Trash-E

Group: 26

Senior Design 1 EEL 4914-0001

Members
Thomas Greco: Computer Engineering

Christian Mayo: Computer Engineering

Alex Rizk: Computer Engineering

Chrizzell Jay Sanchez: Electrical Engineering

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1.0 Executive Summary

The only form of automated commercial vacuum which the average consumer can buy are Roomba®-style devices. The main issue with these devices is the size of objects that can be picked up. Typically, the size of a candy wrapper, small cereal, or dust is the maximum that these autonomous vacuums can grab. These autonomous vacuums also have trouble when they encounter things that can tangle their wheels such as pet or human hair. Our robot will be able to pick up larger objects using an arm and pincer mechanic.

In this project we will create Trash-E, an autonomous robot that detects litter and picks it up utilizing computer vision. It is meant to help automate the process of cleaning up a venue such as a ballroom, sporting event field, or even a backyard. Trash-E differs from a Roomba®-style device because Trash-e is not an autonomous vacuum. Trash-E instead uses an arm to pick up objects such as cups that were thrown on the ground. The purpose of the project is to create a device that reduces the manpower required to do a tedious task such as cleaning up after an event. The robot is not meant to replace Roomba®-style devices, as they perform a different function. The autonomous vacuums are meant for home use.

Our robot may be useful in any event with a large gathering of people such as a concert, football game, or party. In these events the last thing on attendee's minds is their trash and it is not uncommon for the venues to be filled with garbage after the event ends. These events have teams of workers who are dedicated to cleaning up all the trash that is left over. With larger venues, cleaning up may require upwards of 100 people.

The most important part of Trash-E is the ability to detect objects that we determine is trash. For this project, we limit the scope by determining trash only as red solo cups at first. This allows us to have a set goal in mind, rather than finding random objects and determining it is litter. By limiting the description of trash, we can focus on making sure the robot excels at detecting that object and fine tuning any mechanical movements before branching out into things such as aluminum cans, plastic bags, or bags of chips. The object detection of Trash-E also entirely controls all the hardware.

On the hardware side, Trash-E must be able to properly pick up these red solo cups. The entire system should be powered by a single rechargeable battery pack. The voltage from the battery pack will be stepped down to meet the needs of the different components on Trash-E such as the microcontroller, and the different motors that need to be driven. While the battery pack can be charged with a power supply, we also want to implement solar panels, so the robot is slightly charging when it is outside. We will need to implement diodes into the circuit so that the current does not flow from the battery to the panels.

2.0 Project Description

2.1 Project Background

Litter is an increasingly difficult problem to address as the world progresses. Large amounts of money is spent to pay individuals to pick up leftover objects after many different events such as tailgates, and parties. Due to the chaotic nature of those situations, it is extremely difficult to govern and manage each individual and ensure every piece of litter is brought to a place to be disposed of. Therefore, venues choose to clean up after the event rather than take preventative measures. This leads to another problem that once litter reaches a certain size, it is too large to pick up multiple at one time. One must bend down, grab the litter, then put it in a receptacle for storage until they may properly dispose of it.

A robot does not tire from doing repetitive tasks for hours on end, making it a perfect fit for this situation. Robots that pick objects up have an arm apparatus, pincers to grip the objects, and a place to store them. They're driven by different motors which are controlled either manually or autonomously. This robot must also utilize a way to move about an area autonomously and detect a cup using computer vision.

To be autonomous, it needs to have a power source attached to it. One of the most common options is a battery. This either needs to be recharged or replaced, but there's no way to make the robot run continuously without stopping at some point.

One feature that will be implemented is a receptacle that is attached to the robot for ease of storage. This eliminates the need to go back to a predetermined spot to drop the object off.

2.2 Objectives

2.2.1 Motivation

The motivation for this project is to not only utilize the knowledge we have acquired over the course of our academic careers into a single project, but to challenge ourselves and build upon those skills while learning new ones. The team dynamic makes it more realistic in terms of what we will be facing if we exit our undergraduate career and choose to pursue a career in industry or research. The topics that are covered in this project like embedded system design and programming, computer vision and machine learning, and power system engineering are things that each member expressed interest contributing to at least one of, if not more. To put more marketable skills on our resume, we wanted to do a full system design that utilizes multiple different aspects of the engineering design process so we may realize a product from start to finish.

2.2.2 Goals

The goal of this project is to create a functional robot that can:

- Move on its own.
- See an object on the floor.
- Determine if the object is litter.
- Pick up the litter.

Dispose of the litter into the bin on its chassis.

2.2.3 Definition of Litter

Litter is a broad term, and to create a robot that can pick up all litter would not fit within the scope of the project. According to Merriam-Webster, litter is defined as “trash, wastepaper, or garbage lying scattered about”. With such a generic definition, many different objects could fit into that. Examples of some common items that can be referred to as litter include: candy wrappers, cans, cups, and bottles. With the word “garbage” being in the definition also, this makes litter even more ambiguous. The famous saying “one man’s trash is another man’s treasure” truly comes into effect here. Because of this uncertainty, we will define what the robot will see as litter, trash, and garbage. To start off, we plan to use 16-ounce Red SOLO cups. These cups are 3 x 3 x 5 inches in size. We plan to use these cups because they are very popular at large events and often are discarded on the ground at events such as college parties. The cups are a distinct red color and have a distinct shape, which will aid in easing the process of identifying the cups. Once we are able to distinguish the Red Solo Cups, we plan on moving to 12-ounce aluminum soda cans. The reasons being like the Red Solo Cups, except the aluminum cans have more variety of color and design.

