STM32F401 is its support for DMA, which allows for efficient data transfer without overloading the CPU. Unlike the ESP32-S3, which includes additional processing overhead due to its wireless connectivity, the STM32F401 provides a more streamlined and deterministic approach to real-time control. Given these advantages, the STM32F401-CCU6 is the optimal microcontroller for our project, offering a well-balanced combination of computational power, timer precision, ADC performance, and robust development tools.

3.4.4 MCU Selection

Feature	ATmega328P	ESP32-S3-WROOM-1-N8	STM32F401
CPU Core	AVR 8-bit	Xtensa Dual-core 32-bit LX7	ARM Cortex-M4 32-bit
Max Clock Frequency	20 MHz	240 MHz	84 MHz
GPIOs	23 pins	36 pins	36 pins
USB	NA	OTG FS	OTG FS
UART	1xUSART	3	3xUSART
I2C	1	2	3
SPI	1	4	3
Timers	2xTimer 8-bit 1xTimer 16-bit	4xTimer 54-bit (16-bit prescaler)	2xTimer 32-bit 6xTimer 16-bit
PWM	6 channels	8 channels LED PWM, 2 MCPWM	4 channels/timer
ADC	8 channels 10-bit	2xSAR ADC 10 channels 12-bit	10 channels 12-bit
DMA	NA	Yes	Yes
Wi-Fi/Bluetooth	NA	Yes	NA
Cost	~\$3	~\$5	~\$5

Table 15: MCU Selection

3.5 Single Board Computer (SBC)

Single Board Computers (SBCs) are compact, fully integrated computing systems that incorporate a processor, memory, storage, and I/O peripherals on a single circuit board. Unlike microcontrollers (MCUs), which are optimized for real-time control of hardware, SBCs are designed for high computational tasks, advanced processing, and efficient communication between multiple components in an embedded system. They run full-fledged operating systems, such as Linux, allowing for software flexibility, modularity, and networking capabilities.

For our project, an SBC is essential due to the high computational demands that an MCU alone cannot handle. The system must process real-time data from multiple sources, including a camera for object identification, a spectrometer for material classification, and motor control for actuation. The SBC must support high-speed communication protocols that allow efficient data transfer between these modules and ensure smooth integration with other hardware components. Additionally, the requirement for modular parts necessitates an adaptable computing platform capable of handling software and hardware updates without significant reconfiguration.

Another key factor is the necessity of Robot Operating System 2 (ROS2) for seamless integration and control. ROS2 provides a robust middleware framework that enables efficient communication between different subsystems, such as computer vision, motion planning, and sensor fusion. A Single Board Computer is the only device that can efficiently host ROS2 while managing concurrent tasks, such as machine learning inference, sensor data aggregation, and real-time motor control.

The selection of an SBC for our project depends on several key factors, including processing power, memory, I/O capabilities, software compatibility, power efficiency, and expandability. Given that our system must handle image processing, machine learning, and real-time control, the CPU and GPU performance of the SBC are critical considerations. Additionally, the availability of high-speed interfaces like USB 3.0, MIPI CSI for camera modules, and GPIO for motor and sensor control ensures compatibility with all required hardware components.

The following sections will analyze different SBCs, comparing their performance and capabilities before finalizing our selection based on our project requirements.

3.5.1 Raspberry Pi 5

One of the Single Board Computers (SBCs) we are considering for our project is the Raspberry Pi 5 (8GB) due to its high computational performance, extensive I/O capabilities, and flexibility for real-time processing. The Broadcom BCM2712 quad-core Arm Cortex-A76 processor (64-bit) clocked at 2.4GHz is a significant upgrade over previous models, with improved out-of-order execution, larger caches, and enhanced instruction pipelines, making it well-suited for parallel processing of sensor data, motor control commands, and real-time vision processing for robotic applications. The LPDDR4X-4267 SDRAM (8GB) ensures a high memory bandwidth, allowing for efficient data transfer between the CPU and peripherals, particularly crucial for handling multiple high-resolution image streams from cameras and storing large datasets for real-time processing. Additionally, the 8GB of SDRAM allows us to allocate more memory to ROS2 nodes, reducing latency and improving task scheduling efficiency.

For our computer vision system, the dual 4-lane Mobile Industry Processor Interface (MIPI) Camera Serial Interface (CSI) camera connections provide high-bandwidth support for stereo vision or multiple camera feeds, enabling real-time object identification and spatial analysis for robotic arm manipulation. The RP1 I/O controller offloads all USB, GPIO, PCIe, and MIPI CSI/DSI communication from the CPU, enabling independent high-speed data transfer for cameras, sensors, and actuators without system bottlenecks. This allows for full-speed USB 3.0 (5Gbps), optimized GPIO for real-time motor control, and dedicated camera interfaces, ensuring low-latency coordination between vision processing and robotic actuation while maximizing overall system efficiency. Another notable addition is the PCIe 2.0 interface, which, while not essential, provides valuable expansion options such as NVMe SSD storage for high-speed access to image datasets, machine learning models, and logged sensor data. Similarly, the UART debug port, though not a requirement, enhances low-level debugging and system monitoring, making it a useful feature for firmware updates and diagnostics.

While the Raspberry Pi 5 does not support RAM expansion, its 8GB of LPDDR4X memory is sufficient for our workload, enabling us to run ROS2, OpenCV-based vision processing, and AI models simultaneously without major memory bottlenecks. If additional memory bandwidth is required under extreme workloads, we have the option to utilize swap memory on an NVMe SSD via the PCIe interface, providing a potential solution for handling high-resolution image processing and large dataset operations. Overall, the combination of high processing power, fast memory, dual-camera support, and expandable storage options makes the Raspberry Pi 5 a compelling choice for our project, delivering the computational efficiency needed for real-time robotic vision and motor control.

3.5.2 Nvidia Jetson Nano

One of the Single Board Computers (SBCs) we are considering for our project is the NVIDIA Jetson Nano due to its dedicated AI acceleration, powerful GPU, and optimized software stack for machine learning and computer vision applications. The Jetson Nano is powered by a quad-core Arm Cortex-A57 processor clocked at 1.43GHz and an NVIDIA Maxwell GPU with 128 CUDA cores, allowing for parallel execution of AI inference tasks, real-time image processing, and deep learning-based object detection. The 4GB of LPDDR4 memory provides sufficient bandwidth for handling ROS2 processes, computer vision algorithms, and real-time sensor fusion while maintaining low power consumption. While the Jetson Nano has a lower clock speed than other SBCs, its GPU acceleration compensates by enabling faster neural network inference and optimized CUDA-based computations for robotic applications.

For our computer vision system, the Jetson Nano features a single 2-lane MIPI CSI camera interface, which supports real-time video streaming and AI-based object recognition. Although it lacks dual-camera support, it leverages hardware-accelerated image processing using NVIDIA's Vision Programming Interface (VPI) and TensorRT to efficiently handle deep learning models for object detection and classification. The GPIO and I2C interfaces allow for sensor integration and motor control, while four USB 3.0 ports provide high-

speed data transfer for peripherals such as stereo cameras, LiDAR, or external storage. Additionally, the Gigabit Ethernet port ensures low-latency networking, which is useful for remote operation or distributed robotic control.

Although the Jetson Nano is limited to 4GB of RAM and lacks PCIe NVMe storage support, its GPU acceleration makes it a strong candidate for AI-intensive tasks such as image classification, material identification, and real-time decision-making. The ability to optimize deep learning models using TensorRT and deploy them efficiently on CUDA cores makes it an attractive choice for applications where machine learning inference is critical. Overall, the combination of GPU-accelerated computing, optimized software ecosystem, and high-speed connectivity makes the Jetson Nano a compelling option for our project, particularly if AI-based vision processing is a priority.

3.5.3 Orange Pi

One of the Single Board Computers (SBCs) we are considering for our project is the Orange Pi 5 (8GB) due to its high-performance Rockchip RK3588S processor, versatile I/O capabilities, and cost-effectiveness. The Rockchip RK3588S features an octa-core CPU with four Arm Cortex-A76 cores clocked at 2.4GHz and four Cortex-A55 cores at 1.8GHz, providing a significant increase in multi-threaded performance compared to other SBCs. Additionally, the Mali-G610 MP4 GPU offers GPU acceleration for graphics processing and AI inference, making it capable of handling computer vision and deep learning-based robotic applications. The 8GB of LPDDR4X RAM ensures high memory bandwidth, allowing for efficient multitasking between ROS2, OpenCV-based image processing, and real-time motor control tasks.

For our computer vision system, the Orange Pi 5 provides a dual MIPI-CSI camera interface, supporting multiple high-resolution camera modules for stereo vision or real-time image capture. Unlike the Jetson Nano, which relies heavily on its GPU for AI acceleration, the Orange Pi 5 integrates a Neural Processing Unit (NPU) capable of 6 TOPS (Tera Operations Per Second) of AI performance, allowing for efficient deep learning inference on edge devices. This makes it a strong choice for autonomous robotic applications where AI-powered vision processing is required. The USB 3.0 ports and high-speed GPIOs provide seamless integration with additional sensors, actuators, and external storage devices, while the Gigabit Ethernet ensures low-latency communication for networking applications.

While the Orange Pi 5 lacks native PCIe expansion for NVMe storage, its USB 3.0 interface allows for high-speed external storage options if additional swap memory or dataset storage is required. Its NPU acceleration gives it an advantage over standard CPU-based SBCs, making it well-suited for AI-driven material identification, robotic vision, and autonomous navigation tasks. Overall, the Orange Pi 5 balances high computational power, dedicated AI acceleration, and versatile I/O options, making it a strong alternative for real-

time processing and robotics applications that require machine learning and multi-threaded CPU performance.

3.5.4 SBC Selection

Overall, after evaluating the Raspberry Pi 5 (8GB), NVIDIA Jetson Nano, and Orange Pi 5 (8GB), we have decided to select the Raspberry Pi 5 (8GB) as the most suitable SBC for our project. Based on our research, the Raspberry Pi 5 offers the best balance of community support, ease of use, affordability, and sufficient performance to meet our project requirements.

While the Orange Pi 5 provides greater raw computational capabilities, it lacks consistent performance, strong software support, and affordability, making it less viable for long-term development. Similarly, while the Jetson Nano excels in AI-based tasks and GPU-accelerated computing, it falls short in storage expandability, ease of integration, and cost-effectiveness. In conclusion, the Raspberry Pi 5 delivers the necessary performance while maintaining broad compatibility, strong community support, and cost efficiency, making it the optimal choice for our system.

Feature	Raspberry Pi 5 (8GB)	NIVIDA Jetson Nano	Orange Pi 5 (8GB)
CPU Core	Broadcom BCM2712 Quad-Core Cortex-A76	Quad-Core Cortex-A57	Rockchip RK3588S (4x Cortex-A76 + 4x Cortex-A55)
Clock Speed	2.4 GHz	1.43 GHz	2.4 GHz (A76) / 1.8 GHz (A55)
GPU	VideoCore VII	128-core Maxwell GPU	Mali-G610 MP4
RAM	8GB SDRAM	4GB LPDDR4	8GB LPDDR4X
Storage	MicroSD, PCIe NVMe (optional)	MicroSD	eMMC, NVMe SSD (via M.2 slot) 26
MIPI CSI	Dual 4-lane MIPI CSI	Single 2-lane MIPI CSI	Dual 4-lane MIPI CSI

Networking	Gigabit Ethernet, Wi-Fi 6, Bluetooth 5.0	Gigabit Ethernet (No Wi-Fi or Bluetooth)	Gigabit Ethernet, Wi-Fi (via external module)
AI Acceleration	No (External Module needed)	Yes (CUDA, TensorRT)	Yes (6 TOPS NPU)
Power Consumption	Medium	High	Medium
Availability	High	Low	High
Cost	~\$80 (without peripherals)	~\$250 (with peripherals)	~\$110 (Without peripherals)
Software Support	High (Raspberry Pi OS, Ubuntu, Debian, ROS2)	Medium (JetPack SDK, Ubuntu-based, ROS2)	Medium (Debian, Ubuntu, Android)

Table 16: SBC Selection

3.6 Power Components

3.6.1 Power Supply

For the primary power source, a generic AC/DC switching power supply unit was selected to convert 120VAC wall power to a stable 12VDC output, which then feeds the rest of the power delivery system. The choice to obtain a unit instead of designing one was made due to safety issues when dealing with such high voltages and currents.

The key feature when choosing the power supply is the amount of power or current supplied and the cost. A comparison is shown in Table 17. We chose to go with the option with the maximum current and 12V output.

Feature	Mean Well LRS-35-12	Mean Well LRS-35-15	Amazon Universal Switching Power Supply
Voltage Output	12V	15V	12V
Max Current	3A	2.4	10A
Power	36W	36W	120W
Circuit Protection	Yes	YES	Yes

Table 17: Switching Power Supply Comparison

3.6.2 Voltage Regulator

Linear Voltage Regulators, especially Low Dropout Voltage (LDO) ones, are great options when we need to generate a specific voltage level with very minimal noise. However, they are not efficient since they dissipate most of the lost energy as heat. For that reason, we chose to use LDOs for regulating output with a small difference between input and output, such as 5V to 3.3V or 4V. For larger applications, we will utilize switching regulators, which will be discussed in the next section. Table 18 shows a comparison of multiple options we could use to generate the 3.3V rail required by our logic-level components and sensors.

Feature	AMS1117-3.3	MIC5205-3.3	LD1117-3.3
Voltage Output	3.3V	3.3V	3.3V
Max Current	1A	150mA	800mA
Dropout Voltage	1.1V	0.35V	1.1V

Table 18. 3.3V Linear Voltage Regulator Comparison

The reason we chose the AMS1117-3.3 is it has a sufficient current supply for our logic components, it is widely available and it is a simple implementation with minimal external components. Even though it has a higher dropout voltage, the 5V input from the buck converter ensures stable operation

3.6.3 DC-to-DC Buck Converter

This project requires a high-efficiency step-down converter from 12V to 5V to supply both the linear regulators and any 5V components directly. Buck converters are a great option for such tasks. They consist of switching voltage regulators that use transistor switching to regulate the voltage output, which increases efficiency significantly compared to linear regulators.

Feature	LM2678-5.0	MP1584	XL4015
Voltage Output	5V	Adjustable	Adjustable
Max Current	5A	3A	5A
Efficiency	85%-92%	80%-90%	85%

Table 19. 5V Buck Converter Comparison

The choice made in Table 19 was made due to multiple reasons. It has a High current output, a fixed 5V version that simplifies feedback design, and it is a reliable regulator tested and used in many projects we have seen.

3.7 Motors

The motor selection process is critical to ensuring precise and efficient motion control in our robotic system. Motors must be chosen based on factors such as accuracy, torque, speed, power efficiency, and ease of control. This section discusses different motor technologies, compares their advantages and disadvantages, and then selects the appropriate motor type for our project. We then analyze different motor drivers and encoders to ensure optimal control and feedback integration.

Different motor types are used in robotics and automation systems, each with unique characteristics that make them suitable for different applications. The primary motor technologies considered for our project are servo motors, stepper motors, and brushless DC (BLDC) motors.

3.7.1 Servo Motors

Servo motors, particularly the inexpensive RC hobby servos, are commonly used in robotic applications where position control is necessary. These motors consist of a DC motor, a gear train, a potentiometer for position feedback, and an internal controller. They typically operate on pulse-width modulation (PWM) signals, where the pulse width determines the target position of the motor shaft.

Hobby servos, such as the SG90 and MG995, are low-cost and simple to use. They provide reasonable position accuracy, making them suitable for lightweight robotic arms, pan-tilt camera mounts, and simple automation projects. However, they have limitations in torque output, continuous rotation capability, and precision when compared to industrial-grade servo motors. Additionally, they lack direct torque feedback, making them less suitable for high-load applications.

3.7.2 Stepper

Stepper motors are widely used in robotics and automation due to their precise positioning capabilities. They operate by moving in discrete steps, meaning they do not require an internal feedback system for position control. Stepper motors can be bipolar or unipolar, with bipolar motors being the more common choice due to their higher torque efficiency.

One major advantage of stepper motors is their ability to hold a position without requiring continuous power input, making them ideal for applications where stability is essential. However, stepper motors can suffer from **missed steps** under high loads unless

an external feedback system, such as an **encoder**, is used. They also tend to consume power continuously, even when idle, which can generate excess heat.

Stepper motors are commonly available in standard sizes, such as NEMA 17, NEMA 23, and NEMA 34, each offering varying levels of torque and power requirements. Their ease of use, precise step control, and availability make them a strong candidate for our project.

3.7.3 Brushless DC

Brushless DC motors are highly efficient and offer smooth motion control. Unlike brushed motors, BLDC motors use electronic commutation, eliminating the need for physical brushes, which results in a longer lifespan and reduced maintenance.

BLDC motors are commonly used in high-speed applications, such as drones, electric vehicles, and industrial automation. They provide superior efficiency and torque output compared to stepper motors and hobby servos. However, they require specialized motor controllers, such as ESCs (Electronic Speed Controllers), to operate correctly. Additionally, BLDC motors typically rely on Hall-effect sensors or encoders for position feedback, adding to system complexity and cost.

While BLDC motors are excellent for high-speed and efficiency-focused applications, they are not the best fit for our robotic arm, which requires precise, incremental motion rather than continuous high-speed operation.

3.7.4 Motor Selection

After evaluating the different motor technologies as shown in Table 20, we have chosen stepper motors for our main joints due to their high precision, range of motion, and wide variety of holding torque options available at a low cost. Stepper motors provide an ideal balance between affordability and performance for robotic applications.

For the end-effector joints, we decided to use servo motors since they are cheaper, smaller, and lighter. Additionally, we do not need high torque or continuous rotation at these joints, so servo motors would be sufficient.

Features	Servo	Stepper	BLDC
Position Control	Closed Loop	Open Loop	Open Loop
Cost	~\$2 - \$10	~\$10 - \$50	~\$80 - \$200
Durability	~15000 cycles	~10000 hours	~20000 hours
Range of Motion	180°-270°	360°	360°
Precision	1°	1.8° or 0.9°/step	Controller dependent

		(micro stepping available)	
Holding Torque	~0.5 - 3 Nm	~0.1 - 8 Nm	~0.1 - 100 Nm
Driver	PWM Signal	Stepper Driver (e.g., A4988)	ESC (Electronic Speed Controller)

Table 20: Motor Technology Comparison

For the servo motors, we decided to go with the MG996R since it provides the most torque, precision, and durability among the three options shown in Table 21.

Features	SG90	MG90s	MG996R
Position Control	Closed Loop	Closed Loop	Closed Loop
Cost	~\$2–3	~\$4–5	~\$7–10
Durability	~100,000 cycles	~150,000 cycles	~200,000 cycles (metal gear)
Precision	±10° (approx.)	±8° (approx.)	±5° (approx.)
Holding Torque	1.8 kg·cm @ 4.8V	~2.2 kg·cm @ 4.8V	~9–11 kg·cm @ 6V

Table 21: Servo Motor Selection: End Effector

Stepper Motors come in a variety of standard sizes, such as NEMA 14, 17, 23, 34, etc. Each standard size has a range of holding torque it can handle, which depends on the length of the motor used. For our project, we chose to go with the NEMA 17 as shown in Table 22, it provides a good balance of cost and size to torque. Although NEMA 23 motors have greater holding torque, they are significantly larger and can be more expensive.

Features	Nema 14	Nema 17	Nema 23
Step count	200 steps/rev (1.8°/step)	200 steps/rev (1.8°/step)	200 steps/rev (1.8°/step)
current	~0.4 - 1.0 A/phase	~1.2 - 2.0 A/phase	~2.0 - 3.5 A/phase
torque	~0.08 - 0.12 N·m	~0.12 - 0.8 N·m	~1.2 - 4.0 N·m
Phases	2	2	2

Table 22: Stepper Motor Selection: Main Joints

3.8 Motor Encoders

Encoders play a crucial role in motion control by providing feedback on position, speed, and direction. In our robotic system, encoders are necessary to ensure accurate stepper motor positioning and to prevent missed steps. This section explores different encoder types, compares their advantages and disadvantages, and selects the best option for our application.

3.8.1 Optical Encoders

Optical encoders use a disk with alternating transparent and opaque sections, along with a light source and a sensor, to detect motion and position changes. When the disk rotates, the light passes through or is blocked, generating a signal that can be processed to determine the position and speed of the motor. Optical encoders are known for their high accuracy and resolution, making them suitable for applications requiring precise motion control. They provide fast response times and can deliver both absolute and incremental position feedback. However, they are highly sensitive to dust and dirt, which can obstruct the sensor and affect performance. Additionally, optical encoders tend to be more expensive than other types and require careful alignment during installation to function correctly.

3.8.2 Magnetic Encoders

Magnetic encoders use a magnetized disk and a magnetic sensor to detect changes in position. The sensor measures variations in the magnetic field to determine motion and position. Unlike optical encoders, magnetic encoders are more resistant to environmental interference and can function reliably in dusty or vibrating conditions. They are compact and durable, making them suitable for industrial applications where robustness is a priority. While magnetic encoders offer better resistance to harsh conditions, they have slightly lower resolution compared to optical encoders and may introduce small errors due to magnetic interference. Shielding is required to prevent external magnetic fields from affecting their accuracy.

3.8.3 Potentiometers

Potentiometers are simple analog position sensors that measure resistance changes as a shaft rotates. They provide a continuous voltage output corresponding to the shaft position, making them suitable for low-precision applications. Their affordability and simplicity make them widely available and easy to integrate into basic motion control systems. However, potentiometers suffer from mechanical wear over time due to their contact-based design, which reduces their lifespan and reliability in continuous operation. They also have limited rotation range, typically restricted to less than 360 degrees, and do not offer the precision required for high-accuracy applications.

3.8.4 Encoder Selection

For our robotic system, we require an encoder that balances accuracy, durability, and cost-effectiveness. Given the need for robust operation in varying conditions and reasonable precision for stepper motor feedback, we select magnetic encoders. These provide reliable feedback while maintaining durability in an environment where dust and vibrations are present. Optical encoders, while highly accurate, are too sensitive to environmental factors and require careful installation. Potentiometers, while inexpensive, do not offer the resolution or reliability needed for precise motion control.

Feature			
Encoder Type	Potentiometer	Magnetic	Optical
Accuracy	High	Moderate	Low
Resolution	High	Moderate	Low
Durability	Moderate	High	Low
Cost	High	Moderate	Low
Precision	Yes	Yes	No
Response Time	Fast	Moderate	Slow

Table 23: Stepper Motor Encoder Selection

3.9 Motor Drivers

To Be Described...

3.10 Speed Reducer

In order to limit the amount of spending on high-torque motors, it makes more logistical sense to use speed reducers to increase the amount of torque produced by the motors. Therefore, it is important that we select gearboxes that create the most torque reliably. Additionally, unlike motors related to the end effector and spherical wrist, these motors control the linkages of the robot arm and, therefore, can be integrated further from the joint, reducing weight on the robot arm.

		Concept Alternatives							
		Strain Wave Gear		Cycloidal Drive		Capstan Drive		Planetary Gears	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
High Torque Ratio	40%	4	1.60	4	1.60	3	1.20	3	1.20
High Reliability	35%	3	1.05	4	1.40	3	1.05	4	1.40
Low Backlash	10%	4	0.40	4	0.40	4	0.40	2	0.20
Low Cost	10%	4	0.40	3	0.30	3	0.30	4	0.40
Small Footprint	5%	3	0.15	3	0.15	3	0.15	4	0.20
Totals	100%		3.60		3.85		3.10		3.40
Rating	Value								
Unsatisfactory	0								
Just Tolerable	1								
Adequate	2								
Good	3								
Very Good	4								

1. Importance weights assigned
2. Team rates each concept 0 to 4
3. Multiply rating X importance
4. Sum weighted ratings

Table 24: Concept Alternatives – Speed Reducer

3.10.1 Strain Wave Gear

Strain Wave Gears (SWGs) are in high demand in the industrial robotics industry for their precise control of angular positioning and high-power transmission. Additionally, SWGs are compact in size, have a high reduction ratio, and have zero backlash [5], making them perfect for robotics applications. SWGs utilize a unique operating principle based on the mechanics of materials. It is comprised of three parts: the Wave Generator, Flexspline, and Circular Spline [6].

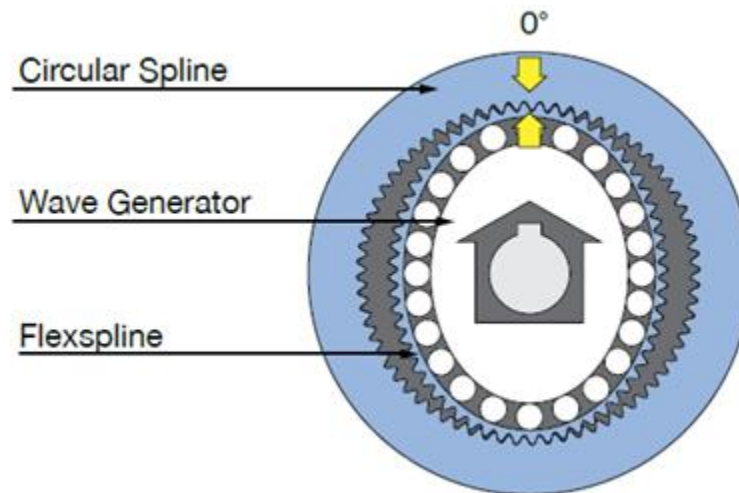


Figure 7 Strain Wave Gear Components [7]

The issue with using an SWG is that they rely on the mechanical properties of the material in order to operate smoothly. For the purposes of our project, our speed reducers will be made using FDM manufacturing. As discussed in 3.2.1.4, PETG is unreliable due to its

inconsistency in manufacturing. Therefore, we would not be able to manufacture our own SWG and would have to spend an unrealistic amount of our budget to acquire a speed reducer.

3.10.2 Cycloidal Drive

Very similar to the Strain Wave Gear, the Cycloidal Drive is a fan favorite in the robotics industry for its compact design, reduction ratios of up to ten times that of planetary or gear drives, and virtually zero-backlash [8]. The cycloidal drive is composed of a high-speed input shaft, an eccentric bearing, two cycloidal disks, a ring gear, rollers, and a slow-speed output shaft.

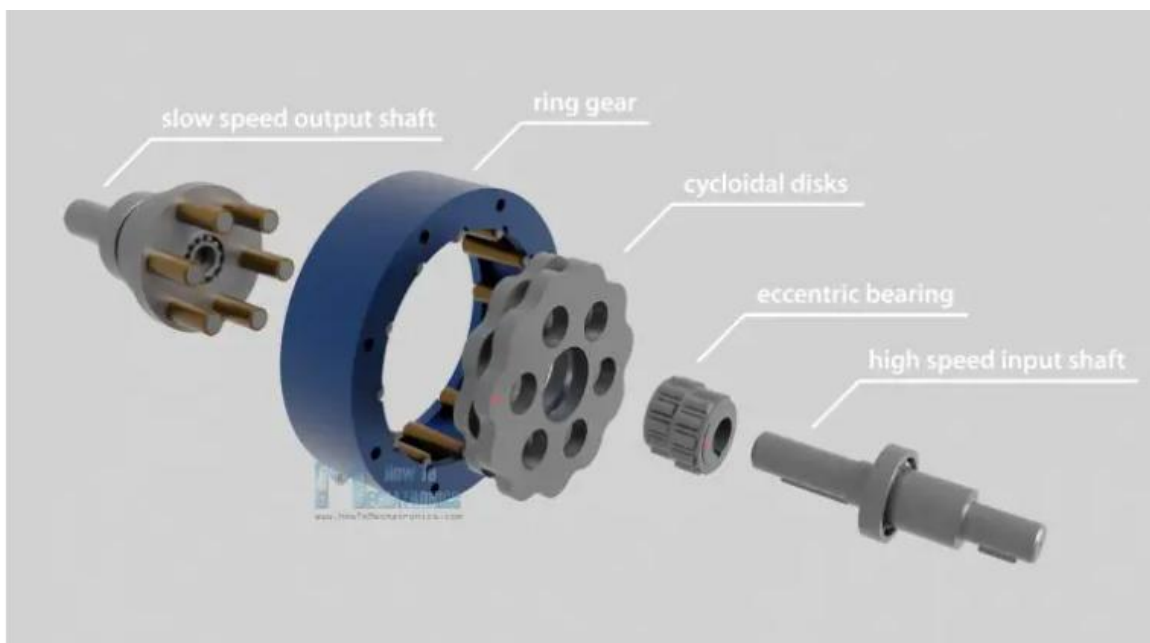


Figure 8: Cycloidal Drive with main component labels [9]

Unlike the strain wave gear, the cycloidal drive does not rely on the mechanics of material, but rather on the motion of the cycloidal disks driving the output shaft. This design has an increase of hardware components, which will raise the cost. However, it is far more reliable than the strain wave gear.

3.10.3 Capstan Drive

A Capstan drive is a quasi-direct-drive (QDD) speed reducer that utilizes cables wrapped in round drums commonly found in medieval machines. The Capstan cable drive is low weight/inertia, has a simple design, and has a high strength-to-weight ratio with haptic feedback, making it perfect for robotics applications [10].

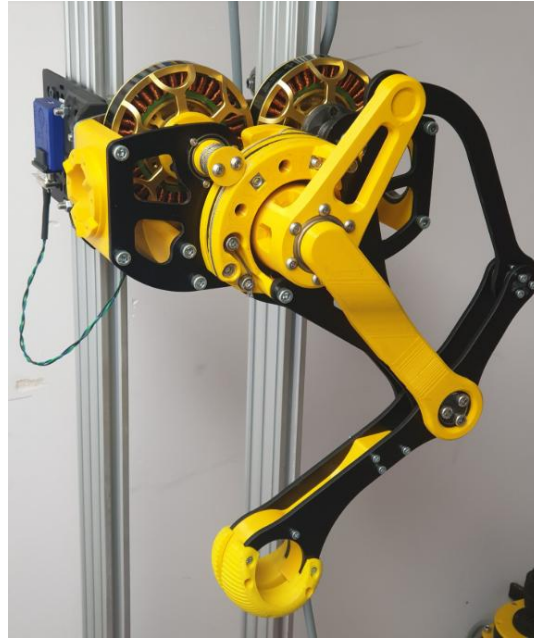


Figure 9: Robot Quadruped Leg Using Capstan Drive [11]

Capstan drives have high torque ratios and are reliable dependent on the cord used to link the two drums together. They also have a reasonably small footprint and weight for the amount of work that the speed reducer is achieving. However, the main limiting factor of a capstan drive is the reduced range of motion. This will further complicate the engineering requirements for the robot arm and would not be an applicable choice for our case.

3.10.4 Planetary Gears

Planetary gears are one of the most common forms of speed reducers. Composing of an outer ring gear, planet gears, and a central sun gear, planetary gears can be found in most automobiles for their compactness and high torque ratios.

For our design, our planetary gears would require little to no hardware making it low-cost and lightweight. However, the torque to footprint ratio is much lower than other options including harmonic and cycloidal drives. Due to the amount of friction and lack of efficiency, it is also much more challenging to make planetary gears back drivable.

3.11 Transmission

		Concept Alternatives					
		Belt		Gear		Tendon	
Criteria	Importance Weight %	Rating	Weighted Rating	Rating	Weighted Rating	Rating	Weighted Rating
Low Weight	45%	3	1.35	2	0.90	4	1.80
Low Backlash	30%	4	1.20	2	0.60	2	0.60
Low Slippage	20%	3	0.60	4	0.80	4	0.80
Low Cost	5%	3	0.15	4	0.20	4	0.20
Totals	100%		3.30		2.50		3.40
Rating	Value						
Unsatisfactory	0						
Just Tolerable	1						
Adequate	2						
Good	3						
Very Good	4						

1. Importance weights assigned
2. Team rates each concept 0 to 4
3. Multiply rating X importance
4. Sum weighted ratings

Figure 10: Concept Alternatives – Transmission

3.12 Camera

For the T.R.A.S.H. system to achieve high-accuracy object identification and precise localization, the selection of an appropriate camera is critical. The camera serves as the primary input for the computer vision pipeline, and its capabilities directly affect the system's accuracy, responsiveness, and integration flexibility. Several core requirements were established to ensure compatibility with the processing platform and to align with the project's goals of modularity, affordability, and performance.

The first fundamental requirement is seamless integration with the Raspberry Pi 5 through the native Camera Serial Interface (CSI) port. Using the CSI port allows direct hardware-level communication between the camera and the Pi without occupying USB bandwidth. This not only frees up USB ports for other essential peripherals but also minimizes latency and allows for compact, efficient hardware layouts on the limited space on the Raspberry Pi board. Native integration ensures that the imaging system can be fully synchronized with image processing and actuation routines, providing real-time responsiveness for sorting operations. Within our selection of cameras, they will all be supporting CSI port,

In addition to hardware compatibility, the camera must support High Dynamic Range (HDR) imaging. HDR enables the camera to maintain visual clarity across bright and dark regions of the scene. This is especially important when capturing the contours and surfaces of reflective or translucent recyclables like plastic bottles, aluminum cans, or coated paper. With HDR enabled, computer vision algorithms can better distinguish between edges, colors, and material transitions, improving both detection accuracy and classification robustness.

Cost is another driving factor in camera selection. One of the core principles of the T.R.A.S.H. system is affordable modularity. The solution must be accessible and easy to replicate using commercial off-the-shelf (COTS) components. Therefore, while advanced imaging capabilities are desired, the selected camera must remain within a reasonable price range to ensure that the system can be produced and scaled cost-effectively. Cameras priced up to \$100 were considered acceptable based on the overall budget allocated to sensors.

Image resolution is also critical for detailed object analysis. Higher resolution allows the system to identify smaller or partially obstructed objects within the field of view. It improves the system's ability to track shapes and contours accurately, especially during post-processing techniques like segmentation or object recognition. However, a balance must be maintained between resolution and processing requirements. Excessively high resolutions can introduce unnecessary computational overhead and reduce real-time performance unless paired with aggressive optimization and hardware acceleration.

An often overlooked but important consideration is lens distortion. Lower distortion is preferred, as it reduces the need for camera calibration and image correction, streamlining the vision pipeline. However, distortion can occasionally provide functional benefits. A slightly distorted lens, for instance, may offer a wider Field of View (FOV), which could reduce the number of scanning motions required by the robotic arm to cover the workspace. In such cases, distortion and FOV exist in a trade-off: a higher FOV may lead to faster object coverage, while lower distortion simplifies positional accuracy.

The system also benefits from higher frame rates whenever possible. Increased frames per second (FPS) allows the T.R.A.S.H. robot to process more data in real time, enabling better object tracking, faster updates to position estimates, and more accurate sorting decisions. A camera capable of capturing 30 FPS or higher provides sufficient resolution for the Pi's processing capabilities and the arm's pick-and-place requirements.

Equally important is the camera's performance under low-light conditions. In realistic environments, lighting may not always be consistent or controllable. Materials such as aluminum and transparent plastics can reflect or refract light unpredictably, causing sections of the workspace to fall into shadow or become overexposed. A camera with strong low-light sensitivity ensures that object features remain visible and detectable even when ambient light is reduced. This allows the system to operate reliably across different installation scenarios, including dimly lit rooms, shaded workspaces, or enclosed environments. Cameras that exhibit high sensitivity and low noise under minimal lighting reduce the burden on artificial lighting systems and improve the system's resilience to environmental variability.

Lastly, library compatibility and ease of software integration play a significant role. The camera must be supported by popular, well-maintained Python and C++ libraries like OpenCV, libcamera, or Picamera2. This ensures that real-time image capture, frame processing, and feature extraction can be easily integrated into the existing codebase without low-level driver development. Library support is crucial for maintaining development velocity, debugging, and enabling future upgrades to the system.

To evaluate potential imaging solutions, six camera modules were selected that meet the outlined technical requirements and interface constraints: the Raspberry Pi Camera Module V2, Raspberry Pi Camera Module V3, Raspberry Pi High Quality (HQ) Camera, and three Arducam models—the Arducam 12MP, Arducam 16MP, and Arducam 64MP. These cameras represent a broad range of capabilities from 8MP to 64MP, including modules with autofocus, HDR, and varying levels of low-light sensitivity. All selected cameras are natively compatible with the Raspberry Pi 5 CSI interface, ensuring direct integration into the system architecture. The Raspberry Pi V3 and Arducam 12MP are nearly identical in specifications and will be evaluated together in a shared subsection.

3.12.1 Raspberry Pi Camera Module V2

The Raspberry Pi Camera Module V2 is one of the most established and widely used camera options for Raspberry Pi platforms. Priced at approximately \$15, it offers a highly affordable solution for basic imaging applications and benefits from extensive community support due to its long-standing availability since April 2016. Its low cost and widespread availability make it particularly well-suited for COTS integration, allowing for simple repairs, replacements, and future upgrades. This makes it a great choice for modular systems such as T.R.A.S.H., where long-term maintainability and ease of part sourcing are critical design goals.

This camera is built around the Sony IMX219 CMOS sensor, which is an 8-megapixel image sensor paired with a fixed-focus lens. In terms of performance, it is capable of capturing video at 1080p60, 720p180, and even 4Kp30 frame rates. However, due to the Raspberry Pi's internal processing limitations, the maximum usable capture resolution on most systems is 1080p30, which remains sufficient for standard computer vision tasks such as object detection and tracking.

The V2 camera does not support HDR, which can limit its effectiveness in high-contrast environments or in scenes with variable lighting conditions. Additionally, its performance in low-light environments is limited, making it less ideal for applications where ambient illumination may be inconsistent or reduced. Under well-lit conditions, however, it provides predictable image clarity and color fidelity for general-purpose use.

Another advantage of the Camera Module V2 is its broad compatibility with Raspbian and mature library support, including seamless integration with tools such as Picamera,

libcamera, and OpenCV. Its long-standing presence in the Raspberry Pi ecosystem ensures reliable documentation, stable drivers, and ease of troubleshooting—factors that continue to make it a dependable baseline solution for developers prioritizing cost, simplicity, and compatibility over advanced imaging features.

3.12.2 Raspberry Pi Camera Module V3/ArduCam 12MP

The Raspberry Pi Camera Module V3, released in January 2023, and the Arducam 12MP, introduced shortly after as a third-party equivalent, represent the next step up in imaging performance for Raspberry Pi platforms, offering enhanced features such as autofocus and High Dynamic Range (HDR) at an accessible price point. Both modules are priced at approximately \$25 and utilize the Sony IMX708 CMOS sensor, delivering 12-megapixel resolution with a significant improvement in image sharpness and adaptability compared to earlier generation models. Given their near-identical sensor architecture and operational specifications, these two cameras are evaluated jointly in this subsection.

Both the V3 and the Arducam 12MP support autofocus functionality, allowing them to dynamically adjust focus for objects at varying distances. This feature is particularly valuable in scenarios involving cluttered workspaces or variable object heights, as it improves overall clarity and ensures consistent edge definition for computer vision tasks. With a Minimum Object Distance (MOD) of 5 cm, these cameras are well-suited for close-range applications such as material classification and detailed feature detection.

In terms of imaging performance, both modules support video capture up to 1080p at 50 frames per second, which falls just under the Raspberry Pi 5's hardware decoding limit of 1080p60, making full use of the available processing capabilities. The inclusion of HDR support—paired with enhanced low-light sensitivity—significantly improves their ability to handle scenes with strong lighting contrasts, dark shadows, or reflective materials. These attributes are especially useful for identifying objects under variable ambient conditions and maintaining reliable detection performance across different environments. With a 66-degree horizontal Field of View (FOV) in the base model, these cameras provide a balanced frame coverage that reduces the number of repositioning movements required from the robotic arm while maintaining sufficient pixel density for accurate object segmentation.

Crucially, both the Raspberry Pi V3 and the Arducam 12MP are fully compatible with Raspbian OS, ensuring seamless integration with the rest of the T.R.A.S.H. system. Supported libraries such as libcamera, Picamera2, and OpenCV offer a stable software interface for development and testing, reducing the effort needed for camera control, frame acquisition, and real-time processing. The V3 module, being an official Raspberry Pi product, benefits from robust community and developer support. The Arducam 12MP, while third-party, closely mirrors the V3 in design and performance, offering a near drop-in alternative.

In summary, both the Raspberry Pi Camera V3 and Arducam 12MP present a highly capable imaging solution with modern features like autofocus, HDR, and strong low-light performance, without departing from the project's commitment to affordability and compatibility. Their shared architecture and reliable operation make them strong candidates for mid-tier vision requirements within the T.R.A.S.H. platform.