2.2.4 Definition of Obstacle

In our use case, an obstacle is anything that can impede the pathing of the robot. Anything greater than the size of a Red Solo Cup, 3 x 3 x 5 inches, will be classified as an obstacle to avoid. We plan to use wheels big enough to roll over anything smaller than the size of a Red Solo Cup if necessary. As we run testing for obstacle avoidance, we may need to refine our algorithm for what counts as an obstacle.

Other obstacles we may need to consider are obstacles that are too big for the camera to see. For example, a wall may throw off the obstacle detection, and thus need to be considered when programming.

2.3 Requirements Specifications

* “The system” refers to Trash-E and all equipment

Table 1: Requirements Specifications

Description	Value	Unit
Maximum amount of trash picked up at once	1	-
Maximum weight of trash picked up at once	2	lbs
Maximum size of trash	3x3x5	in3
The system shall be able to detect Red Solo Cups	-	-
The system shall be able to be moved by a human	-	-
Maximum time to pick up one piece of trash	30	sec
Maximum speed of robot	5	mph
Maximum height of robot	13	in
Maximum width of robot	14	in
Maximum length of robot	20	in
Maximum weight of robot	10	lbs
Maximum rotation of robot	360	degrees
Range of motion of the robot arm	0-100	degrees
Range of motion of the gripper	0-180	degrees
Max cost of robot	400	USD
The robot will have ample heat dissipation to protect the components	-	-
Minimum power supplied to circuitry	12	V
Minimum voltage supplied by voltage regulator	3.3	V
Maximum voltage supplied to microcontroller	3.63	V
Minimum voltage supplied to microcontroller	3.15	V
Maximum voltage supplied by voltage regulator	5	V
Minimum battery life	1	hr

The battery shall be rechargeable	-	-
Maximum size of bucket on the robot	8	L
The battery pack shall be capable of charging through a US wall plug.	-	-
Battery pack maximum current discharge	10	A
Maximum battery pack weight	300	g
Maximum number of batteries	6	-
Minimum battery capacity	1250	mAh

2.4 Customers, Sponsors, Contributors

For this project there are no customers. There is no intention of selling the result of this product on any market, to any company, or to any individual. This project also has no sponsor. Each member of the group will be individually contributing to the expenses of the project. The design of this project was thought of by the members of this group. The decision to do this project was unanimously voted by everyone in the group. Each member has their own section that was agreed upon at the start of the project.

2.5 Marketing and Engineering Requirements

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

Category	Weight	Customer Requirements (Explicit and Implicit) \ Engineering Requirements	1 Weight	2 Cost of Production	3 Power Efficancy	4 Battery Life	5 Items Grabbable	6 Speed	7 Retrival Time/Machine Learning Model	8 Size/Chassis Design	9 Bin Capacity	10 Litter Size	11 Collision Detection	12 Operation Scheme
		Column #	1	2	3	4	5	6	7	8	9	10	11	12
		Direction of Improvement	◇	▼	▲	▲	◇	◇	▲	▲	◇	◇	▲	◇
Safety	0	Human Avoidance						○	●				●	
Safety	0	Safe Speed	▽					●					○	
Safety	0	No Exposed Electronics		▽						●				
Functionality	0	Cleans Litter					●	▽	●		○	○		
Design		Portable	●	▽							▽			
Design		Easy to Operate/Run			▽	○		▽	▽					●
Design		Long Lasting Battery	○	○	●	●		○	▽	○	○			▽
Design		Easliy Rechargable								●				▽
Design		Durable						▽		●			▽	
Design		Size	○	○						●	▽			
Design		Cheap	▽	●	▽	▽				●	▽		○	○
		Target	<= 10 Lbs	<= $400	Enough for >=1 hr Charge	1 hr Lithium Ion	1 per retrival	<=5mph	30 seconds	Composed of Plastics, Metal, or Wood	Around 2 Gallons at 85% capcity	3in x 3in x 5in | <= 2lbs	Ultrasonic	Through given commands or IR remote

Figure 1: House of Quality

2.6 Product Features

The features table is split up between initial, primary, secondary, and stretch goals. The initial and primary goals are what we want to make sure the robot does. The secondary are goals that we hope to accomplish, and the stretch goals are goals that are unnecessary but may be added if we have the time and budget.

Table 2: Project Features

Description	Feature Type
Identify Red Solo Cup	Initial Feature
Move Around Freely with SLAM	Initial Feature
Able To Pick Up Litter	Primary Feature
Move Arm To Litter And Bin Properly	Primary Feature
Identify Aluminum Can	Primary Feature
Identify And Avoid Obstacles	Primary Feature
Store Litter In Bin	Primary Feature
Solar Panels	Secondary Feature
IR Remote Control	Secondary Feature
Sense When Bin Is Full	Secondary Feature
Function For 1 Hour	Secondary Feature
Return Home When Bin Is Full	Stretch Goal
Maneuver Through Hard Terrain	Stretch Goal
Visual And Audio Cue When An Object Is Picked Up	Stretch Goal
Empty Bin Into Large Trash Bag	Stretch Goal
Smart Arm	Stretch Goal

3.0 Research

3.1 Existing Products

A general consumer's options for a device that completes this task autonomously is very limited. Based on our research, there is only a Roomba® style device that can be purchased. One problem with this style of robot is the size of objects it can pick up. Roomba®'s are designed with the intention of replacing vacuum cleaners that companies such as Dyson® and Bissell® manufacture. This means their goal is to pick up very small objects like crumbs, dirt, dust, and other similar things that can be collected without the use of the vacuum wand.

Another problem with the Roomba® is the capacity of the container it stores litter in. Even if a venue only had litter that was capable of being picked up by it, the container would get full too quickly and would require a person to empty it too often.