3.12.3 Raspberry Pi Camera High Quality

The Raspberry Pi High Quality (HQ) Camera, released in April 2020, is a premium imaging module designed for developers and applications that demand advanced optical performance and greater flexibility in lens selection. Priced at approximately \$50, the HQ Camera offers a significant step up in customization and image fidelity compared to standard camera modules, making it a strong candidate for controlled environments where precision and clarity are prioritized.

The module features a Sony IMX477 CMOS sensor with a 12.3-megapixel resolution and a 7.9 mm diagonal sensor size, offering a larger imaging area compared to standard modules. It is paired with a C/CS-mount lens system and also supports M12 lenses through widely available adapters, enabling compatibility with a broad range of optical configurations. This allows the camera's field of view, focus range, and aperture to be tailored to specific use cases—an important advantage for applications requiring tightly framed imaging, high-zoom inspection, or adjustable focal lengths. The flexibility in optics also opens the door to specialized setups involving filters, varifocal lenses, or manual iris control.

While the HQ Camera does not include HDR support, and its low-light performance is not as optimized out of the box compared to sensors with onboard HDR and larger pixel sizes, its larger 1.55 μ m pixel pitch does provide inherently better light sensitivity and signal-to-noise ratio than smaller, lower-cost modules. In well-lit or optically controlled setups, the image clarity and depth of field it provides are unmatched among Raspberry Pi-compatible camera modules. However, for environments with limited ambient lighting or high dynamic range needs, the absence of native HDR can be a limiting factor without careful lighting control or external enhancements.

The camera can deliver high-quality video capture at up to 1080p30, and while the sensor itself supports higher resolutions (including 4K), the Raspberry Pi 5's real-time processing capabilities are best utilized at 1080p, particularly when balancing frame rate with computational demands for image processing and classification tasks.

The HQ Camera is fully supported under Raspbian OS, and integrates smoothly with major libraries including libcamera, Picamera2, and OpenCV. As an official Raspberry Pi accessory, it benefits from extensive documentation, stable firmware support, and broad

community engagement. Its modular lens system is also natively supported through the Raspberry Pi ecosystem, with mounting brackets and accessories readily available.

In summary, the Raspberry Pi HQ Camera offers exceptional optical quality, lens flexibility, and system-level compatibility. While it lacks HDR and enhanced low-light modes found in some newer compact modules, it excels in applications that prioritize resolution, depth of field, and controllable imaging conditions. For the T.R.A.S.H. system, it is best suited for use cases where custom optics and high clarity are required, particularly in well-lit environments with minimal spatial constraints.

3.12.4 ArduCam 16MP

The Arducam 16MP Autofocus Camera, released in Jan 2022, offers a balance of high-resolution imaging and modern autofocus features at a competitive price point of approximately \$25. Built around the Sony IMX519 CMOS sensor, this camera delivers a resolution that is double that of the Raspberry Pi Camera Module V2 and approximately 40% higher than the Raspberry Pi High Quality Camera. This increase in pixel density makes it especially appealing for applications requiring fine detail, such as precision sorting, inspection, and monitoring. Arducam has positioned this series of cameras to support a wide range of industrial and consumer-grade applications, making them versatile tools for embedded systems and smart vision projects.

Although it is not an official Raspberry Pi Foundation product, this module is engineered to be compatible with recent Raspberry Pi software frameworks and is tuned using similar algorithms found in the official camera modules. This results in improved image quality and consistency while maintaining integration with standard pipelines.

The camera supports autofocus functionality, allowing it to adjust dynamically to subjects at different depths, with a MOD of 10 cm. This capability is especially useful in robotic environments where object distances can vary unexpectedly. The module supports video capture at 1080p30, which aligns with the real-time processing capabilities of the Raspberry Pi 5 and is suitable for most visual classification and sorting tasks.

Despite its high resolution, the Arducam 16MP does not include HDR support, which affects its ability to capture detail in scenes with strong contrast between light and dark regions. Consequently, its performance in low-light environments is also limited, making it better suited for consistent, well-lit settings or systems equipped with supplemental lighting.

A significant drawback to note is that this module does not natively support the Raspbian OS, which introduces additional configuration overhead for developers aiming to use it in a standard Raspberry Pi environment. Alternative driver support and adjusted Linux

distributions are often required for full functionality. Similarly, while software libraries are available—typically through Arducam’s own SDK—some customization may be necessary for integration with libcamera and OpenCV workflows.

In summary, the Arducam 16MP camera presents an affordable, high-resolution imaging option with autofocus and flexible usage across advanced applications. However, its limited HDR and low-light support, combined with the lack of native Raspbian compatibility, means it is best suited for controlled environments where resolution is the primary requirement and platform flexibility is less critical.

3.12.5 ArduCam 64MP

The Arducam 64MP Autofocus Camera, introduced in late 2022, represents the highest-resolution imaging solution currently available for Raspberry Pi platforms. Priced at approximately \$60, it brings flagship smartphone camera performance to embedded systems, making it ideal for applications where ultra-high-definition imaging and precision matter most.

This module features a 64-megapixel sensor, capable of capturing still images at an impressive 9152 x 6944 resolution, placing it in a class well beyond typical embedded camera modules. The integration of autofocus, combined with enhanced software features such as electronic pan-tilt-zoom (ePTZ) and continuous autofocus, expands its capabilities in dynamic vision systems. Since September 2023, support for Phase Detection Autofocus (PDAF) has further improved its real-time focusing speed and accuracy—beneficial in fast-moving environments where subject distance may change rapidly.

Designed for the latest generations of Raspberry Pi boards, the Arducam 64MP camera leverages a modern image sensor architecture derived from premium mobile devices. This makes it particularly suitable for projects requiring DSLR-like clarity without the cost, size, or complexity of standalone imaging systems. The sensor’s resolution enables detailed material classification, texture recognition, and wide area scanning with minimal need for mechanical repositioning.

In terms of hardware integration, the module retains compatibility with the v1/v2 form-factor, MIPI CSI-2 interface, and standard tripod mounting systems, ensuring it fits seamlessly into existing Raspberry Pi setups. It is also fully compatible with the latest libcamera software stack, making it easier for developers to transition without rewriting camera pipelines or rebuilding workflows. Despite its third-party origin, the camera is designed to align closely with Raspberry Pi’s ecosystem to provide a smooth development experience for advanced users.

However, it is important to note that while the camera offers cutting-edge resolution, it does not include native HDR support, which can limit its ability to balance exposure in high-contrast scenes. Similarly, its low-light performance, while enhanced by resolution

and optics, may not fully compensate for the absence of dedicated dynamic range enhancement. For best results, this camera performs optimally in well-lit environments or with the assistance of external lighting systems.

Library support includes full integration with libcamera, and with some adjustments, it works well alongside OpenCV for advanced image processing. As a newer module, community support is still growing but actively maintained by Arducam.

In summary, the Arducam 64MP is an exceptionally powerful imaging tool that brings ultra-high resolution and autofocus features to the Raspberry Pi platform. While its lack of HDR and limitations in low-light sensitivity must be considered, its clarity, modern interface compatibility, and support for advanced focus modes make it a leading choice for vision applications where detail and precision are paramount.

3.12.6 Camera Selection

After evaluating six Raspberry Pi-compatible camera modules across multiple technical dimensions—including resolution, field of view, low-light capability, HDR support, and software compatibility—the Raspberry Pi Camera Module V3 and the Arducam 12MP stand out as the most balanced and effective choices for the T.R.A.S.H. platform.

Both modules utilize the Sony IMX708 12MP CMOS sensor, support HDR, and offer autofocus with a Minimum Object Distance of 5 cm, making them well-suited for close-range inspection and object classification tasks. Their 66° field of view is wide enough to reduce mechanical repositioning while still maintaining clarity, and they perform well in low-light conditions, which is vital for consistent performance in indoor and varied lighting environments.

Importantly, both cameras offer full Raspbian OS support, ensuring seamless integration with the Raspberry Pi 5 and compatibility with widely used libraries like libcamera, Picamera2, and OpenCV. Their \$25 price point also aligns well with the project's focus on affordability and COTS-based modularity.

Given these strengths, the Raspberry Pi Camera Module V3 is the primary choice for T.R.A.S.H. due to its official support, wide availability, and superior developer documentation. However, should the V3 become unavailable due to its high demand and frequent stock shortages, the Arducam 12MP will serve as the direct alternative. With nearly identical hardware and software support, it ensures uninterrupted development without compromising system performance or compatibility.

Feature	RPi Cam V2	RPi Cam V3 and ArduCam 12MP	RPi HQ	ArduCam 16MP	ArduCam 64MP
Cost	\$15	\$25	\$50	\$25	\$60
Sensor/MP Count	IMX219 / 8MP	IMX708 / 12MP	IMX477 / 12.3MP	IMX519 / 16MP	64MP Sensor
FOV	62.2	66	Lens Dependent	66	Lens Dependent
MOD (cm)	5	5	Lens Dependent	10	Lens Dependent
1080p Performance	1080p30	1080p50	1080p30	1080p30	1080p30
HDR Support	No	Yes	No	No	No
RaspBian Support	Yes	Yes	Yes	No	Yes
Support	Excellent	Excellent	Excellent	Moderate	Good

Table 25: Camera Comparison

3.13 ROS & ROS2

Robot Operating System (ROS) is an open-source framework designed to facilitate the development and integration of robotic systems. It provides a structured way for multiple components, such as sensors, actuators, and control systems, to communicate efficiently. Rather than developing custom communication protocols for every hardware and software module, ROS allows developers to utilize pre-built libraries, messaging systems, and well-established communication methods. This significantly reduces development complexity while ensuring system flexibility and scalability.

For our project, ROS is a critical component in managing communication between different hardware and software subsystems. Our robotic system involves multiple interconnected components, including a vision system for object detection, motion planning algorithms, and motor controllers for actuation. ROS provides the necessary framework to integrate these elements into a unified system. By using ROS, we can break down the project into modular nodes, each responsible for a specific task, improving maintainability and system stability.

Additionally, ROS has a large and active community, which provides extensive documentation, troubleshooting support, and a vast collection of pre-existing packages. This strong support network accelerates development and ensures that we can incorporate industry-tested solutions rather than developing every component from scratch.

3.13.1 Robot Operating System 1 (ROS)

ROS has been the dominant framework for robotic applications for over a decade. It has powered a wide range of robotic systems, from research projects to industrial automation. One of its key advantages is its modularity, allowing developers to create independent software packages (nodes) that communicate using a publish-subscribe model. This enables seamless integration of different components without requiring direct dependencies between them.

Despite its strengths, ROS has some fundamental limitations. One of its primary drawbacks is that it relies on a centralized master node for communication between components. This creates a single point of failure, if the ROS Master crashes, the entire system loses communication. Furthermore, ROS lacks real-time processing support, making it less suitable for applications requiring precise timing, such as robotic motion control and high-speed sensor data processing.

Another limitation of ROS is its security. Since it was primarily designed for research and prototyping, security features such as encrypted communication and authentication were not a priority. This makes ROS less viable for commercial and industrial applications where data security and reliability are critical.

Additionally, ROS was developed primarily for Linux-based systems, limiting its cross-platform compatibility. Although some workarounds exist to run ROS on Windows, they are not officially supported or optimized for real-world applications.

Due to these limitations, ROS reached its end of life on May 31st, 2025, and is no longer actively maintained. While it still has a large user base, its long-term viability has diminished, making ROS2 the preferred option for modern robotic development.

3.13.2 Robot Operating System 2 (ROS2)

ROS2 was designed as the next-generation replacement for ROS, addressing many of its predecessor's limitations while introducing new features that make it more robust and scalable. One of the most significant improvements in ROS2 is the transition from a centralized ROS Master to a decentralized communication architecture based on the Data Distribution Service (DDS). Unlike ROS, where all nodes had to communicate through a

master node, ROS2 allows for direct peer-to-peer communication, eliminating single points of failure and enabling more scalable multi-robot systems.

Another major advantage of ROS2 is its real-time processing capabilities. It includes improved scheduling and execution models, making it better suited for applications that require precise timing, such as robotic motion control and sensor fusion. This makes ROS2 a superior choice for real-time robotics applications compared to ROS.

Security has also been significantly improved in ROS2. Unlike ROS, which lacked encryption and authentication mechanisms, ROS2 includes built-in security features, such as secure node-to-node communication and access control policies. This makes ROS2 more suitable for commercial and industrial applications where data security and integrity are crucial.

Additionally, ROS2 introduces cross-platform support, allowing it to run not only on Linux but also on Windows and macOS. This provides greater flexibility for integrating ROS2 into a wider range of embedded systems and industrial environments.

3.13.3 ROS Selection

By adopting ROS2 for our project, we gain access to better performance, reliability, and future-proof software support. Its real-time capabilities, improved communication framework, and security features make it the ideal choice for building a robust and scalable robotic system.

Feature	ROS	ROS2
End Of Life	May 31 st , 2025	Actively Supported and being Developed
Middleware	Centralized ROS Master	Decentralized DDS (Data Distribution Service)
Real-Time Performance	Not designed for real-time applications	Improved execution timing and scheduling
Multi-Robot & Distributed Systems	Limited support	Built-in support for multi-robot and distributed applications
Security	Minimal security features	Encrypted communication and authentication
Cross-Platform Support	Primarily Linux-based	Supports Linux, Windows, and macOS
Community & Package Availability	Large community with many legacy packages	Growing community with most major ROS1 packages ported over

Table 26: Ros Comparison

3.14 Spectroscopy Methods

Spectroscopic techniques serve as powerful analytical tools for material identification and characterization, each leveraging distinct principles of light-matter interactions. Reflection-based spectroscopy, transmission-based spectroscopy, Laser-Induced Breakdown Spectroscopy (LIBS), and Raman spectroscopy represent prominent methods, each uniquely suited to different types of material analysis. As an optical engineer, my goal is to select a spectroscopic system that is straightforward to construct, safe to operate, and sufficiently precise to enable accurate material identification.

The subsequent discussion systematically outlines and compares these spectroscopy methods, emphasizing their suitability for particular sample types, sensitivity levels, and instrumentation complexities Table 27. This comparative framework aims to elucidate why specific techniques, such as Raman spectroscopy for molecular precision or LIBS for elemental detection, emerge as optimal choices under defined analytical contexts. Through such detailed analysis, this section provides a comprehensive basis for selecting appropriate spectroscopic methodologies to achieve accurate material identification and characterization objectives.

Parameter	Reflection-Based Spectroscopy	Transmission-Based Spectroscopy	Laser-Induced Breakdown Spectroscopy (LIBS)	Raman Spectroscopy
Principle	Measures light reflected from a sample	Measures light transmitted through a sample	Analyzes light emitted by a plasma formed from the sample	Measures light scattered by molecules; energy shift or Raman effect
Information Obtained	Surface properties, surface chemical composition	Bulk properties, concentration of absorbing spectrum	Elemental composition, trace elements analysis	Molecular structure, chemical composition, crystallinity
Material States	Mostly solids, or reflective surface	Suitable for gases, liquids, and thin or transparent solids	Solids, liquids, and gases	Solids, liquids, and gases
Samples Preparation	Minimal to none	Can requires careful sample preparation for path length	Minimal to none, though the sample is often destroyed	Minimal to none
Destructive	Non-destructive	Non-destructive	destructive	Non-destructive

Typical Application	Material surface analysis, paint characterization, thin films	Environmental monitoring, solution chemistry, medical diagnostics	Metal analysis, environmental monitoring, forensic analysis	Pharmaceutical analysis, materials science, mineralogy
Sensitivity	Dependent on surface smoothness and optical properties	High sensitivity to changes in concentration and path length	High sensitivity to all elements, capable of detecting trace levels	High sensitivity to molecular vibrations
Advantages	Quick and adaptable to in-line manufacturing processes	Accurate concentration measurements, clear and direct data	Fast, requires no sample prep, provides immediate results	Provides detailed molecular information, versatile
Limitation	Limited to surface analysis, can be influenced by surface roughness	Limited by sample transparency, thickness, and homogeneity	Requires high-powered lasers, safety considerations	Requires specialized equipment, fluorescence can interfere
Instrumentation Complexity	Moderate	Moderate to high, depending on the setup	High, due to the need for laser and spectrometer	High, due to the need for lasers and sensitive detectors

Table 27: Spectroscopy Methods Comparison

3.14.1 Raman Spectroscopy

Raman spectroscopy is a spectroscopic technique used to observe vibrational, rotational, and other low-frequency modes in a system. The Raman effect is a form of inelastic scattered light. Incident light from a laser strikes a molecule, most of the scattered light scatters elastically not resulting in an energy change. However, a small portion of the light scatters inelastically these photons have an energy change. The energy change is associated with molecular vibrations to rotations based on the material type. The energy change are classified as Stokes Raman Scattering (SRS) or Anti-Stokes Raman Scattering (ASRS). SRS is defined as if the scattered light has a lower energy than the incident light because the photon has transferred some of its energy to the molecule. The molecule experiences an exciting vibrational mode resulting in a shift to a longer wavelength. ASRS is defined as if the scattered light has higher energy than the incident light because the molecule was initially in an excited vibration state and has lost energy to the incident photon. This results in a higher energy photon with a shorter wavelength.

Material identification is made possible by SRS and ASRS by providing a unique spectral fingerprint based on the vibration energy level of the material. Making Raman spectroscopy a powerful tool for studying the molecular composition of materials. Which is key to achieving material identification for our project.

What does the optical setup need?

3.14.2 Reflection Based Spectroscopy

Reflection-based Spectroscopy is a technique that analyzes the spectrum of light reflected from a sample to determine its properties. A broadband light source is incident on the sample. The reflected light interacts with the samples' surface some wavelengths will be absorbed while others are reflected dependent on the material properties. For spectral analysis the reflected light is collected, and the intensity of the light is measured based on wavelengths. The spectral data provided a fingerprint of the sample. Data Interpretation provides a way to classify the spectrum of an unknown sample to reference spectra.

3.14.2.1 Diffusion Reflectance Spectroscopy

Reflection based spectroscopy has three main methods depending on the type the material we are taking samples from: Diffuse Reflectance Spectroscopy, Specular Reflectance Spectroscopy, and Angle-resolved Spectroscopy. Diffusion Reflectance Spectroscopy (DRS) measures the light that is scattered in many directions after interacting with the sample. Samples for these methods are in the categories of powders, rough surfaces and opaque materials that produce low intensity reflections. Unlike specular reflection, diffuse reflections does not follow the law of reflection; instead, light is scattered spectrally at a various angles due to the irregularities or granularities in the surface.

3.14.2.2 Specular Reflectance Spectroscopy

Specular Reflectance Spectroscopy involves measuring the reflected light that obeys the law of reflection or Snell's Law. Meaning the angle of incidence is equal to the angle of reflection. Suitable samples include smooth and shiny surfaces (e.g. metal, glass, and polished stones). Common application for specular reflectance is used for characterizing thin films, coatings and the semiconductor industry. For our use case this would limit the sample choice of what we could identify; however, is also the simplest optical setup.

3.14.2.3 Angle-Resolved Spectroscopy

Angle-Resolved Spectroscopy *modus operandi* involves changing the angles of incidence and/or observation to measure how much the reflective properties of the surface change with angle. Application is used most commonly in optical engineering for designing and analyzing optical components (e.g. lens and mirrors). In addition, it is used in photonics for quality control in layered materials manufacturing. Out of the three methods for reflection-based spectroscopy I believe that specular reflectance offers the most option for our sample choice.

3.14.3 Laser Inducted Breakdown Spectroscopy

Laser Inducted Breakdown Spectroscopy is an analytical technique that is used for determining the elemental composition of materials. A high-powered pulsed laser is focused at the samples to ablate the surface of the material. Pulse times in this study application of LIBS were 4 ns to 8 ns [12]. The ablation process vaporizes the material creating plasma. As the excited ions in the plasma return to a lower state, they emit light. Since each element has its own characteristic wavelengths. Thus materials can be resolved. Human's fingerprints are akin to materials characteristic wavelength it's a unique identifier. To achieve Spectral Analysis the emitted light is collected and analyzed using a spectrometer.

Advantages to LIBS is its application across a wide variety of sample types. Unlike reflection-based spectroscopy which has a variety of set up to cover a limited number of samples. LIBS has applications across various fields. LIBS is used in material science, Environmental Science, Archaeology, Forensic Science and Space Exploration. LIBS is highly versatile, but it comes at a cost both financially and safely.

Most of the down sides of LIBS come from the Instrumentation complexity and safety concerns. The use of laser with nano second pulse times which on Thor labs can cost \$4750. The choice of lasers and it's characters, wavelength and pulse width are critical for plasma generation. To take full account of the plasma generation a broad spectral range is needed to resolve low energy photons. Timing Systems are required to synchronize and laser pulse with the exposure time of the sensor.

Safety considerations due to the use of higher-powered laser risk eye and skin damage. Proper safety measures will have to be taken when showcasing or developing the laser system. High-Voltage systems used to drive the laser pose risk pose a safety factor as well. Plasma Generation depending on material type may generate ultraviolet light and harmful byproducts. The operation and testing of such a hazardous system in the shared lab environment of senior design

Optical setup find a good LIBS Diagram and get copyright permission.

3.14.4 Transmission Based Spectroscopy

Transmission-based spectroscopy is the fundamental principle of measuring how much light passes through a sample. By analyzing the transmitted light, it provides valuable information about the bulk properties of a material, including the concentration of absorbing species and structural characteristics. This method is suitable for analysis on gases, liquid, and thin or transparent solids.

Variable	Definition
$I_t(\lambda)$	Transmitted light intensity
$I_0(\lambda)$	Relative to the incident intensity
T	The transmittance Error! Reference source not found.
ϵ	Molar absorptivity (L/mol·cm), a material-specific constant.
c	Concentration of the absorbing species (mol/L).
l	Path length (cm), the distance the light travels through the sample.
A	Absorbance, a measure of how much light is absorbed. Equation (2)

Table 28: Specular Reflectance Variables

$$T = \frac{I_t(\lambda)}{I_0(\lambda)} \quad (3.9)$$

$$A = -\log(T) \quad (3.10)$$

$$A = \epsilon cl \quad (3.11)$$

Molar absorptivity (ϵ) in spectroscopy quantifies how strongly a substance absorbs light at the given wavelength. It is a material-specific constant that can be used to resolve unknown materials. Higher molar absorptivity values result in deeper absorption features in the transmitted spectrum. Transmission-based spectroscopy exhibits high sensitivity to even minor changes in both concentration and path length. This sensitivity arises from the Beer-Lambert Law *equation (3)*. The thickness of the sample directly affects the amount of light absorbed. To work around this the sensor can be exposed to greater exposure times.

In conclusion, For high-accuracy material identification, Raman spectroscopy is the most effective due to its ability to provide distinct molecular fingerprints through vibrational analysis, ensuring precise differentiation of chemical compositions. LIBS excels in elemental analysis, offering rapid, high-sensitivity detection across diverse materials, though it is destructive and requires a high-power laser. Transmission-based spectroscopy is ideal for bulk analysis of transparent or thin materials, leveraging high sensitivity to concentration and path length changes but is constrained by sample transparency and uniformity. Reflection-based spectroscopy is best suited for surface characterization but is highly influenced by surface roughness, limiting its application to bulk identification. For molecular-level accuracy, Raman spectroscopy is superior, while LIBS is optimal for elemental composition analysis, making them the most viable techniques for high-precision material identification.

An alternative is to enhance material identification is the integration of Reflection-Transmission Hybrid Spectroscopy (RTHS), combining the strengths of both reflection-based and transmission-based techniques. This method simultaneously analyzes surface and bulk properties by capturing both reflected and transmitted spectra, significantly improving accuracy in heterogeneous or semi-transparent materials. By incorporating dual-path optical configurations, RTHS enables comprehensive spectral analysis, overcoming the limitations of individual techniques—reflection's surface dependence and transmission's transparency constraints. This hybrid approach is particularly beneficial for multi-layered materials, thin films, and biological tissues, where both surface interactions and internal composition are critical for precise characterization.

With a cartice design it may be able to incorporate two light sources

New way to frame the project, the arm can be pitched a assistive robot for lab work.

Paired with sufficient optical power creates a small quantity of plasma.

3.15 Linear CCD Sensor

Write a technology comparison between types of sensors

Liner CCD, Photo diode, CMOS

TCD1304

Make sure to site the spect sheets in the references

Specification	TCD1501D	TCD1304DG
Number of Elements	5000 elements	3648 elements
Pixel Size	7 μm	8 μm by 200 μm
Sensitivity	10.4 to 15.6 V/lx·s	110 to 160 V/lx·s
Dark Signal Voltage	2 mV	Up to 5 mV
Dynamic Range	3000	Up to 300 (no unit specified)
Saturation Output Voltage	3 V	450 to 600 mV
Output Impedance	0.5 to 1 k Ω	0.5 to 1 k Ω
Output Signal Voltage	Not specified	1.5 to 3.5 V
Operating Temperature	-20°C to +60°C	-25°C to +60°C
Package Type	22 pin Cerdip	22 pin Cerdip

Table 29: Linear CCD Sensor Comparison

3.15.1 Optical Performance of Linear CCD

Note for Sayed: could you write some of the electrical driving circuits needed for the CCD's. I am going to write about the optical related side of the sensor.

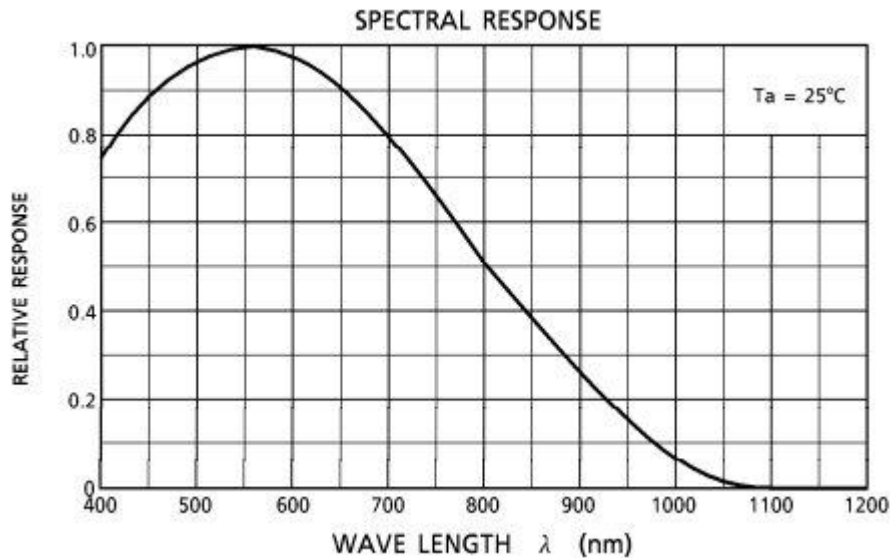


Figure 11: The Spectral Response of Silicon-Based Detectors

3.16 Illumination Sources

The goal of the illumination source is to provide sufficient incident optical power across the wavelength range of 400nm to 1100nm. This range is due to the responsivity of a silicon detector.

Feature	Incandescent Source	WLED Source	RGB LED Source	IR LED Source
Illumination Power				
Power Requirements				
Cost				
Spectral Illumination range				

Spectral uniformity				
...				
...				
...				
...				
...				

Table 30: Illumination Source Comparison

3.14.1 Incandescent Source

Incandescent lamps consist of a filament typically tungsten inside of an evacuated glass bulb with the necessary wired connections. The tungsten filaments are excited with electrical power thus creating heat. Once the filament has reached Approximately 850 Kelvin a red glow will appear [13]. The emitted light for a given element when heated in this matter can be approximated by black body radiation.

$$I(\lambda,T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1}$$

(3.12)

$$\lambda_{max}T = 2.898 \times 10^{-3}m \cdot K$$

(3.13)

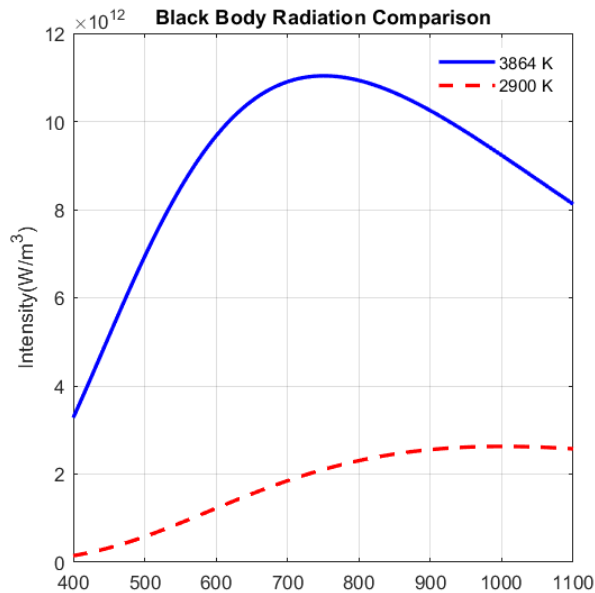


Figure 12: Black Body Radiation Comparison
Theoretical

Using equation 3.27 we can solve for the peak wavelength and T the resulting temperature necessary to heat the filament too. With a center wavelength of 750 nm the temperature needed to heat is 3864 K (**Error! Reference source not found.**). The blue line in the Figure 12: Black Body Radiation Comparison shows the intensity of the source across our interested wavelength range .For context compared to the sun with an average temperature of 6600 K, which defines the wavelengths of light we are accustomed to seeing [13].

Of all possible solid filament tungsten has the highest known melting temperature of 3680 Kelvin and the lowest rate of evaporation of pure metals. In contrast carbon can withstand higher temperatures without melting however it evaporates too quickly. It is because of tungsten high melting point and low vaporization pressure that makes it the ideal case for a incandescent source. To ensure the stable operation of a tungsten incandescent source the useful maximum temperature is about 3000 K with an average of 2900 K [13]. From the ideal temperature of 3864 K to a realistic operating temperature of 2900 K. This temperature shift greatly affects the output intensity of the visible range as seen in Figure 12: Black Body Radiation Comparison Theoretical.

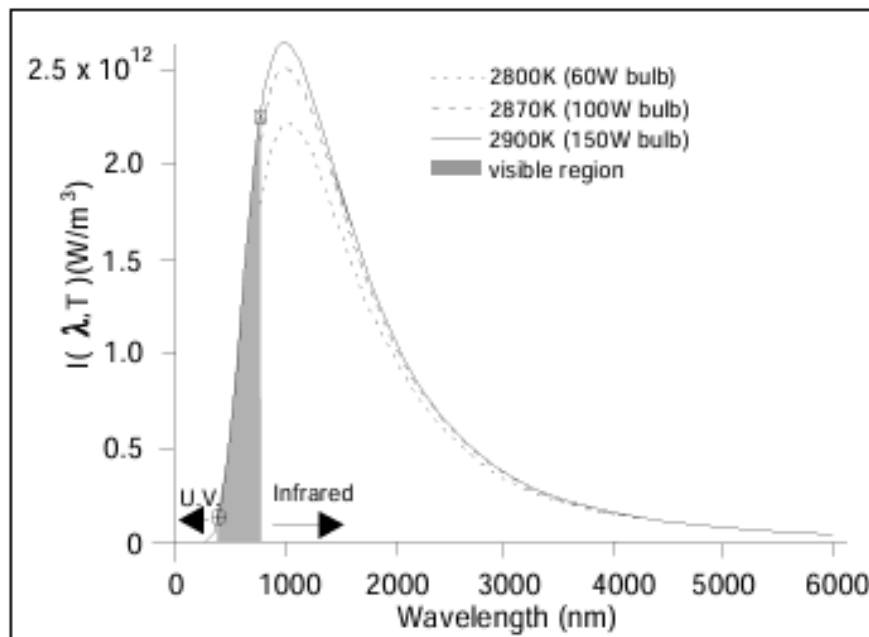


Figure 13: Black Body Radiation Comparison Actual [13]

With the stretch goal of embedding the illumination source and light capturing system into the end effector of the robot we have a limitation. The end effector is going to be 3D printed in PETG My mechanical engineer has placed the constraint The light bulb cannot heat this material above 373 K. In Figure 13 all of the white space under the curve is not

contributing to useful optical power. Considering that all of the light that is outside the visible range will be considered as heat production an incandescent source is not suitable with the end effector.

The driving circuitry necessary for an incandescent source is also cumbersome. Incandescent bulbs are a resistive load that requires a controlled current or voltage source to operate safely and effectively. Traditionally incandescent bulbs were designed for AC line voltage; However, DC power supplies can be used in modern incandescent sources. Components of the driving circuit include current limiters, series resistors, power supply requirements, control and monitoring systems. When an incandescent source is first turned on it has low resistance which causes a large inrush of current to prevent damage. Current limiting resistors are necessary. Current limiting or series resistor must be chosen to provide appropriate power dissipation as well as keeping the current within safe limits. If an incandescent source is chosen because of its uniform illumination, across the desired wavelength range control and monitoring will be essential to limit the thermal transfer into the PEGT end effector.

3.14.2 Light Emitting Diode (LED) Source

The output spectrum of an cannot be described as simply as the black body distribution. Thus, a more in-depth explanation of how LED have their spectrum is required to make justified decision on the choice of LED's. The wavelength of an emitted photon is not simply bandgap the of the semiconductor material. Because electrons in the conduction band of the semiconductor material are a distribution of energies that are greater than the bandgap energy. The purpose of this section 3.12.2 is to justify the design choices in the following section about WLEDs, RGB LEDs and IR LEDs.

To extract light out of an LED the diode device must be forward biased. Now, the P-type material must be active thus excess electrons are being injected into that region. The excess electrons or the electron distribution $n_E(E)$, in the conduction band of the p -type material is a function of the density of states $g(E)$, and the fermi-Dirac probability, $f(E)$ (**Error! Reference source not found.**)[14]. The peak energy $h\nu_0$ of the electron distribution can be approximated by *equation 4. Error! Reference source not found.*[14]. The peak energy $h\nu_0$ of the electron distribution can be approximated by *equation 4*. The term $\frac{1}{2}k_B T$, describes the approximate peak of the distribution $n_E(E)$ above the conduction band and E_g is the energy difference between the valence band and the conduction band [14]. T being the temperature of the material and k_B the Boltzmann constant. There is a similar distribution p_E for the holes in the valence band of the semiconductor; however, the p_E distribution is much bigger than then that electron distribution $n_E(E)$ we can assume the rate of recombination will depend primarily on the injected electron distribution [14].

The purpose of understanding the electron distribution is to better understand how this effects photon energy distribution and thus the emission spectrum.

$$n_E(E) = g(E)f(E) \quad (3.14)$$

$$h\nu_0 \approx E_g + \frac{1}{2}k_B T \quad (3.15)$$

Now that we have defined the electron distribution lets understand how this effects the emission spectrum. When these electrons recombine with holes near the valence band edge E_v , they emit photons. The photon energy is the difference between the electron and hole energy levels. Since most recombination occurs from electrons near the peak of n_E because they have the highest energy state **Error! Reference source not found.** and visualized in Figure 14.

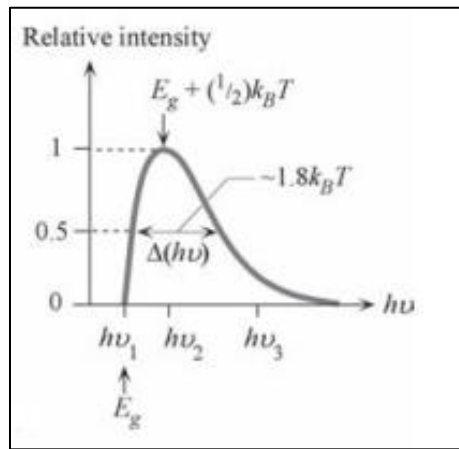


Figure 14: Relative Intensity of Light as a Function of Photon Energy [14]

The relative intensity of light as a function of photon energy based on a direct bandgap semiconductor and the electron distribution described in Next, wavelength and photon are inversely related to each other defined in **Error! Reference source not found.**

$$\lambda = \frac{hc}{E} = \frac{hc}{h\nu} \quad (3.16)$$

h is planks constant, c is the speed of light and E is energy **Error! Reference source not found.** is how to connect the wavelength to the electron distribution. Using $h\nu$ from **Error! Reference source not found.** and finding the relative spread by **Error! Reference source not found.** The result of is the range is the emitted wavelength from the LED. The peak of this range is the results of **Error! Reference source not found.**

$$\Delta(hc) \approx E_g + 2 \times \frac{1}{2} k_B T = E_g + k_B T \quad (3.17)$$

$$\lambda_0 = \frac{hc}{E_g + \frac{1}{2} k_B T} \quad (3.18)$$

To summarize the purpose of the previous discussion, the goal was to build a foundational understanding of how LEDs emit light and to evaluate the suitability of various illumination sources for integration into the robotic end effector. The analysis clearly indicates that LEDs offer substantial advantages for this application. Specifically, mechanical engineering constraints impose a temperature limit of 373 K on the end effector, making thermal management a critical consideration. Given that the project's stretch goal is to incorporate a spectrometer into the robotic hand, thoughtful and proactive design decisions must be made to minimize integration challenges.

LED illumination sources are favorable primarily due to their low thermal output, making them suitable for the temperature constraints mentioned above. Additionally, LEDs only require a low-voltage (typically 5 V DC or less) power source, simplifying the driving circuitry significantly compared to incandescent sources. While it is true that incandescent sources offer relatively uniform optical emission across the targeted wavelength spectrum (400–1100 nm), their practical challenges, including high thermal emission and complex power requirements, outweigh this benefit.

Consequently, the subsequent section of this research will focus on addressing the challenges associated with achieving comprehensive spectral coverage from 400 nm to 1100 nm using LED-based solutions.

3.14.2.1 White LED (WLED)

A blue LED with phosphor (WLED) operates by emitting high-energy blue photons through direct recombination, as described in the previous section 3.16.2. These photons, centered around 450 nm, excite a phosphor layer that re-emits light at longer wavelengths, producing a broader spectrum across the visible range. The resulting white light combines the sharp blue LED emission with the broad, down-converted phosphor emission. Unlike direct band-to-band recombination, the phosphor spectrum does not follow the electron distribution described $n_E(E)$ **Error! Reference source not found.**, but rather reflects the material's fluorescence response, which broadens the overall spectral output. The broad and relatively wide range of emissions make it a favorable selection for a light source.

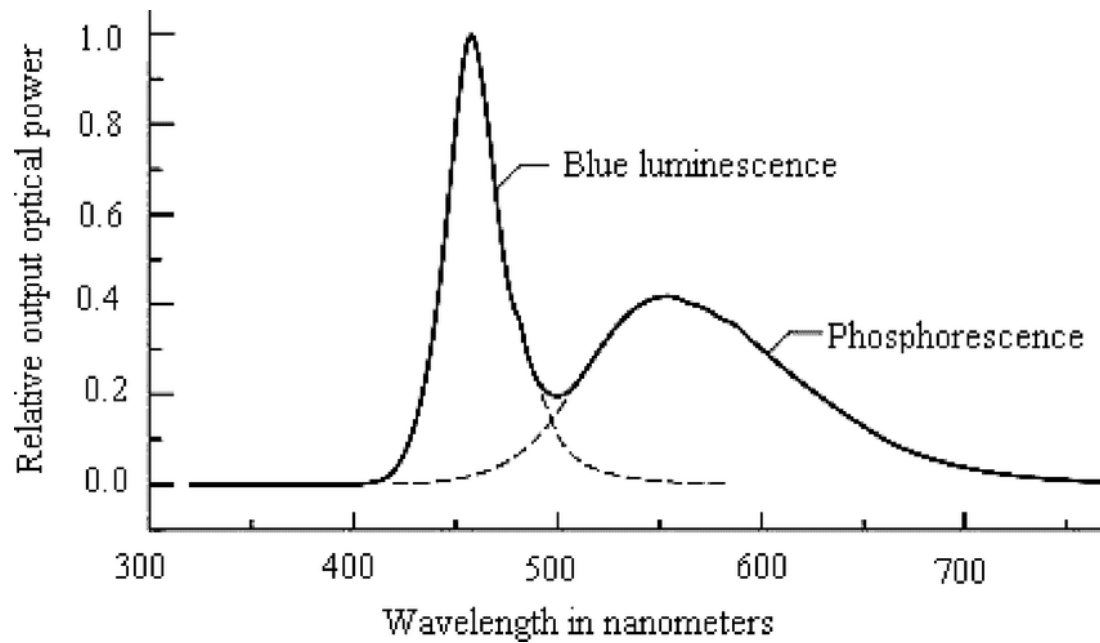


Figure 15: Emission Spectrum of WLED

3.14.2.2 RGB LED

An RGB LED consists of three individual LEDs — red, green, and blue — each with its own semiconductor material and corresponding bandgap. The emission from each sub-LED follows the electron distribution behavior explained earlier, with a spectral peak at defined by **Error! Reference source not found.** These emissions are relatively narrow, and when combined, the LED outputs a multi-peak spectrum as seen in **Error! Reference source not found.** The overall color can be adjusted by controlling the current through each LED, allowing for dynamic color mixing. Unlike phosphor-based white LEDs, RGB LEDs produce color directly from semiconductor recombination, making them ideal for

display

applications.