3.2 Microcontrollers

A microcontroller will be used to control the movement of Trash-E. The Jetson Nano, which is responsible for computer vision and object detection, will send information regarding the position of the cup with a serial communication protocol using GPIO pins on both the microcontroller and Nano. Microcontrollers are an optimal choice to accomplish this task due to their versatility and low cost. Since they have many operations built in like pulse-width modulation and analog-to-digital converters, the overall PCB design will be simpler since we don't have to implement these circuits ourselves.

3.2.1 Communication Protocols

3.2.1.1 Universal Asynchronous Receiver/Transmitter (UART)

UART is the simplest of the three. Using a maximum of two pins per device, receiving and transmitting can be achieved between two devices easily. Since this protocol is asynchronous, it does not need a pin for a clock signal which will free up a pin on our microcontroller that can be used for other functions. While this method is very straightforward, it has major drawbacks. Due to the asynchronicity of UART, data can be transmitted whenever it wants and both devices must be listening constantly. Another drawback is that only two devices can communicate at once.

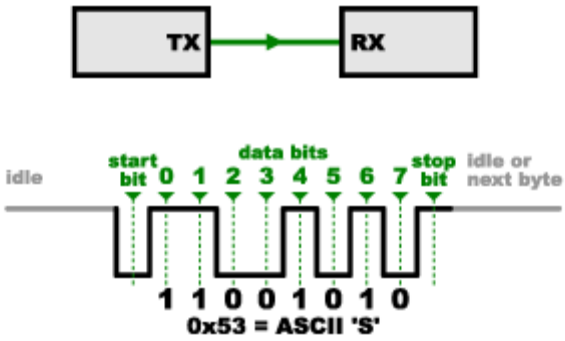


Figure 2: Example Transmission Using UART (Courtesy of SparkFun)

With this information in mind, UART would be a good choice to communicate between the microcontroller and the Jetson Nano. We can minimize the number of pins utilized since data will only be sent from the Nano to the microcontroller. Since the communication will always be happening due to the asynchronicity, more processing power will be consumed on both the Jetson Nano and the microcontroller. Figure 2 illustrates how we will send data from the Jetson Nano to the microcontroller using a low start bit, a high stop bit, and no parity bits. On the other hand, it would be troublesome to utilize this protocol between the microcontroller and the peripherals. A separate UART would need to be created for each microcontroller and peripheral, resulting in excess pins being used.

3.2.1.2 Serial Peripheral Interface (SPI)

Unlike UART, SPI is a synchronous protocol meaning it utilizes a clock signal to communicate between two devices. SPI also offers multiple peripheral capabilities by utilizing a chip select signal per device. With the addition of the clock signal and chip select signals, this can greatly increase the number of pins needed to implement this protocol which isn't ideal for a project with many different peripherals.

SPI could be used for the communication between the Nano and microcontroller but is not needed due to the one-way transmission between the devices and will be wasting pins. It is very helpful for the communication between the microcontroller and the peripherals. Having a dedicated way to talk to multiple destinations from one source is very beneficial even with the extra pin cost. This method also allows for one way communication to movement peripherals such as continuous servos, while having two-way communication between others like the precision servos all in the same system. If pin space becomes a problem, the daisy-chaining method can be a potential solution to reduce the amount of pins used.

3.2.1.3 Inter-Integrated Circuit (I2C)

I2C is a synchronous communication like I2C but only uses two pins, much like the UART. I2C offers the advantages of both UART and SPI but falls short in speed.

For a single frame of data, UART and SPI can accomplish this task in one total frame, whereas I2C accomplishes it in two. This method is certainly viable for the communication between the Jetson Nano and microcontroller, but again is unnecessary since there is only one controller and one device. I2C is very useful for the communication between the microcontroller and peripherals because of the low number of pins used, as well as the two-way communication. Many boards, like the TM4C1232H6PMI7, have an I2C interface which will help us implement this protocol.

3.2.2 STMicroelectronics (STM) vs. Texas Instruments (TI)

	STM32G0B1KCT6	STM32L151CCT6J	STM32L071CBT6	TM4C1233H6PZI	TM4C1232H6PMI7	STM32G0B1KET6N
Price	$5.62	$5.44	$5.01	$8.66	$7.14	$6.30
Core Processor	ARM Cortex-M0+	ARM Cortex-M3	ARM Cortex-M0+	ARM Cortex-M4F	ARM Cortex-M4F	ARM Cortex-M0+
Operating Voltage	1.7V – 3.6V	1.8V – 3.6V	1.8V – 3.6V	1.08V – 3.63V	1.08V – 3.63V	1.7 – 3.6V
Core Size (Bit)	32	32	32	32	32	32
Speed (MHz)	64	32	32	80	80	64
# of I/O pins	30	37	40	69	49	29
Program Memory (kB)	256	256	128	256	256	512
CoreMark ®/MHz	2.46	3.34	2.46	3.42	3.42	2.46
Mounting Type	SMD	SMD	SMD	SMD	SMD	SMD
Package	LQFP	LQFP	LQFP	LQFP	LQFP	LQFP

Table 3: Microcontroller Comparison

To determine the candidates in Table 3, we decided to narrow the manufacturers to two companies. Even though two microcontrollers could utilize the same core processor, there are many differences in how companies design their microcontrollers and expect the user to interact with them. For this project we decided to research microcontrollers made by TI and STM.

TI is a company that we became familiar with through our academic program at UCF, making it a great choice to pick a microcontroller from. We previously utilized the MSP430FR6989 to learn common embedded practices which allowed us to get accustomed to the recommended IDE, as well as utilize their syntax and processes to accomplish the basics. We didn't want to reuse the MSP430FR6989 for this project so we can learn more about what different TI microcontrollers have to offer, while not straying too far from our current knowledge base.

STM is another company that has a good reputation through word of mouth and forums on the internet. With many different microcontrollers that are specific to embedded applications, they also have plenty of development boards that we can utilize to prototype our system with before ordering a custom PCB. None of us have worked with an STM microcontroller or their software. This makes STM microcontrollers perfect for us to research and compare to the more familiar TI.

3.2.3 ARM Cortex-M

ARM Cortex-M is a 32-bit Reduced Instruction Set Computer (RISC) processor core which is optimized for low-cost, energy efficient integrated circuits in many embedded applications[1]. With the huge popularity of this instruction set, we wanted to pick a microcontroller that utilizes this technology.

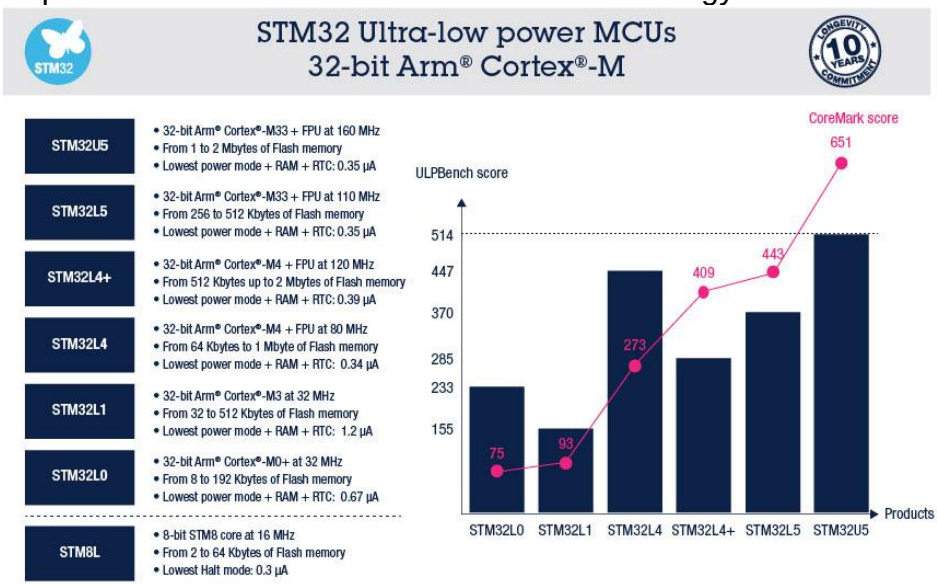


Figure 3: Benchmarks for Different Cortex-M Processors (Courtesy of ST)

3.2.3.1 CoreMark and ULPBench Analysis

To determine how well a processor performs, we looked at the ULPBench score as well as the CoreMark score. ULPBench (Ultra Low Power Bench) determines how energy efficient a particular microcontroller is. CoreMark tests the functionality of a specific processor core. Table 3 has the CoreMark score divided by the frequency it was running at to get a more accurate representation of the score as this considers how many instructions the processor can execute in a second. [2][3] Figure 3 displays the ULPBench scores in the bars and the CoreMark score on the line for each STM32 variation. While this information isn't for the specific microcontrollers in our table, each Cortex-M in the figure utilized the same specs as the microcontrollers we were researching. We investigated the official EEMBC benchmark table for these scores, the company in charge of maintaining the benchmarks these scores are made from but couldn't find anything regarding the microcontrollers we picked. This is because scores do not have to be submitted, but also can only be submitted by members or licensees of EEMBC [4]. Therefore, this is the closest information we can acquire without buying each microprocessor and conducting the benchmarks ourselves.

Due to product availability, we considered three different Cortex-M variations: Cortex-M0+, Cortex-M3, and Cortex-M4. With M0+ and M3 being run at much lower processor speeds, we compared them more closely to each other than with M4. We see that M0+ has a significantly lower CoreMark score than M3, it also has a larger ULPBench score, indicating that the processor could potentially be more energy efficient. When looking at M4, we see that the CoreMark and ULPBench scores are drastically higher than the other two, making the architecture more enticing. This is due to "The combination of high-efficiency signal processing functionality with the low-power, low cost and ease-of-use benefits of the Cortex-M family". [5] Based on these results, Cortex-M4 is very enticing for us to choose.

3.2.4 Core Size

Core size of the microcontroller's processor indicates how many bits of information can be passed into the data bus and processed in one clock cycle. The higher the core size, the more bits can be processed and the larger the value can be for one variable, but also requires more storage even for variables with few amounts of bits used. We decided to go with a 32-bit core size since many languages utilize this size and we are familiar with programming languages that have 32-bit variables standard.

3.2.5 Core Speed

Core speed tells how many clock cycles happen in one second. Generally, the higher the core speed means that more instructions can be computed in one second although this is not always true since it is based on the instruction set used. All the microcontrollers we investigated have a minimum core speed of 32MHz which will be adequate for Trash-E's application.

3.2.6 I/O Pins

These pins will be used to connect to other devices/peripherals and communicate between them. We must be careful that we don't choose a microcontroller with too few pins since we won't be able to implement all planned functions of Trash-E. We also want to have some excess pins in case we can implement some of our stretch goals later. For this reason, we decided the microcontroller should at least have 40 I/O pins.

3.2.7 Program Memory

The amount of FLASH storage in the microcontroller is critical to the decision-making process. This storage is the area where our code will reside. The more complex the application, the more lines of code we write which, in turn, increases the size of our file. If we get a microcontroller that has too little storage space, we have to either buy a new microcontroller that has more storage or increase the storage capacity by adding an external storage device of some sort. Without having any code written it is extremely difficult to determine how much is "too little". Two different algorithms can achieve the same thing but take two different approaches. If one approach is poorly optimized or has more lines of code, that option will be larger and could go over the FLASH capacity. With our inexperience in the subject we decided on 256kB as the minimum FLASH storage.