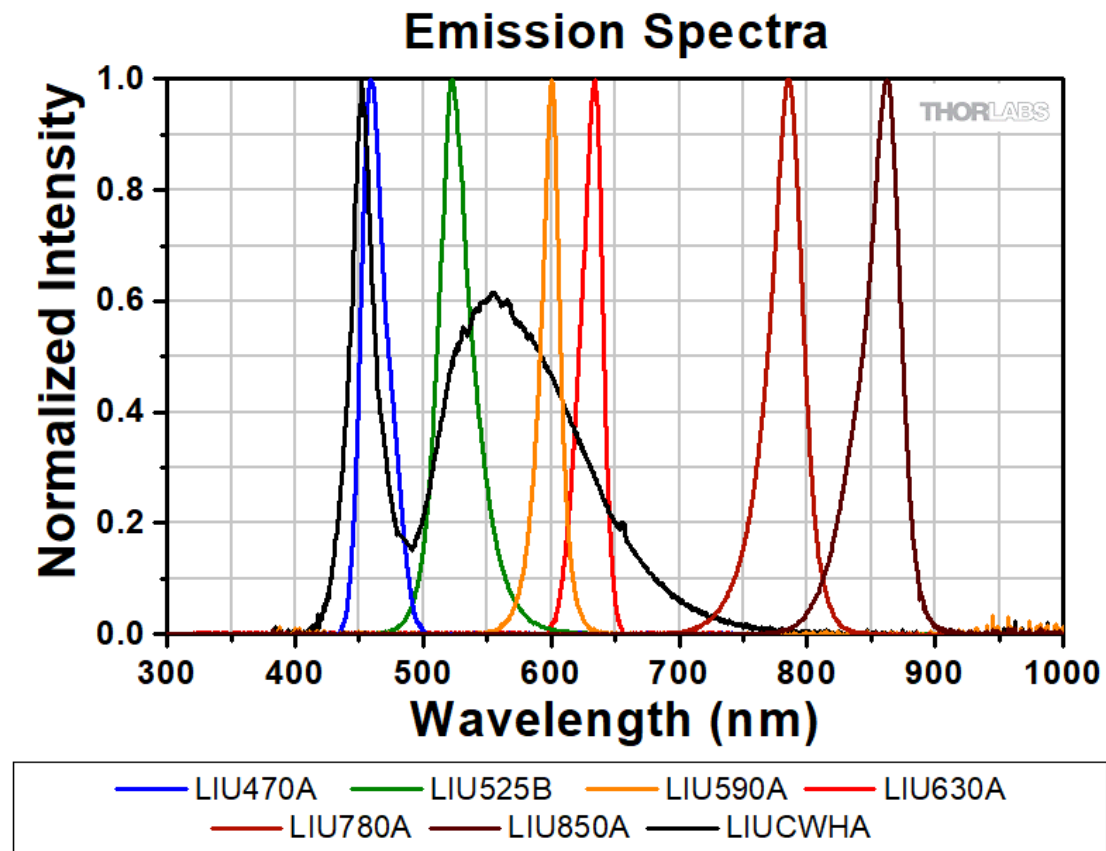


Figure 16: Spectral Information of a Variety of LEDs from Thor Labs.

3.14.2.3 Infrared LED (IR LED)

Infrared LEDs emit photons in the near-IR region, typically around 850–950 nm. These devices use semiconductor materials with smaller bandgaps, such as GaAs or AlGaAs. The emission spectrum follows the same principles discussed earlier, with the peak wavelength determined by *Error! Reference source not found.*. However, the observed IR LED spectra often show greater asymmetry and broader linewidths than predicted by the ideal model. This discrepancy arises from heavy doping effects, which introduce impurity bands that effectively lower E_g , as well as from photon reabsorption and recombination-induced energy redistribution. With that said illumination for WLEDs drop off at 800nm. So, to cover the entire spectrum LED's from 800nm to 1100nm are required. it would be idea to have some LEDs to cover the missing spectra. Thor labs have just the LEDs we need. The LED930L has a FWHM cover from 890nm to 960nm. In addition, the LED 1050E which covers the range from 995nm to 1105nm. The LEDs do have some overlap between these values which will be helpful for full spectrum coverage.

For the final system an array of these three LED types: LED930L, LED1050E and a WLED. Is a favorable array because to replace the WLEDs spectrum requires four to five LEDs types. To put frank it's easier to drive an array of WLED and have them in parallel. Then the IR LEDs cover for the WLED in the NIR range.

3.15 Resolving Position with Optics System

For the computer vision with a single camera setup resolving depth can be quite difficult. Knowing the depths from the end effector of the robot is the first step in the process of the final goals of the computer vision resolving the position data. I am going to address the fundamentals of triangulation to understand how optics can assist the computer vision in resolving position.

In a computer vision system utilizing a single camera, resolving depth information is inherently challenging due to the loss of three-dimensional context in a two-dimensional image. For robotic applications, however, accurately determining the depth of objects relative to the robot's end effector is a crucial first step toward reliable position estimation and spatial awareness.

Method	Configuration	Principle	Pros	Cons	Hardware Complexity	Depth Accuracy
Monostatic	Single source & detector (collocated)	Time-of-flight	Simple, compact, easy integration	Limited to single-point depth; ambiguities with multiple scatterers	Low	Moderate limited in complex scenes
Bistatic	Source and detector separated	Time-of-flight	Greater flexibility; diverse measurement geometries	ambiguities remain for multiple scatterers	Medium	Moderate still limited for complex scenes
Range Tomography	Multiple sources and/or sensors at multiple positions	Intersection of multiple spherical or ellipsoidal constraints	Resolves multiple scatterers; precise 3D localization; robust reconstruction	Requires multiple measurement points	High	High; accurate 3D reconstruction
Depth from Defocus (DfD)	Single camera with known PSF	Image blur analysis & deconvolution of defocus PSF	Single camera setup; no additional viewpoints needed;	Requires precise calibration; sensitive to optical	Low	Moderate; depends heavily on calibration and blur-

			computationally efficient	parameters and noise		model accuracy
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Table 31: Comparisons of Optical Positioning Systems

3.15.1 Triangulation

The fundamentals of triangulation via a practical example. Using probes that are both source and the sensor know as a monostatic configuration [15]. The source emits a pulse as the pulse hits the object then creating scatter. That scatter then received by the sensor using their relationship in **Error! Reference source not found.** we can solve for the range of the object to the detector [15]. Using probes that are both source and the sensor know as a monostatic configuration [15]. The source emits a pulse as the pulse hits the object then creating scatter. That scatter then received by the sensor using their relationship in **Error! Reference source not found.** That scatter then received by the sensor using their relationship in **Error! Reference source not found.** we can solve for the range of the object to the detector [15]. The variables for **Error! Reference source not found.** The variables for **Error! Reference source not found.** The fundamentals of triangulation via a practical example. Using probes that are both source and the sensor know as a monostatic configuration [15]. The source emits a pulse as the pulse hits the object then creating scatter. That scatter then received by the sensor using their relationship in **Error! Reference source not found.** we can solve for the range of the object to the detector [15]. The variables for **Error! Reference source not found.** τ is the time of arrival, R is the range or distance from object to detector, and v is the velocity of the pulse.

$$\tau = \frac{2R}{v}, \quad (3.19)$$

While the basic triangulation principle using a single source/sensor provides valuable depth information for a single point, a practical computer vision system, especially one intended for use in robotics requires the ability to resolve multiple scatterers or features in a scene. This introduces the need for additional measurements and system complexity.

To stay consistent with the design of the robot where we may only want one camera in the end effector, I will discuss a system to resolve position. Then discuss why adding additional detectors with the goal of improving the spatial resolution is necessary. The first system is classified as a multi-static setup, where the sensor passively receives signals from various emitters after they are reflecting or scatter from objects in the workspace. Since the setup involves the separation of source and sensor. What are the fundamental principles that resolve the range in that type of system.

The separation of the source and sensor is known as the Bistatic Configuration [15]. To solve the projection surface in the case is an ellipsoid. The source and sensor are at the foci. r_s is the position of the source, r_d is the position of the detector, r is the position of the

scatter, v is the velocity in the medium, and t is the pulse time of flight **Error! Reference source not found..**

$$|r - r_s| + |r - r_d| = vt \quad (3.20)$$

Now we have discussed both monostatic and bistatic configuration to resolve range. Each of these methods in their simple forms are unable to identify multiple scatters at unknown locations. By gathering a sufficient number of measurements from various locations (which provide multiple views), the positions of the scatterers can be determined. This approach calls for a tomographic method, specifically known as range tomography [15].

Range tomography does require more than one detector. Meaning having only one sensor in the end effector is not viable for this solution. However, if tomography can affect the best solution to 3D positioning implementing more sensors is viable. As previously discussed, monostatic and bistatic configurations each provide valuable but limited spatial information due to ambiguities when multiple scatterers are present [15].

By acquiring multiple range measurements from distinct locations, one can intersect numerous spherical or ellipsoidal constraints, effectively pinpointing the positions of the scatterers. This method, known specifically as range tomography, emerges as an ideal solution to the challenges faced by single-view triangulation approaches. Therefore, while incorporating tomography would necessitate deploying additional detectors or emitters, its substantial improvement in spatial resolution and accuracy makes this increased complexity both justified and strategically beneficial for robust 3D positioning in robotic vision systems.

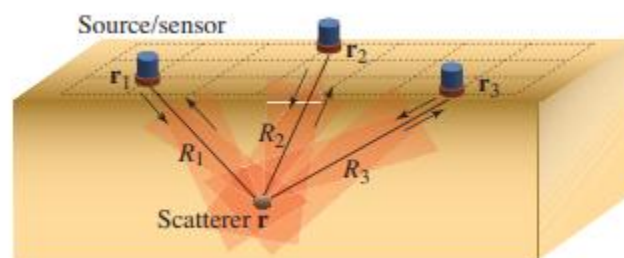


Figure 17: Range Tomography [15]

Figure 17 was taken from source [14], the purpose of this image is to visualize the method of range tomography. It is three monostatic units to resolve the location of a single scatterer.

Triangulation serves as the fundamental principle for resolving depth and spatial position using time-of-flight measurements as seen in Figure 17. In a monostatic configuration,

where the source and sensor are collocated, range is determined based on the round-trip time of a pulse reflected from a scatterer. This setup is simple and compact—ideal for robotic systems with limited hardware capacity, such as a single camera mounted on an end effector. In contrast, a bistatic configuration separates the source and detector, enabling more diverse measurement geometries. Each bistatic measurement constrains the scatterer's position to an ellipsoidal surface, offering greater flexibility and potential accuracy in complex scenes. While both configurations can determine the range to a single point, they are limited when multiple scatterers are present. To resolve full spatial distributions of unknown scatterers, these configurations must be extended into a tomographic system, where multiple measurements from different locations are combined. This process, known as range tomography, enables the reconstruction of a 3D scene by interpreting the overlapping constraints from each measurement. In robotic vision, such tomographic approaches—rooted in triangulation—allow a single mobile sensor, paired with multiple emitters, to build a depth-aware understanding of the environment for accurate positioning and navigation.

If the addition of depth sensing is necessary range tomography is the most comprehensive system to solve the distance problem.

3.15.2 Deblurring method

If you have a single camera (or lens) and can measure how large the defocus blur spot is—along with calibrations of lens aperture and focal length—then, in principle, you can infer the distance of the underlying object plane. Range tomography requires the implementation of an additional optical system the deblurring method can be implemented with the initial hardware design.

One way to recover three-dimensional information from a single camera is by exploiting the phenomenon of defocus blur. When an optical system images a scene that extends beyond a specific focal plane, points away from that plane appear blurred. By modeling this blur—often with a known point spread function (PSF)—you can systematically “invert” the blur effect and estimate how far each point is from the camera. This approach, commonly referred to as Depth from Defocus (DfD), effectively derives depth by measuring and interpreting the size of the blur circle in the recorded image[15].

$$g(x, y) = h(x, y) \otimes f(x, y), \quad (3.21)$$

where $f(x, y)$ is the true scene and $h(x, y)$ is the PSF associated with the blur **Error! Reference source not found..** Because this blur is linear and shift-invariant (i.e. often well-approximated by a Gaussian for defocus), one can perform deconvolution or deblurring to recover $f(x, y)$ from $g(x, y)$ [15]. In principle, once the shape or width of the blur kernel is known at each pixel or region, the resulting variations can be mapped back to scene depth, since objects further from the lens's focal plane will produce larger blur spots. Furthermore, by leveraging the kinematics of a robot arm, multiple images can be acquired at different

distances from the object; in each image, the deblurring effect is measured and used to refine the relationship between blur radius and focal plane offset, ultimately enabling precise localization of the object in three-dimensional space.

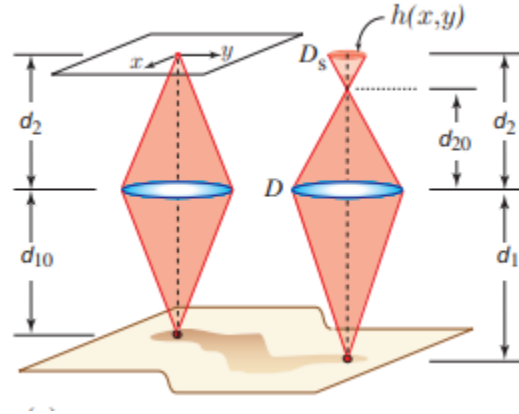


Figure 18: Deblurring Effect [15]

This image was taken from source [14]. To illustrate how a change in distance results in deblurring. As well as serve as a reference of the variable location for the following equations **Error! Reference source not found.** and **Error! Reference source not found.**

$$h_{in}(x, y) \propto \left| P_1 \left(\frac{2\pi}{\lambda d_2}, \frac{2\pi}{\lambda d_2} \right) \right|^2 \quad (3.22)$$

$$\frac{1}{d_e} = \frac{1}{d_1} + \frac{1}{d_2} - \frac{1}{f} \quad (3.23)$$

The underlying geometry in Equations (3.22) and (3.23) shows that moving an object away from the plane of best focus increases the blur spot, in the recorded image. By measuring this blur diameter and calibrating it against known lens parameters (such as the aperture size and focal length), one can systematically infer how far each part of the scene is from the lens by the variable d_e in (3.25). (3.24) is to help solve the PSF associated with the blur.

Hence, even with a single camera, the amount of defocus provides valuable depth cues. After acquiring one or more images at specific focus settings, deblurring algorithms estimate the PSF and its variation, allowing them to reconstruct both a sharper image and an approximate depth map of the scene. This technique, depth from defocus, does not require stereo vision or multiple viewpoints and can be implemented on ordinary hardware, provided the blur model is well defined and the system is adequately calibrated.

3.16 Grating Physics

Spectrometers rely on dispersive elements to separate light into its component wavelengths. In dispersive spectrometers – including modern imaging spectrometers – this is achieved by either a prism or a diffraction grating, which spreads the incident spectrum across a detector array. Imaging spectrometers (used in hyperspectral remote sensing) form a two-dimensional image while simultaneously dispersing light in the orthogonal direction to encode spectral information[16].

3.18.2 Principle of Operation

Optical gratings are precisely engineered optical components that produce dispersion through the physics of diffraction and interference. A grating typically consists of a surface or volume with a periodic structure. When light strikes this periodic structure, it is diffracted into multiple directions, corresponding to different diffraction orders m .(3.24) which quantify how each wavelength is sent into a different angle. This means that as wavelength changes, the outgoing angle of a given order changes, leading to spatial separation of colors. $\Delta\lambda_{min}$ (3.25) quantifies the minimum resolvable spectral separation. Notice that it's not constant across the system it's also wavelength dependent.

$$\sin\theta_d = \sin\theta_i + m \frac{\lambda}{\Lambda} \quad (3.24)$$

$$\Delta\lambda_{min} = 1.22 \frac{\Lambda \cos\theta_d}{D m} \lambda \quad (3.25)$$

Symbol	Meaning
Λ	grating period
D	beam diameter
$\Delta\lambda_{min}$	minimum-resolvable spectral separation
m	diffraction order
θ_i	incident angle
θ_d	dispersion angle

Table 32: Relevant terms for (3.24) and (3.25) from [16].

Gratings are especially favored in imaging spectrometers because they can provide the required spectral resolution and range while maintaining a compact form factor [16]. Gratings are used in spectrometers over prisms in many cases because of their superior dispersion control and flexibility in peak transmission point. A well-designed grating

spectrometer can achieve much higher resolving power than a prism-based design of similar size [16]. Equation (3.25) helps to approximate the minimum-resolvable spectral separation I can expect to get on the final design. Gratings can also be used over a wider range of wavelengths including ultraviolet and infrared bands where prism materials become impractical [16]. These advantages make diffraction gratings ubiquitous in modern spectrophotometers, monochromators, and imaging spectrometers.

Next, a deeper dive into prisms and their spectral cover. Prisms have a limited spectral coverage dictated by the transmission window of the prism material[16]. For example, common optical glasses can cover the visible and part of the near-infrared (up to $\sim 1.5 \mu\text{m}$), and fused silica can extend into the short-wave IR ($\sim 2.5 \mu\text{m}$)[16]. To reach further into the infrared, one must use specialized IR prism materials (such as CaF_2 , ZnSe , or alkali halide crystals), which often come with drawbacks like high refractive indices leading to large reflection losses[16]. Using Prisms as the Dispersion mechanism can be cost prohibitive due to the material choice. As well as greatly increasing the foot print of the spectrometer.

In conclusion, diffraction gratings have become the dispersive element of choice in most modern spectrometers especially imaging spectrometers due to their high dispersion efficiency, tunable resolving power, and broad spectral usability[16]. They enable compact, high-performance spectrometers that can operate from the UV through the IR with appropriate configurations. Prisms, being the older technology, still offer advantages in simplicity and spectral purity, and are well-suited for moderate-resolution applications over limited wavelength ranges [16]. The choice between a grating and a prism ultimately hinges on the instrument requirements: for high resolution or extended spectral coverage, gratings typically outperform, whereas for low stray light and simplicity in a restricted band, a prism spectrometer may be preferable. This section 3.18 has outlined the fundamental working principles of optical gratings and justified their prevalent use in spectrometers, while also comparing and contrasting them with prism-based approaches in terms of dispersion mechanism, resolving power, spectral range, and optical performance.

3.19 Spectral Characteristics of Recycled Materials

A critical aspect of the project is the successful identification of the materials, so the robot arm knows where to place the appropriate. The goal of this section is to see which materials can be identified in the 400 nm to 1100 nm range. The goal of this section is to find a set of materials that have sufficient enough peak wavelengths to successfully identify the materials.

3.19.1 Distinguishable Materials

Materials that lack distinctive characteristic wavelengths we can applying the first derivative transformation to the Spectra can greatly enhance the subtle specular differences. Recalling from calculus the first derivative accentuates inflection points in the spectrum and turning small absorption features into pronounced features.

Identifying common plastics (e.g. PET, HDPE, PP, PVC, PS) Fewer reflective spectroscopy in the defined range is challenging because their raw reflectance spectra are often similar looking.

I found a source that can identify PET from PVC with spectral information that is less than 1100 nm. For the samples of the plastics they used a variety of colors and age of the plastic[17]. The separation of these two plastics is critical for recycling efforts. The Presents of PVC in plastics waste may generate hazardous chlorinated compounds[17]. This accuracy is needed for successful material identification using a spectrometer; however, this accuracy is overkill for our goals of identifying trash against recycling.

Paper and cardboard are cellulose-based, giving them a different spectral signature than plastics. Dry paper (especially white office paper) tends to have high diffuse reflectance throughout the visible and NIR, resulting in a bright, relatively flat spectrum from 400 nm up to about 1300 nm. Cardboard (brown fiberboard) contains lignin and other impurities, which absorb more in the blue and violet end of the spectrum – this is why brown cardboard appears dull brown. No sharp absorption features occur in paper's reflectance below 1100 nm – the chemical bonds in cellulose (C–H, O–H) do have overtone absorptions, but the strongest are at ~1450 nm and 1940 nm (water/OH) and ~2100 nm (cellulose combination band), outside our range. The lack of strong absorption bands below 1100nm make it harder to distinguish against other objects.