3.2.8 Mounting Type

Since the PCB will be soldered ourselves, the mounting type of our components has a big influence on our decision. There are two types of components we can choose from: Through-hole (TH) and Surface Mount (SM).

3.2.8.1 Through-Hole

Since this mounting type utilizes pins that go through the board and the components being relatively large, it's easier to solder and can normally be done using only a soldering iron and solder. It will be easy to verify the solder process went well and there's no solder bridging due to the spacing between pins being greater than SM components. They are also compatible with solderless breadboards which is a huge advantage. Prototyping on breadboards will allow us to attach the components directly into the breadboard, exchange parts, and alter our design without needing to solder and desolder each component. With the larger sizes of TH components, they take up more space and increase the total PCB size. A disadvantage to microcontrollers specifically is that as the microcontroller increases in complexity and adds more features, more pins are needed, and TH is no longer viable. This restricts the complexity of circuits if TH is being used for a microcontroller. We wanted to utilize TH for all the components to make the soldering process simpler but it isn't viable for the scope of our project.

3.2.8.2 Surface Mount

SM utilizes pads instead of holes for the component to connect to. SM components are much smaller than a TH component which greatly reduces total PCB cost and size. Size can potentially be further reduced, or functionality can be increased for the same size, by mounting components to both sides of the PCB. Soldering SM components by hand can be very challenging compared to TH since the pads are very close together. Verifying the quality of the completed solder is also more difficult and will require the use of a microscope to ensure there is no solder bridging and the pins are making direct contact with the pads. To ensure costs of the PCB and components stay down, we will be utilizing SM technology for our microcontroller and any other basic components as much as we can.

3.2.9 Package

The package refers to the way a component connects with the PCB. For the microcontroller, there were three different SM package variations: Quad Flat Package (QFP), Ball Grid Array (BGA), and Quad Flat No-Lead (QFN).

3.2.9.1 QFP

The closest to a TH component, QFP has little leads coming out of the chip that allows it to sit directly on the pads. Due to the leads being visible, this makes it easier for an individual to solder by hand and is a highly sought-after package for us. The problem with this package is that as the number of pins on a chip increases, the size of the leads and pads, as well as the space between them, decreases. We determined that a total pin size of around 64 pins is ideal to reasonably be able to solder this by hand. This package will also help us keep utility costs down as it can be soldered with a regular soldering iron. This package is also very prone to mistakes since we will be using a soldering iron. If we are not careful, we can damage the board itself and have to restart on a new one.

3.2.9.2 QFN

This package is very similar to the QFP but instead of the leads coming out of the chip, the leads are tucked under the chip, and has a metal pad that acts as a heat sink in the center. This can be more beneficial for our PCB than the QFP due to this extra heat dissipation from the center pad. Without having leads extending from the chip, this makes it more difficult to solder. An easier solution is to coat the pads with a flux paste and drag the solder across. The chemical interaction between the flux and solder will allow the solder to fall into place on the pads. This is still not ideal for us but is doable while also keeping costs low.

3.2.9.3 BGA

BGA is the least optimal for us to use and we steered clear of when looking for potential microcontrollers. Because the connections are on the bottom of the board, more can be placed than the other two packages. The more connections mean more placement of solder balls and doing this by hand can take a long time and requires high precision. To solder them, a hot air solder gun or reflow oven is needed which we do not have and will increase our costs since we would have to purchase a hot air solder gun. Because of this, we decided QFP or QFN are the packages we need to restrict our search to.

3.2.10 Price Per Unit

We want to select a microcontroller that fits the above needs/preferences, while also keeping costs to a minimum since the price per unit of the microcontroller can break our budget. With it being our first time getting PCBs printed and soldering components onto them for a project, we have to account for mistakes. This means we will be ordering multiple PCBs and microcontrollers to verify our prototype still works after soldering on the components. With this in mind, we set our absolute max price to $10 per microcontroller.

3.2.11 TM4C1232H6PMI7

With the considerations of sections 3.2.1 through 3.2.10, we have decided to select Texas Instruments' TM4C1232H6PMI7. One key factor to this decision is the familiarity of the software IDE will allow us to move quickly while developing and not spend unnecessary time relearning the basics. Another key factor is the cost. We want to keep everything under budget and this microcontroller allows us to buy multiple in case one gets damaged and needs to be replaced. Most of the following information comes from the TM4C1232H6PMI7 datasheet and is not my work.

3.2.11.1 JTAG

Since we aren't using a development board, we need to implement a way to program the microcontroller. "The Joint Test Action Group (JTAG) port is an IEEE standard that defines a Test Access Port and Boundary Scan Architecture for digital integrated circuits and provides a standardized serial interface for controlling the associated test logic." [6] JTAG allows us to flash our code onto the microcontroller with an IEEE backed protocol. Only four pins will be used on the microcontroller due to this protocol. Those pins are: TCK, TMS, TDI, and TDO. Using serial transmission, we can send data to the microcontroller with TDI with the TCK clock signal for controlling the speed.

3.2.11.2 Clock Signal

The TM4C1232H6PMI7 has multiple options for clock signals that can be used in the microcontroller. The Main Oscillator (MOSC) provides a very accurate clock source by utilizing an external crystal oscillator. The microcontroller supports crystal oscillators with frequencies between 5 and 25 MHz. While the speed and accuracy is enticing, using the MOSC will introduce more required capacitors on the PCB, increasing size and decreasing space on the PCB while increasing production costs. Due to this reasoning we will be selecting the Precision Internal Oscillator (PIOSC).

The PIOSC is a clock source that is integrated onto the chip and used by default. There is no required use of external parts or crystals for it to function. It provides a 16-MHz clock source to the chip with a +/- 3% accuracy due to temperature. The internal clock is implemented using resistors and capacitors which makes it less accurate than a crystal oscillator due to the increased temperature of the components. While the max speed of the PIOSC is 36% slower than the MOSC and also less accurate, it will be more than sufficient for Trash-E which only needs to generate signals for servo/stepper motors and ultrasonic sensors.

3.2.11.3 PWM Generation

To generate the PWM signals for the motors and sensors, multiple timers need to be used which the microcontroller is in no short supply of. “The TM4C1232H6PM General-Purpose Timer Module (GPTM) contains six 16/32-bit GPTM blocks and six 32/64-bit Wide GPTM blocks. Each 16/32-bit GPTM block provides two 16-bit timers/counters (referred to as Timer A and Timer B) that can be configured to operate independently as timers or event counters, or concatenated to operate as one 32-bit timer or one 32-bit Real-Time Clock (RTC). Each 32/64-bit Wide GPTM block provides 32-bit timers for Timer A and Timer B that can be concatenated to operate as a 64-bit timer.” [6] With twelve GPTM blocks and two timers per block, we have the potential to generate twenty four PWM signals. This will be plenty to implement our original design as well as accommodate for any stretch goals that can be implemented in the future

3.2.11.4 UART Interfaces

The TM4C1232H6PMI7 also has eight separate UART interfaces that are fully programmable. With baud rate generation of 5 Mbps for regular speed and 10 Mbps for high speed, there will be no problem sending data between the microcontroller and Jetson Nano. There’s also separate transmit and receive FIFOs that reduce the CPU interrupt service loading and also have programmable length. The interface also gives us full control over the serial communication characteristics such as the amount of data bits, either one or two stop bit, and even, odd, or no parity bit.

3.2.11.5 Sleep Modes

Arguably the most important feature that this and many other microcontrollers offer is the Low Power Modes, or in the TM4C1232H6PMI7's case, Sleep Modes. By entering a Sleep Mode, power consumption is kept to a minimum. Depending on what functions are needed to keep running during sleep, either Sleep mode or Deep-sleep mode can be chosen. Sleep mode only stops the processor clock while Deep-sleep mode stops the system clock as well as switches off the Phase Locked Loop (PLL) and Flash memory. Since Deep-sleep mode turns off not only the processor clock but the system clock, PLL and flash, we will want to use Sleep mode. This mode will allow us to keep Trash-E moving while there is nothing to process from the Jetson Nano. In comparison to other microcontrollers, like the MSP430 family which has four different Low Power Modes, the power conservation options of this microcontroller is pretty limited but is sufficient for our power needs since we can't go into too deep of sleep with Trash-E doing continuous movement at almost all times. It's also important to note that the deeper sleep modes might reduce the power consumed by the microcontroller, but also increase the amount of time required to sleep and wake.

3.3 Computer Vision

3.3.1 Computer Vision Overview

For computer vision to work, a lot needs to get done before it is used for cases like Trash-E identifying trash in real time. Computer vision requires a lot of data and would need to use machine learning techniques to accomplish it. It needs to analyze a lot of data and learn from it until it can make certain distinctions in images and ultimately recognize what it needs to find in an image or video. Figure 4 is an example of what a computer sees after identifying objects via computer vision.

Figure 4: Object Detection Using Computer Vision (Courtesy of TowardsDataScience.com)

To accomplish computer vision, we need certain algorithms that can learn from given inputs and produce an outcome on its own in a way that the human brain would. The best way to accomplish this is to use a form of machine learning called deep learning.

3.3.2 Machine Learning

Machine Learning is the term that refers to a machine becoming capable of learning from a large data set and performing actions based on what the computer has learned and the input data it is receiving. There are many types of learning that machine learning can be done in.

Supervised learning datasets are labelled manually prior to being given to a machine learning model for training. These datasets also include the expected output that the model will use to become very accurate at predicting when it comes to new input data. Unsupervised learning uses datasets that are not labelled and have no specified structure. The model will learn on its own and make classifications based on the data.

Semi-supervised learning is an approach that combines a small portion of labelled input data along with a large amount of data that is not labelled that the model will use to learn. This is typically used when there isn't a lot of labelled data available or having a complete set of labelled data is too challenging or expensive but still want to use some amount of labelled data. This type of learning can achieve better performance and accuracy than its supervised counterpart.