The some of the only materials I have found where the material is distinguishable is glass. Glass behaves very differently from plastics or paper in this spectral range. Clear glass (e.g. flint glass bottles) is mostly transparent from 400–1100 nm, meaning it does not reflect or absorb much – instead, most light passes through. Thus, a light sources will have to be placed in such to use transmission spectroscopy. Colored glass, however, has deliberate additives that absorb specific wavelengths: Green glass (e.g. wine bottles colored with iron chromite) strongly absorbs in the red and NIR part of the spectrum, while transmitting green wavelengths. amber glass effectively filters out <500 nm “high-energy” light almost completely, giving it a dark brown appearance.

Material	Wavelengths	Unit
PET (Polyethylene terephthalate)	1130, 1170, 1420, 1660	nm
PVC (Polyvinyl chloride)	1200, 1420, 1480	nm
HDPE (High-density PE)	1210	nm
PP (Polypropylene)	1180, 1190	nm

PS (Polystyrene)	1675	nm
Paper	High reflectance from 400 to 1100	nm
Aluminum	High reflectance from 400 to 1100	nm
Copper	High reflectance in the 600 to 700	nm
Green Glass	600 to 700	nm
Brown Glass	400 to 500	nm

Table 33: Materials and Their Characteristic Wavelengths

This table information is a collection of data form studies [18] and [17]. Notice that lack of materials that have discernible features in the 400nm to 1100nm range.

Add the Stuff from the other CREOL senior design project

3.19.2 The Usefulness of The Spectrometer

After evaluating the spectral characteristics of plastic, paper, cardboard, and glass. Each common recyclable would be suitable for the scope of the project. It is evident that almost all of these common recyclables have at least some measurable features within the wavelength range of interest. The near infrared reflect data from 900 nm to 1100 nm which falls within our sensitivity of detector. Even if these points are often subtle output changes, I will raise the concern that the responsivity of our sensor also drops off in these longer wavelengths. If the spectrometer makes it into the final design optimization will have to be done in these sensors' lowest responsivity area. For the materials that fall within the more visible higher responsivity of the sensor in the case of paper and aluminum there's a lackluster of distinguishable features. Of the possible items that I would consider distinguishable it leaves us with copper, green glass and brown glass.

There is a lackluster of distinguishable features that reside inside the wavelength of our silicon-based detector. It begs the question of whether a spectrometer limited to this range is a suitable identification method. A silicon-based spectrometer may not be sufficient to reduce the ambiguity to identify a wider range of recyclables.

Since this project already was going to use computer vision to solve location; however, challenges have been faced with resolving distance and position. There is a question that an optical-based time of flight system can help with finding the locations of the objects. Then for the computer vision use object identification. Since the accuracy in which the trash and recycling will be defined as blue and yellow bins used in home recycling.

4 Standards and Design Constraints

4.14 Relevant Standards

4.14.1 Universal Asynchronous Receiver-Transmitter (UART)

UART is a serial communication protocol that enables asynchronous serial data transfer between devices. It is based on the industry standard TL16C550 asynchronous communications element [19]. It works with just two wires—transmit (TX) and receive (RX) and doesn't need a shared clock between devices. This makes it simple to implement and ideal for basic communication between microcontrollers or for debugging purposes. In our project, we use UART mainly to send serial output for testing and logging system behavior during development.

4.14.2 Inter-Integrated Circuits (I2C)

I2C is a de facto world standard for low-speed serial communication, originally developed by Philips (now NXP)[20]. It uses just two lines, SDA for data and SCL for clock, and supports multiple devices on the same bus by using addresses for communication with a specific device, which makes it perfect for systems with limited pins or space. In our design, I2C allows microcontrollers like the STM32 and sensors to communicate with each other and with the Raspberry Pi.

Because it's a widely adopted standard, I2C ensures compatibility with a large variety of components. It's especially useful for connecting multiple devices efficiently without a lot of wiring or extra complexity.

4.14.3 Serial Peripheral Interface (SPI)

SPI is a more complex serial communication protocol, mainly used for short distance wired communication between ICs. It's a de facto standard designed by Motorola during the 1980s, and it's known for being faster and more reliable than I2C in many use cases. It uses four wires—MOSI, MISO, SCLK, and CS—and supports full-duplex communication. We plan to use SPI in areas of the system where speed is critical.

Even though it uses more pins, SPI is great for data-heavy applications, which makes it a solid choice for performance-sensitive parts of our robotic system, and it is a great interface to integrate into a PCB.

4.14.4 Robot Operating System (ROS) Compliance

For our robotic software framework, we selected ROS 2 due to its strong presence in both industry and academia, as well as its compatibility with compact hardware like the Raspberry Pi. ROS 2 allows us to build a modular system where each part of the robot—such as vision, motion, and control—can operate independently but communicate seamlessly. This structure supports efficient debugging, future expansion, and clean integration across all subsystems.

ROS 2 also provides access to a wide range of open-source tools essential to our development. We are using MoveIt 2 for motion planning and manipulation of the robotic arm, Nav2 for potential navigation applications, OpenCV for real-time object detection and classification, RViz for live system visualization, and Gazebo for simulating the complete robotic workflow in a controlled environment. These tools help us streamline both testing and deployment without the need for costly third-party software.

By leveraging ROS 2 and its ecosystem, we ensure that our system is scalable, cost-effective, and aligned with modern robotics standards. It enables us to simulate, visualize, and control the robot smoothly, all while meeting key design constraints related to performance, power, and ease of development.

4.14.5 ISO 10218

ISO 10218 is an international standard that outlines safety requirements for industrial robots. While our project isn't an industrial robot in the traditional sense, we're still referencing this standard to guide how we handle safety. For example, we're considering things like emergency stop buttons, safe operating speeds, and minimizing risk during human interaction.

Following ISO 10218 helps us build a system that's not only functional but also safe to operate in a lab or demo setting. It also prepares us in case this system ever needs to meet stricter safety regulations for more professional use.

4.15 Design Constraints

4.15.1 Economic Constraints

When it comes to designing a robot arm, there are many aspects to take into account. For most industrial robots, the main area of concern relates to accuracy and precision. Both of these criteria relate to the field of controls, which is a highly complex mathematical field. As the environments these industrial robots operate in become more complex creating more variables, the robots require ever more complex control systems to maintain proper functionality. One way that many roboticists in the industrial automation sector combat the

complexities that deal with control systems is by increasing the weight of these robots. Increasing the weight of the robot makes robot harder to move, reducing the amount of backlash and overshoot. This then creates a new issue of settling time with the robot end effector taking a considerably larger amount of time to reach its desired goal. To address this new challenge, roboticists use large speed reducers and higher torque motors to be able to move the now thousand-pound robot arm. With higher density material increasing the weight, along with complicated speed reducers, custom machine milled, and actuators capable of moving multi-ton payloads, industrial robot arms are an expensive price tag for manufacturing plants and are completely unreasonable for small-scale operation.

In the waste management industry a significant amount of revenue is earned through processing and recycling of waste material. Some waste is sorted for waste-to-energy facilities to generate electricity. Other items are collected for compositing. Some items are collected and sold as recycled material. Therefore, it is of great interest for waste management facilities to efficiently organize and collect different materials.

4.15.2 Safety Constraints

A major concern in the field of robotics is the safety of workers around industrial robotics. Because industrial robots are designed to be extremely heavy with very powerful motors, collaborative workspaces with industrial robots working alongside humans or other robotic systems is impossible. Therefore, it is of great interest for companies to invest in robots that do not suffer from these design parameters and can allow for workers and other systems to work safely together.

TRASH aims to as lightweight as possible allowing for less powerful motors to be used. This will result in a lower cost for the customer as well as a safer work environment. With a safer work environment waste management facilities can operate on or around the robots without needing to conveyor line.

4.15.3 Environmental Constraints

One of the main concerns in the realm of robotics is energy. While robotics are more effective than manual laborers, they are not as energy efficient. Human beings are extremely energy efficient. However, machinery requires a substantial amount of power in order to operate as desired. This power comes at an environmental cost. While there are many green forms of energy, the industry is not advanced enough to cover an industrial robotics revolution. Therefore, all required energy for these industrial robots will utilize an increasing amount of non-renewable energy, negatively affecting the environment.

Because TRASH utilizes weaker motors than conventional industrial robots it will not have as much of a power draw as other industrial robots. It will, therefore, be more environmentally friendly. It is also possible that with enough optimization and efficiency, waste management plants will be able to generate their own electricity from waste products, helping combat the increasing power requirements generated by the facilities. Someday, waste facilities may even reach a net positive in power consumption.

4.15.4 Manufacturability Constraints

Common industrial robots are made completely in-house with little purchasing of parts. Some robotics industries go so far as to manufacture their own motors to fit their design requirements. While these companies do create beautiful and innovative products, they also require a lot of funding to manufacture and tend to deviate a company's resources to areas it does not need to focus.

TRASH will not be taking a component design approach. Instead, our project will use readily available resources and components to reduce the necessary time and resources spent on fitting design requirements. There will be a number of custom-designed components. However, these components will be easily manufactured using FDM printing. We will use this manufacturing process as the 3D printing industry as become more available at higher quality.

4.15.5 Time Constraints

For the our project we have a very limited time to complete TRASH. Our team will be completing Senior Design 1 and 2 during the Spring and Summer semesters, respectively. The Summer semester is 4 weeks shorter than the normal Fall semester. Additionally, multiple members of our team have been dealing with major family events, reducing the amount of time and mental resources being allocated to the project.

5 Comparison of ChatGPT and other Similar Platforms

A.I. is a revolutionary development and it's been the villain of countless sci-fi movies of the best few decades. The purpose of this chapter is to understand it's effects in the context of our senior design project. Whether we believe these platforms are beneficial or harmful in the learning experience of senior design. AI is a tricky subject to decide whether good or bad in an academic setting because it's akin to Pandora's box. Pandora's box in the story symbolizes a curiosity and desire for knowledge that have both negative and positive outcomes. It's this symbolic meaning of Pandora's box that is most similar into AI. It holds great potential for insight but can also lead to superficial understanding if misused. The use of AI in academic settings is simply a battle of overuse versus strategic use.

If students depend too much on AI, they will fail to develop a deeper understanding of their projects. In my opinion the purpose of senior design is meant to challenge students to think critically to solve the open ended problems akin to the challenges faced in the real world. When AI is used as a crutch instead of an aid, this mentality will lead them to, without developing their own insight into the project they will have a superficial understanding. These superficial understandings of the challenges that lay ahead in senior design 2.

Without internalizing the meaning behind design choices students may find themselves ill equipped to troubleshoot and thus face unforeseen setbacks.

Not all uses of AI in senior design are detrimental. When AI platforms like ChatGPT and Grok 3 can be used responsibly. A student can leverage AI to accelerate routine tasks such as generating graphs for applicable equations and summarizing technical papers to gauge whether the paper is appropriate for the report. Rather than relying on AI for answers, the student can test the AI by comparing the students' best guess against the AI's. In this way, it becomes a productive tool that supports greater understanding and accelerates research.

6 Hardware Design

6.14 First Subsystem: Power Management

The power management system is designed to efficiently distribute power to various components in the robotic system while ensuring stability and reliability. the system will be powered using a wall outlet through a 12V power supply unit, which serves as the primary voltage source for the stepper motors and is also used to generate the lower voltages required by other subsystems. The voltage conversion process involves a 5V DC/DC buck converter and a 3.3V low-dropout voltage regulator (LDO), each serving specific roles in powering different parts of the system.

The 12V power supply is primarily used to drive the stepper motors, as they require a higher voltage to operate. Stepper motors draw significant amounts of current, and all other devices will also be powered from the same source, so the power source must be capable of supplying enough current to run the whole system. The Voltage regulators will regulate the power delivery and prevent sudden fluctuations from affecting the components.

Since the Raspberry Pi, servo motors, and TCD1304DG linear CCD sensor require a stable 5V power source, a 5V buck converter is used to step down the 12V input efficiently. A buck converter is chosen instead of an LDO for this step due to its significantly higher efficiency, minimizing power loss and heat dissipation, especially when having a large difference between the input voltage and the desired output voltage. The servo motors used for the end effector in the robotic arm and the Raspberry PI will be connected to the buck converter directly since they require a consistent 5V input to ensure smooth operation. Additionally, the TCD1304DG linear CCD sensor operates at 4V and the STM32 Microcontroller operates at 3.3V, so the Buck converter will serve a pre-regulator for the LDO regulators, deriving power from the 5V rail instead of the 12V supply to improve efficiency.

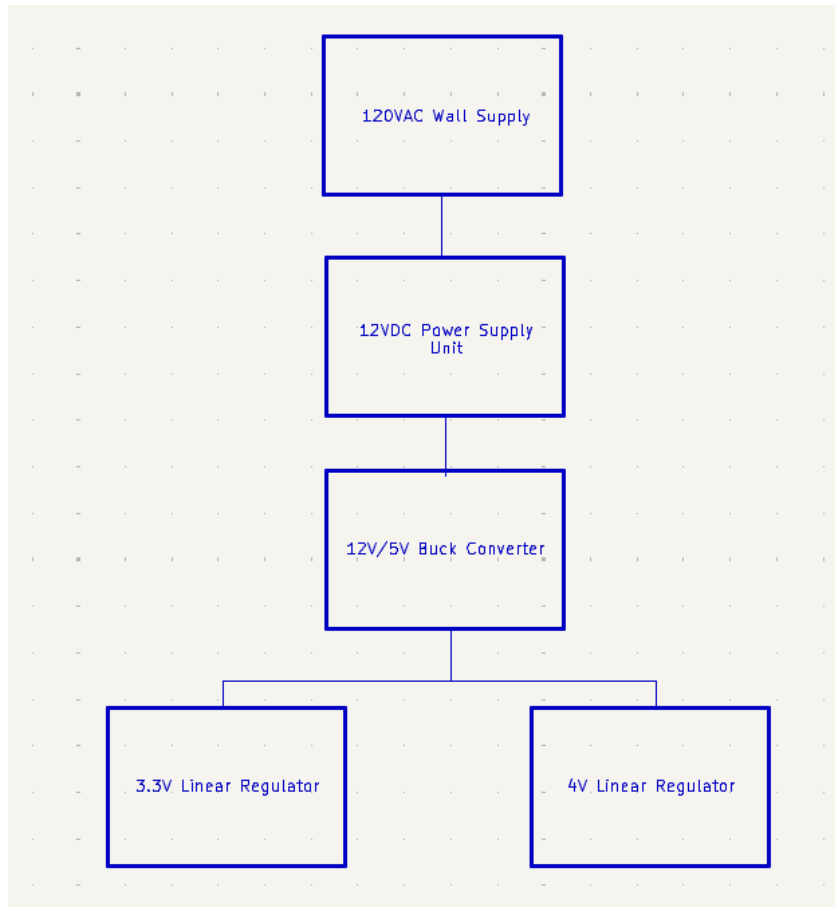


Figure 19: Power System Architecture

In summary, as illustrated in Figure 19, the 12V power supply serves as the main supply of the system, directly powering the stepper motors while also feeding the 5V buck converter to support other components. The power distribution system is designed to optimize efficiency, minimize heat dissipation, and ensure reliable operation across all subsystems. The block diagram provided below illustrates the complete power management architecture, showing how each voltage rail is derived and distributed throughout the system.

6.14.1 12V to 5V DC/DC Buck Converter Schematic

The schematic in Figure 20 shows the schematic diagram of the 12V to 5V Buck Converter. We have designed this circuit using TI WEBENCH tool which created a customized power supply circuits based on system requirements. This circuit output 5V, up to 5A of current. If more power is needed for our system, we could either use two of this buck converter, one for the servos power input and one for all other devices, which could possibly help with efficiency as well. Alternatively, we could design a more complex power supply circuit with a different switching regulator that can handle the extra power need to be delivered.

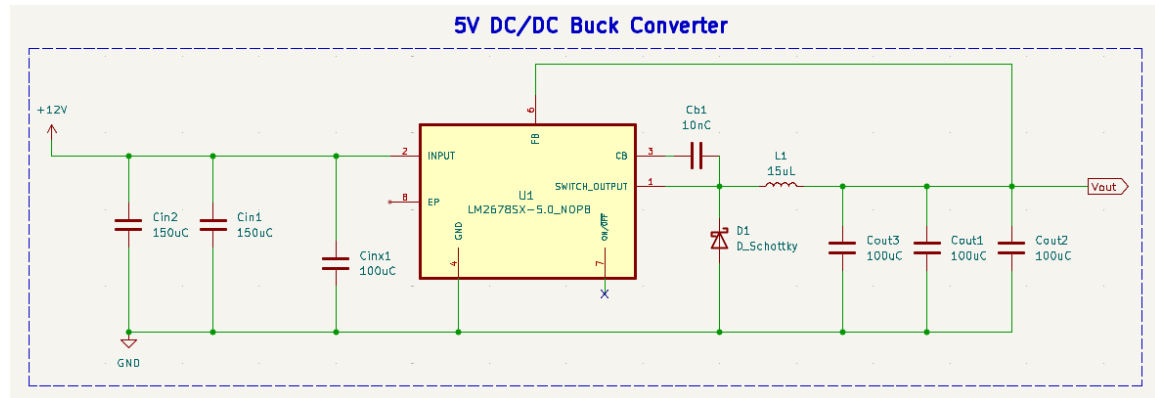


Figure 20: 5V Buck Converter Schematic

6.14.25V to 3.3V LDO Regulator Schematic

This schematic in Figure 21 shows the circuit for the 3.3V low dropout voltage linear regulator that is used to power the STM32F401 Microcontroller, it a very simple and generic regulator design using the AMS1117-3.3 IC with decoupling capacitors at the input and output pins. The AMS1117-3.3 can output up to 1A of current which is plenty for our microcontroller. The dropout voltage is around 1V to 1.3V according to the datasheet. So using a 5V as an input to the regulator wouldn't be an issue.

Additionally, a red LED was added to debug and verify that the LDO is working as expected. The 1k ohm resistor is used to limit the current going into the LED to prevent it from burning out. Red LEDs have a forward voltage of 1.8V and a max current of 20mA. The voltage across the resistor would be $3.3V - 1.8V = 1.5V$, with a 1k ohm resistor, the current through this loop is 1.5mA, which is below the maximum allowed.

Currently, the regulator is designed to take the input from the USB connection (VBUS) used for the microcontroller. However, we will also design a power multiplexer to safely switch between the 5V rail and the USB power, depending on which one is present.

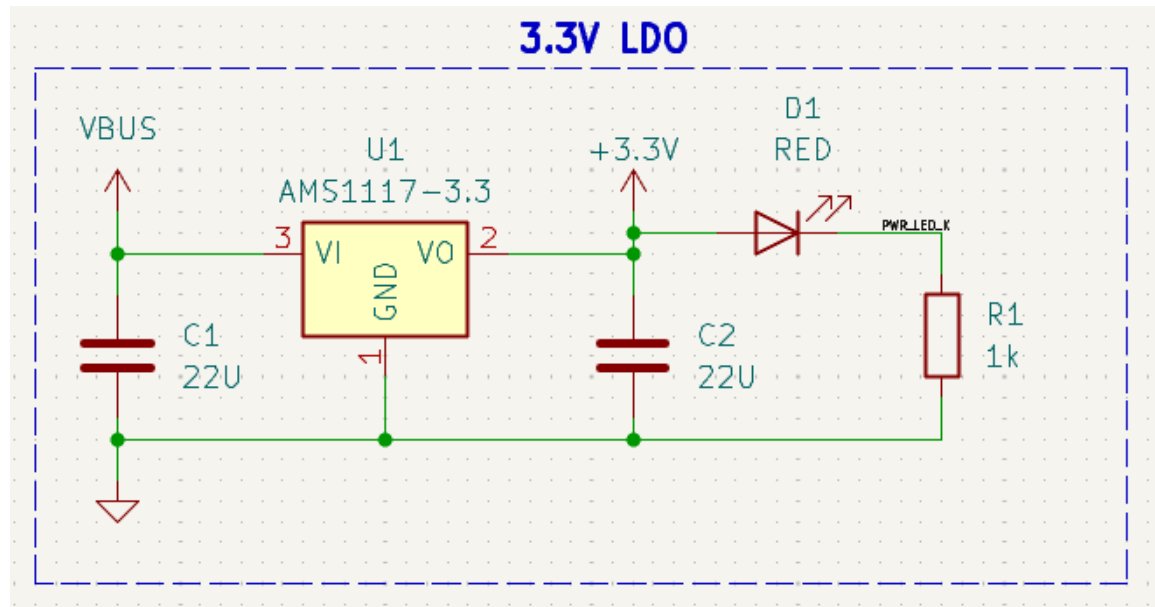


Figure 21: 3.3V LDO Regulator Schematic

6.15 Second Subsystem: Spectrometer TCD1304DG Sensor

This subsystem focuses on driving the TCD1304DG linear CCD used in our spectrometer system. Linear CCDs collect photons in pixels, convert them into electrical charges, and shift these charges sequentially to the output pin. **Put reference**. The sensor operation relies on precise timing control for charge transfer and readout. The driving circuit and timing requirements provided in the TCD1304DG datasheet [21] ensure that the sensor receives the correct clock signals for charge transfer, pixel shifting, and analog signal output. The design includes a PNP transistor that acts as a buffer for the output signal (OS) before sending it to the ADC to digitize it and a hex inverter to invert pulses generated by the MCU before feeding them into the sensor. A 4V power supply, along with some decoupling capacitors to minimize noise are recommended.

The circuit requires three essential clock signals:

1. ICG (Integration Clear Gate):
 - This pulse defines the integration period, during which the sensor accumulates charge based on incident light.
 - A high pulse of at least 1 µs is required to reset and start a new exposure cycle.
2. SH (Shift Gate):
 - The SH pulse controls the charge transfer from the sensor's photodiodes to the CCD shift register.

- It should have a pulse width of at least 1 μ s, ensuring proper charge movement.
3. Master Clock (MCLK):
- A continuous high-frequency clock is required to shift the pixel charges sequentially.
 - This signal determines the readout speed and pixel clocking rate.

While the STM32F401 microcontroller on the main PCB will generate these signals, this subsystem will be implemented on a separate PCB mounted on the spectrometer system. It will interface with the main PCB via a 5-pin connector, providing 5V power input and MCU connection wires for the pulses and output signals.

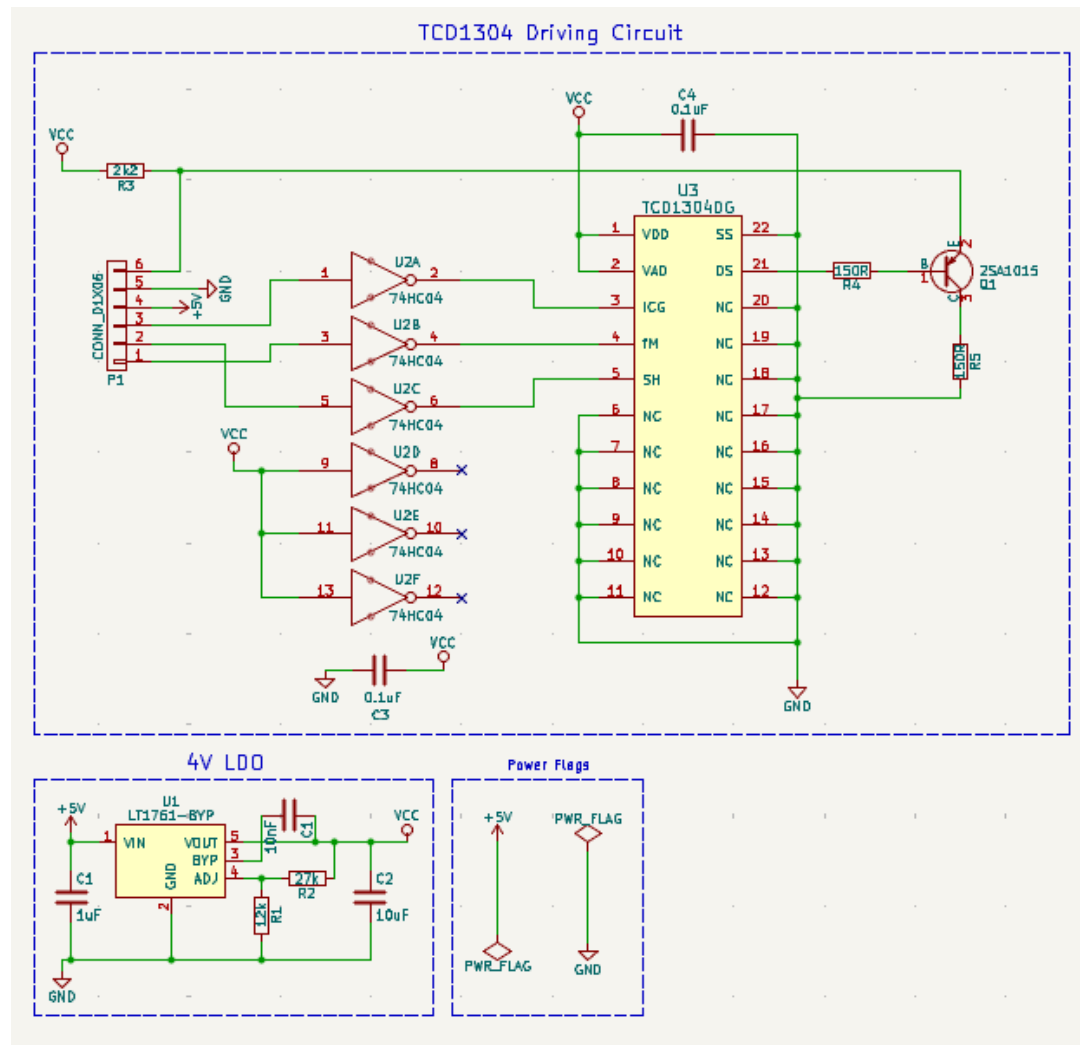


Figure 22: TCD1304DG Linear CCD Sensor Schematic

The schematic shown in Figure 22 follows the typical driving circuit in the datasheet, with an additional 4V low dropout voltage regulator to step down the 5V power coming from the main PCB.

6.16 Third Subsystem: STM32F401 and Motor Control

6.16.1 MCU Schematic

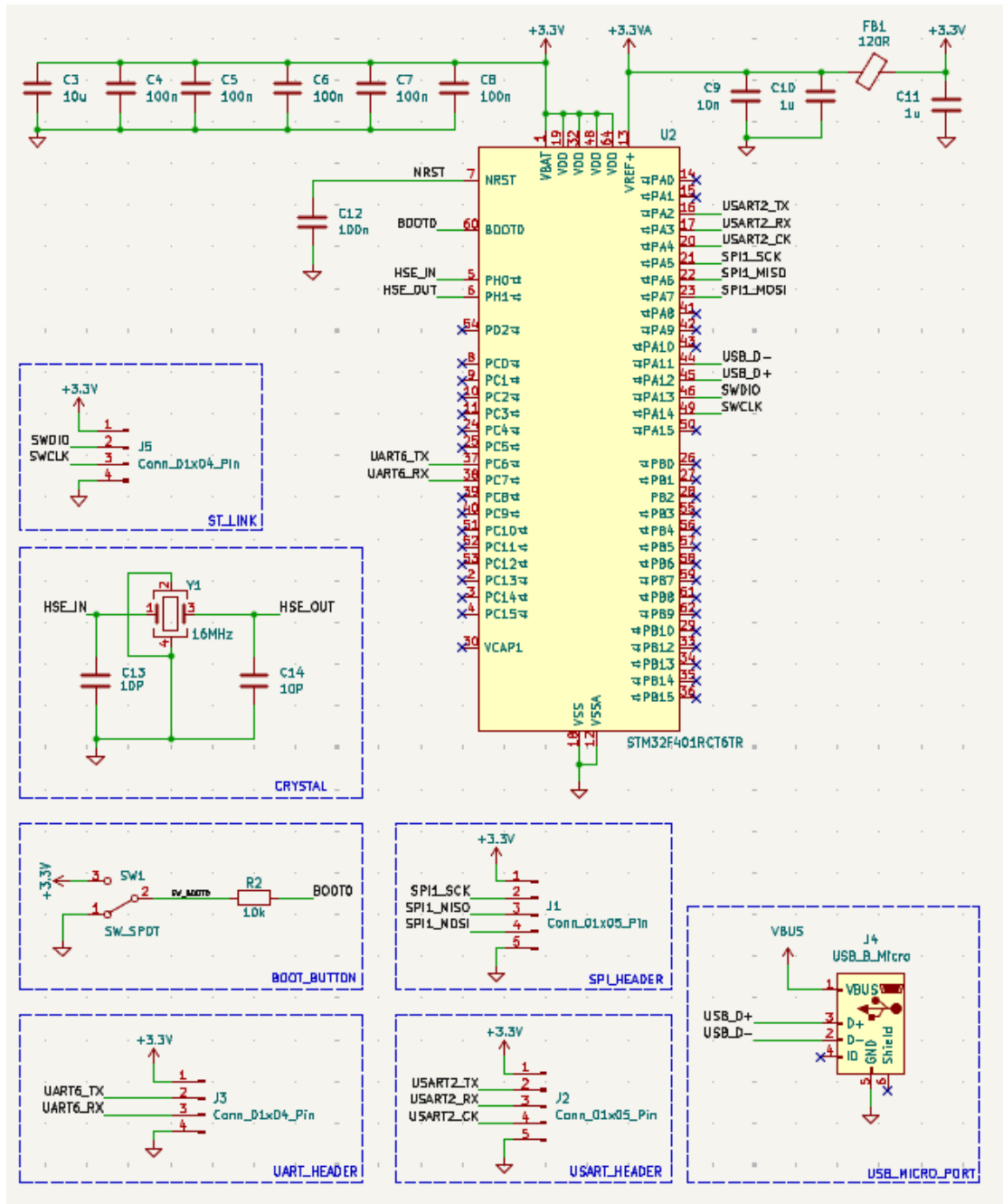


Figure 23: STM32F401 MCU Schematic

6.16.2 Stepper Motor Connections

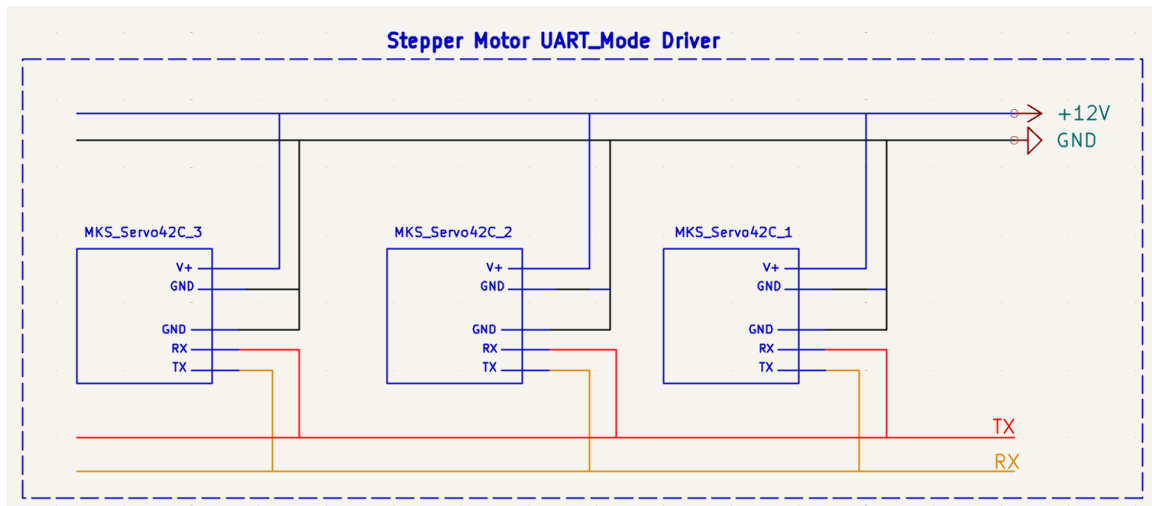


Figure 24: Stepper Motor Wiring Diagram

6.16.3 Servo Motor Driver Schematic

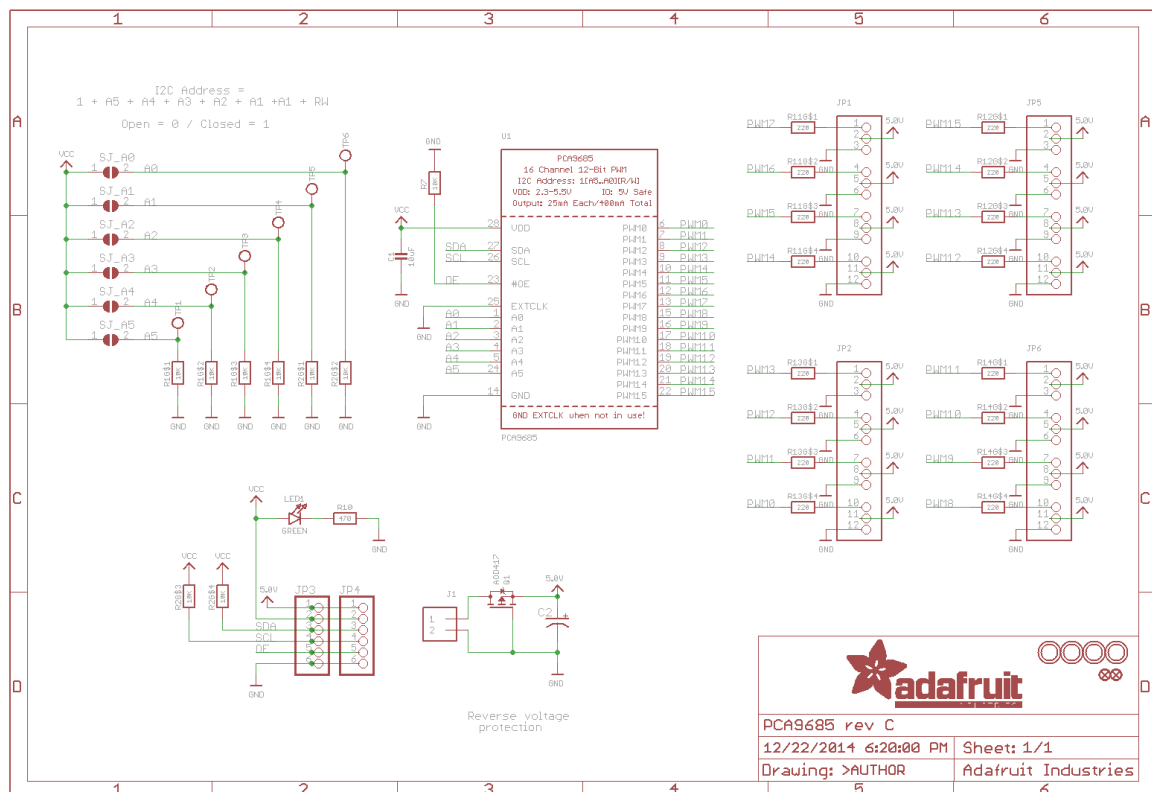


Figure 25: Adafruit PCA9685 PWM Driver Schematic

The PCA9685 I2C-controlled PWM Driver schematic shown below is provided by Adafruit, the designer of this module. We will integrate this driver circuit into our PCB

design to drive the servo motors. Since this design is a 16-channel PWM driver and we only have three servo motors, we can remove any unnecessary channels in our custom design to reduce footprint.

The schematic consists of a terminal block for power input, reverse polarity protection, an LED to verify power connection, multiple 3-pin connectors to connect the motors and some resistors. For our purposes, other than removing the extra channel connectors, we can remove the terminal block since we will power the circuit directly from the PCB.

6.17 Fourth Subsystem: Raspberry Pi and Other Peripherals

6.18 Hardware Design Summary

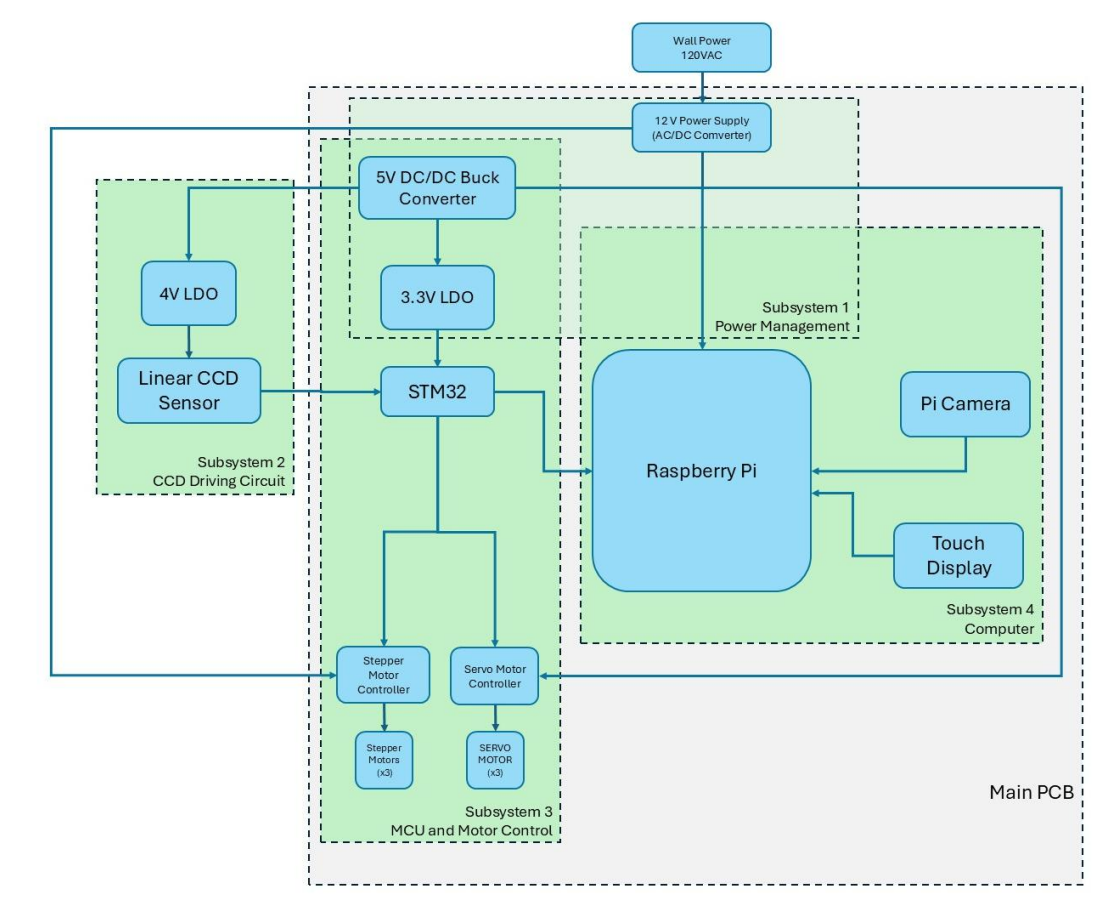


Figure 26: Hardware Design Summary Block Diagram

7 Software Design

The T.R.A.S.H. (Tracking Recyclables Automated Sorting Hand) system is designed around a layered software architecture that coordinates object detection, motion planning, material identification, and robotic actuation. The software pipeline is divided across three main subsystems: the Raspberry Pi, which performs high-level computation and control; the STM32 microcontroller, which handles low-level motor execution and decision logic; and the spectrometer, which performs material classification to inform the sorting decision.

The process begins with image capture from onboard cameras, one providing a bird's-eye view of the workspace and the other mounted on the end-effector. Captured frames are sent to the Raspberry Pi, where image processing and object detection are executed using OpenCV. If an object is detected, the system calculates its location and performs inverse kinematics to determine the joint angles required to reach it. These calculated motor angles are transmitted to the STM32.

Upon receiving the inverse kinematics data, the STM32 coordinates motor movement to execute a pick operation. The arm advances toward the target location and uses onboard sensors to confirm successful object acquisition. Once the item is in hand, the system checks whether material classification is required. If so, the object is presented to the spectrometer, which adjusts the arm's position for accurate reading. The spectrometer then performs a spectral scan and identifies the material type.

After classification, the STM32 continues executing the placement sequence. It verifies the drop-off location, moves the arm accordingly, and completes the operation by releasing the item. Throughout the entire process, each stage includes verification checkpoints to ensure reliable handling and accurate sorting.