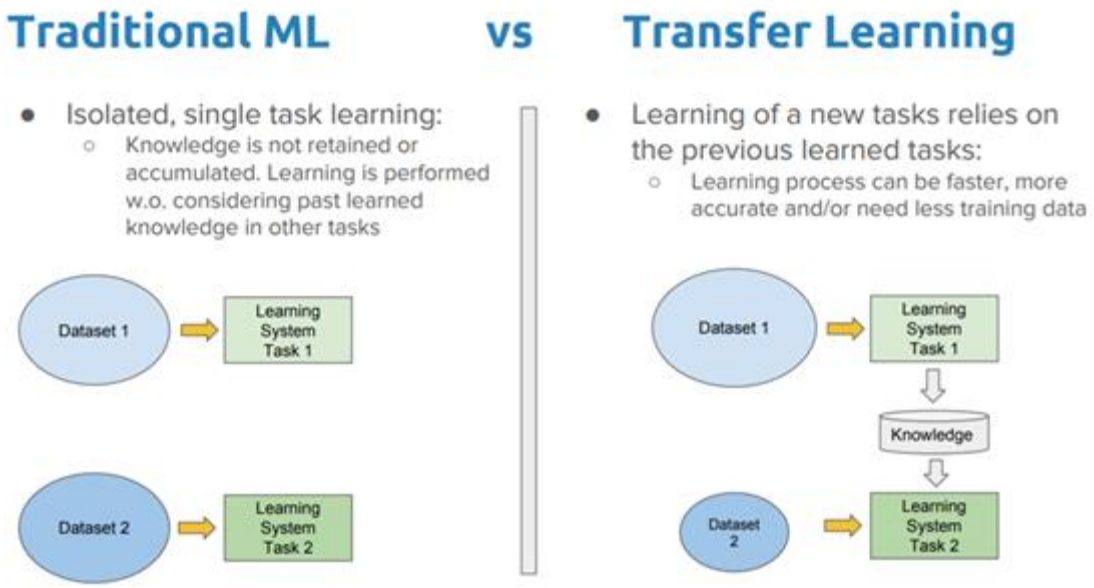


Figure 5: Traditional Learning (Courtesy of TowardsDataScience.com)

Transfer learning involves using a pretrained model and using the existing knowledge from previously learned tasks and applying that knowledge to a new task that is related as shown in Figure 5. If we had trained a previous model for object detection on cars, we could use that model's knowledge to learn how to detect trucks and other forms of vehicles and make learning faster.

3.3.3 Deep Learning

Deep learning is a subset of machine learning that uses neural networks to learn large amounts of data through lots of training.

Neural Networks are the brain of the AI and are used extensively in deep learning. These networks are meant to simulate the way that humans learn with the brain. Our brain has neurons that make connections and so does the neural network that we use for machine learning. All the neurons in a neural network are interconnected and are organized into multiple layers. These layers consist of the input layer, the hidden layers, and the output layer. The input layer of our neural network receives information to learn via our input data. The next few hidden layers in between the input and output layers are where most of the work and training is done in a neural network.

In these layers many mathematical computations are performed on our input data. The connections between all the neurons in these layers have weights which determine the importance of the input value and the strength of the connection. Each of these go through an activation function which in simple terms standardizes the outputs of the neurons. The number of hidden layers you could have in a neural network is arbitrary. These are the layers where people usually spend time tweaking and testing this area by increasing and decreasing the number of hidden layers and number of neurons in each layer. With deep learning, the neural networks have more than one hidden layer, which is where the deep term comes from.

Once these layers have been passed and we reach the output layer, there is a loss function that determines how wrong our network's output was from the real output data. We want that function to be as close to zero as possible to get the most accurate output from our deep neural network. To improve accuracy and reduce loss, we use optimization algorithms called gradient descent and backpropagation which find the minimum of a function and in this case that is the loss. It allows a deep neural network to change its weights automatically in incremental steps after each iteration of training to achieve a loss as close to zero as possible.

Deep learning networks can be supervised but they can also be unsupervised as well. Unsupervised training is where deep learning typically shines. With deep learning, data preprocessing can be mostly eliminated. Deep learning algorithms can process unstructured data and automate feature extraction. For example,

feature extraction for computer vision can be a very challenging task to do manually and involves a lot of manual work. Images must be put through many processes to extract features such as edges, colors, and brightness. A deep learning network can be given a set of images and it will be able to determine important features that allow it to distinguish objects from each other. Through algorithm processes and training with the neural network it can learn from the data and become very accurate. This allows it to make accurate predictions based on new input data.

3.3.4 Convolutional Neural Networks

There are many types of neural networks out there. For our purposes of this project, the most tried and true deep learning algorithm for computer vision is a convolutional neural network. A convolutional neural network should be the best algorithm to implement for Trash-E to detect trash objects using image recognition. Convolutional Neural Networks (CNN) are deep learning algorithms that can take an input image and then learn various patterns and features about that image and make decisions about the image. Figure 6 is a diagram of a convolutional neural network showing its general architecture.

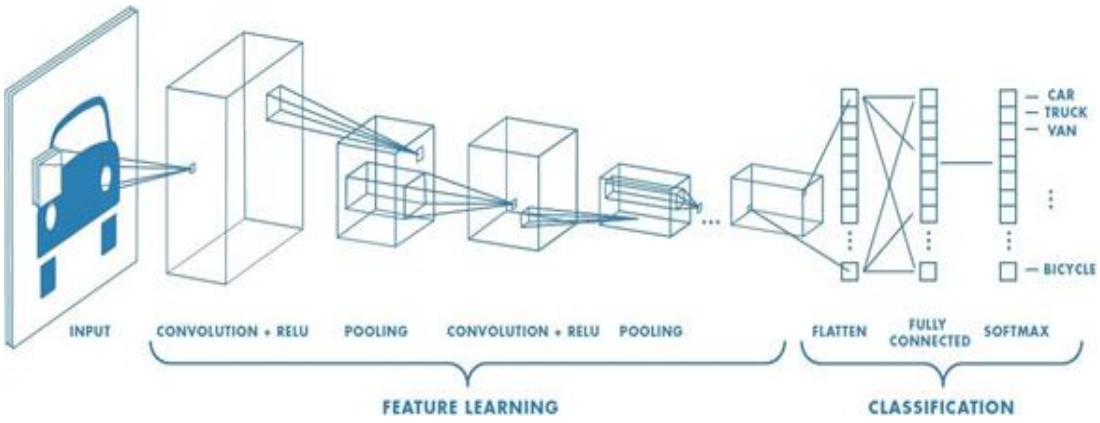


Figure 6: Convolutional Neural Network Architecture (Courtesy of TowardsDataScience.com)

The first step in the convolution neural network is the convolution layer. An image is fed into a CNN in the form of a matrix with pixel values. In the convolution layer a kernel/filter, which is a square matrix of a certain size, is typically used to hover over the original image in a certain number of shifts and strides. Each time the filter is over a new section of the image matrix, a matrix multiplication is performed and produces a new value for the image matrix. Depending on the kernel/filter values, different types of high-level features can be extracted from the input image. A CNN can capture spatial and temporal dependencies in an image through these filters. The main objective of the convolution is to extract high level features from the input image such as edges, color, gradient orientation and more. There can be more than one convolutional layer.