By dividing responsibilities between the Raspberry Pi, STM32, and spectrometer, the software system ensures modularity, efficiency, and fault tolerance. Each component is able to operate independently within its defined scope, while still communicating effectively with the others to complete the overall autonomous sorting task.

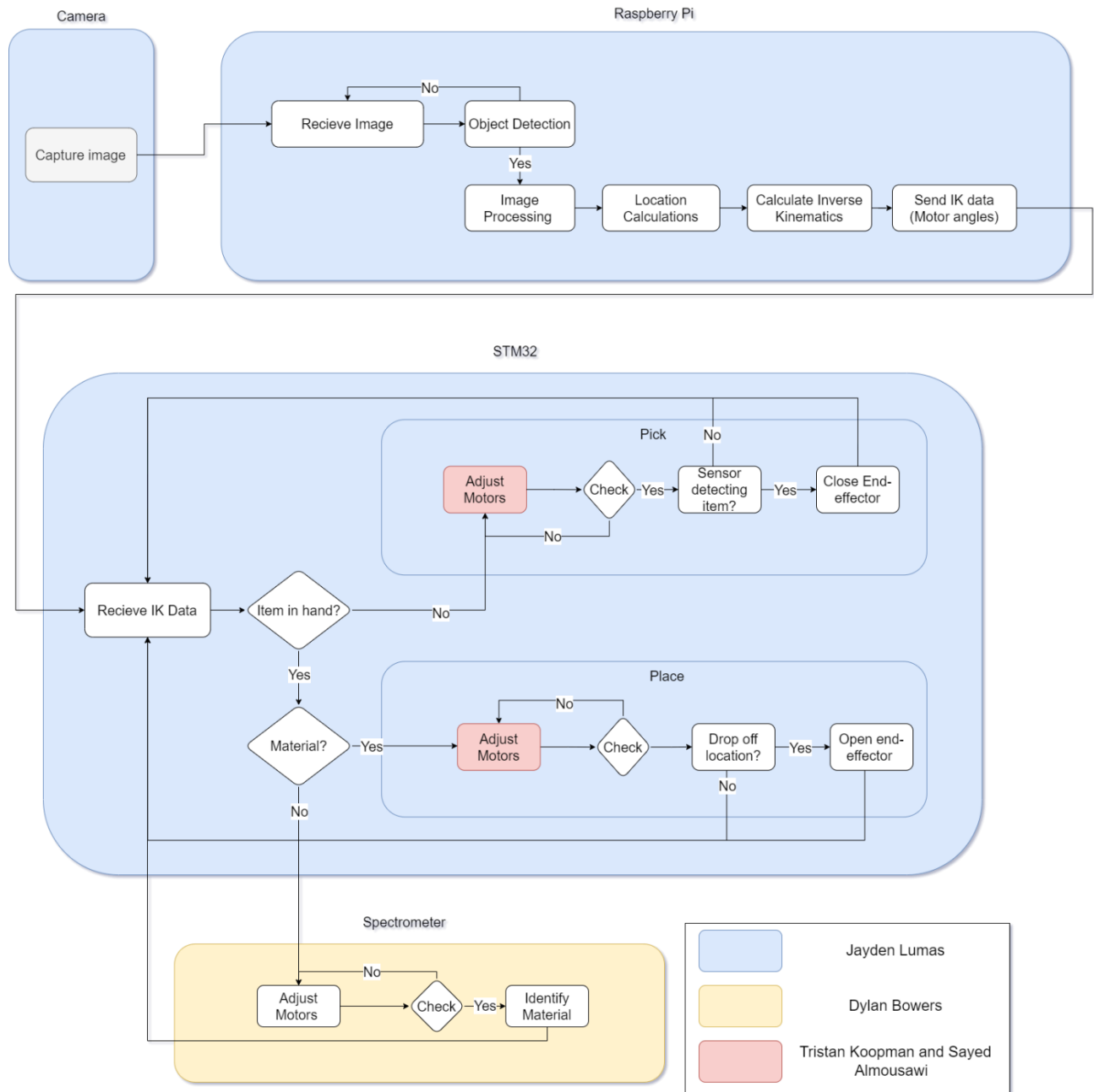


Figure 27: Software Design Logic Flowchart

7.1 ROS2

The T.R.A.S.H. (Tracking Recyclables Automated Sorting Hand) system utilizes a distributed, ROS2-based software architecture running on the Raspberry Pi 5. Acting as the central processing hub, the Raspberry Pi executes nearly all system-level functionality through modular ROS2 nodes. This structure allows for scalable integration, real-time data flow, and concurrent task management across the perception, planning, and control subsystems.

The following ROS2 nodes form the core of the system:

- Bird_Eye_Camera_Node
- EE_Camera_Node
- GUI_Node
- IK_Node
- Range_Node

The Bird_Eye_Camera_Node continuously monitors the entire workspace from a fixed overhead view. Its primary purpose is to detect the presence of new objects and manage spatial awareness to prevent unnecessary or unsafe robotic arm movement. When a new object is detected, this node activates the EE_Camera_Node, which is mounted on the robot arm. This second node performs close-range, high-accuracy object detection using OpenCV libraries, publishing the precise target location once an item is identified.

The IK_Node is responsible for calculating joint angles and planning motion trajectories. After receiving the object's position and estimated depth, it determines the optimal path for the robotic arm to pick up the item. This node manages all IK calculations, joint limit enforcement, and pose-to-joint transformations required for accurate manipulation.

To support depth estimation and enhance pick precision, the Range_Node operates in parallel with the EE_Camera_Node. This node provides real-time distance measurements between the robot arm and the detected object. The range data is passed to the IK_Node to fine-tune the approach and execute the grasping operation.

The GUI_Node provides user-facing interaction and displays real-time system feedback through a display integrated into the custom PCB. It reflects system state, object detection status, and operational metrics, while allowing for simple user commands or manual overrides.

All nodes communicate through ROS2 topics and services, enabling synchronized operation and modular debugging. This software design ensures each subsystem performs its role independently while contributing to the overall autonomous sorting workflow.

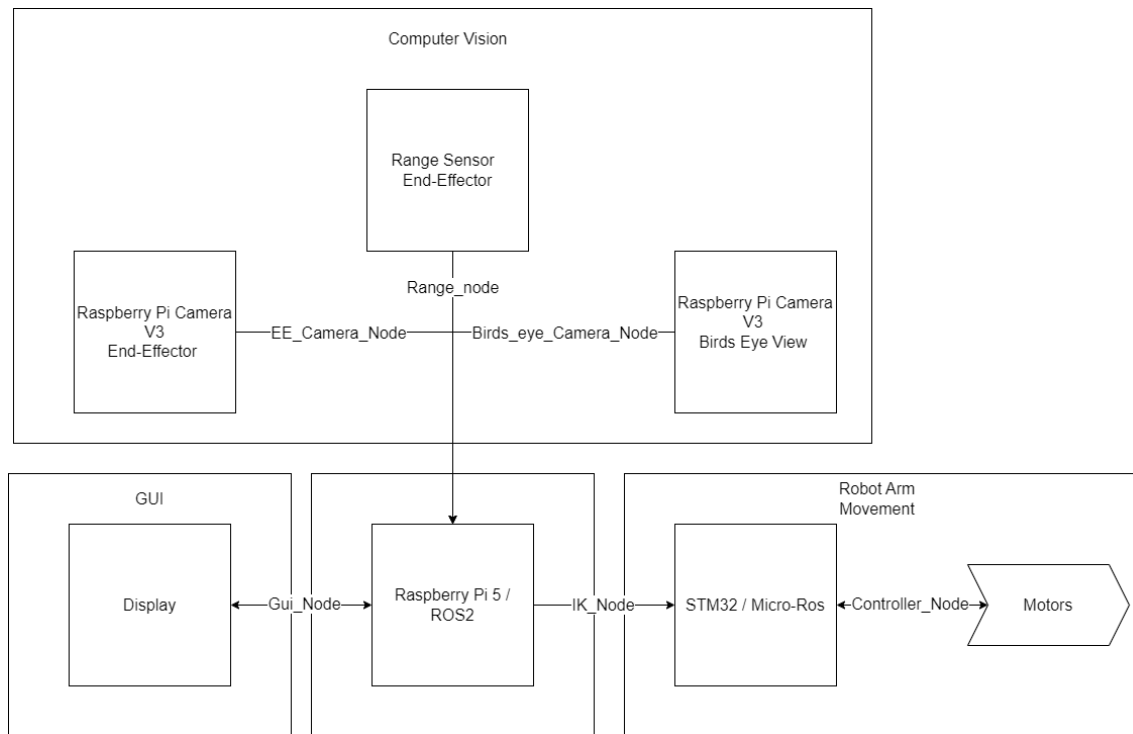


Figure 28: Software Case Diagram

7.2 Computer Vision

The computer vision system in T.R.A.S.H. is implemented using the OpenCV library, integrated within two ROS2 nodes: `Bird_Eye_Camera_Node` and `EE_Camera_Node`. OpenCV provides the foundational tools necessary for image acquisition, preprocessing, object detection, and position estimation. These ROS2 nodes operate on the Raspberry Pi 5 and enable real-time visual processing required for automated object handling.

The `Bird_Eye_Camera_Node` provides a fixed, overhead view of the sorting workspace. Its primary function is to detect when a new object enters the field of view. Once an object is identified, this node activates the `EE_Camera_Node`, which is mounted on the robot arm and tasked with performing close-range analysis to refine object localization and classification.

Both camera nodes subscribe to image data through ROS2 topics and convert the incoming frames into OpenCV-compatible format using `cv_bridge`. The images are then processed through a series of OpenCV functions such as grayscale conversion, Gaussian blurring, thresholding, and contour detection. These steps help isolate object boundaries, allowing the system to calculate centroids and determine object positions. The `EE_Camera_Node`, in conjunction with the `Range_Node`, resolves a 3D location for the object, which is then passed to the `IK_Node` to initiate pickup.

To validate and refine the vision system before hardware implementation, the camera nodes are simulated using Gazebo and visualized in RViz. This simulation workflow allows for real-time testing of camera feeds, object detection logic, and inter-node communication in a controlled environment. By simulating vision behavior ahead of deployment, the system ensures robustness and reduces risk during physical integration.

Through OpenCV's processing capabilities and ROS2's modular structure, the T.R.A.S.H. system achieves reliable and scalable computer vision suitable for autonomous sorting operations.

7.3 Inverse Kinematics

The IK (Inverse Kinematics) system in T.R.A.S.H. is responsible for converting the spatial coordinates of detected objects into joint angle commands that guide the robot arm. This functionality is managed by the IK_Node, which receives real-time object position data from the EE_Camera_Node and depth information from the Range_Node. Together, these inputs are used to resolve a 3D target position within the workspace.

To compute valid joint configurations, the IK_Node performs geometric kinematic calculations based on the physical structure of the robot arm, including link lengths, degrees of freedom, and joint limits. These results are then published as joint angle commands and passed to the motor controller for execution.

To ensure accurate and safe motion before deployment, the T.R.A.S.H. system leverages a full ROS2 simulation environment. Tools such as MoveIt 2 are used to handle motion planning and trajectory generation, while Nav2 assists with workspace navigation logic if needed. RViz provides a visual interface for real-time feedback, and Gazebo allows the team to simulate the robot arm's behavior in a physics-based environment. The Control stack further manages low-level actuation interfaces and simulates hardware controllers.

This simulation environment enables thorough testing and refinement of motion planning, perception integration, and arm control without the risk of damaging hardware. It allows for validation of pickup sequences, object alignment, and end-effector precision in a virtual space before physical implementation.

By incorporating these ROS2 tools into the development pipeline, the system ensures that all robotic behaviors are properly tested, optimized, and verified ahead of deployment on the actual hardware.

7.4 Display

The display subsystem of the T.R.A.S.H. system is managed by the GUI_Node, which operates as a ROS2 node on the Raspberry Pi 5. This node is responsible for providing real-time visual feedback and system monitoring throughout the sorting process. The display itself is fully integrated into the system's custom PCB, eliminating the need for external HDMI connections and supporting a compact, self-contained design.

The GUI presents critical information to the user, including system status, current camera activity, object detection results, and arm movement updates. It also visualizes the overall sequence of operations, such as when an object is detected by the bird's-eye view, scanned by the EE camera, or picked up by the robotic arm. This interface allows users to quickly understand what stage the system is in, whether it is actively sorting or awaiting new objects in the workspace.

In addition to status monitoring, the GUI may include basic control functionality, such as enabling or disabling autonomous behavior, resetting the system, or pausing operation. Because it is implemented as a ROS2 node, the GUI subscribes to relevant topics across the system and displays updated information in near real time. This setup ensures seamless integration with the rest of the software architecture and supports future expansion of display features without requiring a major redesign.

The display is essential for debugging, demonstration, and operational transparency, especially during testing and evaluation phases. Its integration into the PCB contributes to the project's goal of delivering a compact and user-friendly autonomous sorting solution.

7.5 Summary

The software architecture of the T.R.A.S.H. system is designed to support real-time perception, decision-making, and robotic control using ROS2. Computer vision is implemented through OpenCV-based ROS2 nodes for object detection and localization, while the IK_Node handles arm movement based on calculated 3D target positions. The system is fully testable in simulation using Gazebo and RViz, ensuring reliability before hardware deployment. A dedicated GUI displays system activity through an integrated PCB-mounted screen, providing intuitive feedback and monitoring. Altogether, the software enables efficient and autonomous sorting behavior in a modular, scalable framework.

8 Structure Design

In this section, we discuss the structural design and limitations of TRASH.

8.14 Linkages

For a robotic arm, the linkages serve multiple purposes. The most obvious function of the linkages is to serve as an intermediary offset between joints. This offset dictates the available workspace the robot is able to work within. Linkages are studied based on their geometry, and as such, links are considered to be rigid [22]. These rigid links are additionally the transmission system of power from the robot actuators. Therefore, the linkages are required to be load-bearing devices. Finally, it is important to note that mechanical linkages are used to transform a given input force and motion into a desired output force and motion. The ratio of the output force to the input force is known as the mechanical advantage of the linkage, and while the ratio of the input speed to the output speed is known as the speed ratio, the speed ratio and mechanical advantage are defined as yield the same number in an ideal linkage [22].

8.14.1 Workspace (with mechanical advantage)

<https://www.omnicalculator.com/physics/mechanical-advantage#how-do-i-calculate-the-mechanical-advantage>

8.14.2 Internal Loadings

8.15 Joints

The joints of the robot arm are the sources of force and motion. Whether direct or indirect drive, the joints of the articulated robot create the compounded resultant motion of the end effector. Along with the transmission of motion, the joints also serve as the connection point between the mechanical linkage chain. These joints can house electronics like motors or cables or speed reducers like gearboxes or belt drives.

8.15.1 Linkage Coupling

8.15.2 Speed Reducer (with transmission)

8.16 End Effector

Easily the most versatile system of the entire robot arm, the end effector (EE) serves multiple purposes for our robot arm. The primary purpose of the EE is to grip 0.5kg at its tip with a stretch goal of 1kg. The equally important purpose of the EE is to serve as a housing for hardware. The EE will hold the camera system, powering the computer vision of the robot while also housing the direct drive servo motor controlling the gripper. Additionally, as a part of the stretch goal, the end effector should also have the ability to integrate an optical fiber through the end effector to allow material identification without the need to physically pick up the item in advance.

8.16.1 Gripper

8.16.2 Cable Management

8.17 Spherical Wrist

The spherical wrist for the precision and flexibility of a robot arm. The wrist of a robot arm provides fine-tuned motion to position the end effector and payload in the correct position with little error. By necessity, the wrist system of the robot also has load-bearing capabilities. The spherical wrist allows rotation in all directions, making them suitable for tasks requiring flexible orientation of the end-effector [23]. Our robots application requires that it can pick items that may be in less than ideal orientations. Therefore, it is critical that the robot end effector can be orientated in any direction.

8.17.1 Motion (with DOF)

8.17.2 Cable Management

9 System Fabrication/Prototype Construction

10 System Testing and Evaluation

11 Administrative Content

11.14 Budget and Financing

Sub-System	Description	Budget
Development	Dev board, jumper wires, and breadboards	\$50
PCB and Electricals	PCBs, ICs, resistors, switches, etc.	\$120
Motor System	Motors, drivers, and encoders	\$220
Frame/Robotic Arm	Construction/assembly components, PLA filaments, mounting hardware	\$180
Optics and Sensors	Sensors, lenses, light sources,	\$140
Computer Vision System	Raspberry Pi, Camera, etc.	\$140
Total		\$850

Table 34: Budget Estimates

11.15 Bill of Materials

Item	Quantity	Price	Total Cost
STM32F401 MCU	1	\$6.69	\$6.69
LT1761-BYP LDO	1	\$5.07	\$5.07
LT1761-3.3 LDO	1	\$4.71	\$4.71
LM2678SX-5.0/NOPB Buck Switching Regulator	2	\$5.67	\$11.34
STM32F401 Dev Kit	1	\$14.99	\$14.99
TCD1304DG	1	\$6.95	\$6.95
NEMA 17 Stepper Motor	3	\$22.00	\$66.00
MKS_Servo42C Encoder/Driver	3	\$11.00	\$33.00
25KG Servo Motor	3	\$13.99	\$41.97
PCA9685 PWM Driver	1	\$14.95	\$14.95
Raspberry Pi LCD - 7" Touchscreen	1	\$60.00	\$60.00
12V 30A AC/DC Power Supply	1	\$18.99	\$18.99
Main PCB	1	\$40.00	\$40.00
CCD Sensor PCB	1	\$20.00	\$20.00
Electronic Components	NA	\$30.00	\$30.00
Raspberry Pi 5	1	\$135.99	\$135.99
Camera	2	\$35.00	\$70.00
Carbon Fiber Rods	3	\$21.29	\$63.87
PLA Filament	2	\$19.99	\$39.98

Bearings Pack	1	\$17.59	\$17.59
Assorted Hardware	NA	\$60.00	\$60.00
Ø1/2"N-BK7 Plano-Convex Lenses f = 50mm	1	\$21.98	\$21.98
Ø2"N-BK7 Plano-Convex Lenses f = 50mm	1	\$34.75	\$34.75
LEDW25E	5	\$1.81	\$9.09
IRLED (LED930L)	2	\$8.28	\$16.56
IRLED 2 (LED1050E)	2	\$21.14	\$42.28

Table 35: Bill of Materials

11.16 Work Distribution

Component	Primary Member	Secondary Member
Robot Arm	Tristan	
Frame		
Motors/Drivers	Sayed	Tristan
Power Source		
Hardware and PCB		
Camera	Jayden	
Raspberry pi		Sayed
Software		Everyone
Lenses	Dylan	
CCD Sensor		Sayed
Spectrometer Design		

Table 36: Work Distribution

11.17 Milestones

Task Description	Start Date	End Data
D&C	1/7/25	1/24/25
Revised D&C	1/24/25	2/7/25
Midterm Report	1/24/25	3/24/25
Revised Report	3/24/25	4/4/25
Final Report Draft / Demo Video	4/4/25	4/14/25
Final Report	4/14/25	4/22/25

Table 37. SD1 Milestones

Task Description	Start Date	End Data
Subsystems integration	TBD	TBD
PCB Assembly	TBD	TBD
Testing and Adjustments	TBD	TBD
Final Testing	TBD	TBD
Final Presentation/Demo	TBD	TBD
Final Paper	TBD	TBD

Table 38. SD2 Milestones

12 Optoelectronics Feasibility Study and Testing

13 Conclusion

Appendix A: References

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Appendix E: Design Competence Evaluation

ME Design Areas	Critical/Main contributor	Strong contributor	Necessary but not a primary contributor	Necessary but only a minor contributor	Only a passing reference	Not included in this Design Project
Thermal-Fluid Energy Systems						X
Machines & Mechanical Systems	X					
Controls & mechatronics	X					
Materials Selection			X			
Modeling & Measurement Systems				X		
Manufacturing				X		

Mechanical Topics Utilized in this Senior Design Project:

Topic	Criticality	Section and Page(s)	Comments
Machines & Mechanical Systems	Main		
Controls & mechatronics	Main		
Materials Selection	Necessary	3.2.1	
Modeling & Measurement Systems	Minor	3.1.1, 3.1.2, 3.2.2	
Manufacturing	Minor	3.2, 3.10, 8.15, 8.16, 8.17	