Following convolutions, the pooling layer follows which is responsible for further extracting dominant features and reducing the spatial size of the convolved feature by using a smaller kernel and certain techniques. This reduces computational power that Is needed further into the network. There are two types of pooling techniques: average pooling and max pooling. Max pooling returns the maximum value of the image matrix that the pooling kernel is on. Average pooling returns the average of all the values of the image currently in the pooling kernel.

Now, the output is flattened into a column vector and fed into a feed-forward neural network and backpropagation is applied in every training epoch. This layer is referred to as the fully connected layer and is where the network learns the many features we have extracted from the image. After a certain number of epochs, the model can distinguish between features of the input image and classify them using the SoftMax activation function. This function will produce multiple probabilities ranging from 0 to 1 for all the classes our CNN is trained to find and output what the image likely contains.

3.3.5 Convolutional Neural Network Architectures

There are many CNN architectures out there. Some of the notable ones are: LeNet, AlexNet, VGGNet, GoogLeNet, ResNet, and ZFNet. Each are different takes and variations on the general CNN architecture shown earlier. For Trash-E, we have many options available to choose for the CNN architecture and would likely involve more experimentation and fine tuning down the line to decide which architecture would return the best results. There are also many pre-trained state of the art models available on Google's TensorFlow GitHub that were trained on the COCO 2017 dataset. Some of the most popular ones that we could use are SSD MobileNet V2 and SSD ResNet. Each of these architectures have configurations for certain image sizes such as 320x320, 640x640, etc.

Model name	Speed (ms)	COCO mAP	Outputs
SSD MobileNet v2 320x320	19	20.2	Boxes
SSD MobileNet V1 FPN 640x640	48	29.1	Boxes
SSD MobileNet V2 FPNLite 320x320	22	22.2	Boxes
SSD MobileNet V2 FPNLite 640x640	39	28.2	Boxes
SSD ResNet50 V1 FPN 640x640 (RetinaNet50)	46	34.3	Boxes
SSD ResNet50 V1 FPN 1024x1024 (RetinaNet50)	87	38.3	Boxes
SSD ResNet101 V1 FPN 640x640 (RetinaNet101)	57	35.6	Boxes
SSD ResNet101 V1 FPN 1024x1024 (RetinaNet101)	104	39.5	Boxes
SSD ResNet152 V1 FPN 640x640 (RetinaNet152)	80	35.4	Boxes
SSD ResNet152 V1 FPN 1024x1024 (RetinaNet152)	111	39.6	Boxes
Faster R-CNN ResNet50 V1 640x640	53	29.3	Boxes
Faster R-CNN ResNet50 V1 1024x1024	65	31.0	Boxes
Faster R-CNN ResNet50 V1 800x1333	65	31.6	Boxes
Faster R-CNN ResNet101 V1 640x640	55	31.8	Boxes
Faster R-CNN ResNet101 V1 1024x1024	72	37.1	Boxes

Figure 7: Available Models (Courtesy of Tensorflow)

A higher resolution architecture will take more computational power and won't be as fast as a lower resolution one but offers better mean average precision as shown in Figure 7, where the speed in milliseconds is on the left and the mean average precision is on the right. This is a tradeoff we will have to decide on for Trash-E's computer vision implementation.

3.3.6 Programming Languages for Machine Learning

We have many options for the programming language we could use for writing Trash-E's software. Several programming languages are used for AI and machine learning nowadays. Some of the popular ones are Python, C/C++, and Java. The most popular of these languages for AI and Machine Learning is by far Python. For computer vision and robotics, the most popular languages to use are C/C++ and Python.

Python is an interpreted high level programming language, so it is less performant than a compiled language since the code is executed line by line. Python is one of the most supported machine learning languages out there. It is a relatively simple language in comparison to C/C++ and Java. Python has an extensive number of tools and libraries for machine learning such as TensorFlow, scikit-learn, PyTorch, and Keras to name a few. These libraries support computer vision and deep

learning allowing the ability to easily create convolutional neural networks and train them.

C/C++ are very much used in embedded and robotics programming. C/C++ are compiled languages and have very high performance. The areas they're used most for in AI are gaming and robot locomotion. They're not as simple as python when it comes to building new machine learning applications and getting what you want quickly. However, they are favored when control, high performance and efficiency is needed. C/C++ have some libraries for machine learning and computer vision such as MLPACK, SHARK, and OpenCV.

Java is less popular for embedded and robotics and is used more for desktop and enterprise applications. Java does come with a decent amount of machine learning libraries such as TensorFlow, Deep Java Library, Kubeflow, and Java-ML.

3.3.7 Libraries and Tools for Machine Learning and Computer Vision

There are many libraries available for machine learning and computer vision. We decided to investigate the most popular libraries since they have the most support and have everything we would need for Trash-E.

3.3.7.1 TensorFlow

TensorFlow is a machine learning open-source library by Google. It allows users to build and train machine learning models using high level Keras APIs. It is a more general machine learning library for python but still offers functions that can be used for computer vision.

3.3.7.2 PyTorch

PyTorch is an open-source machine learning library for Python developed by Facebook. PyTorch can work for both Python and C++. It provides tensor computing with acceleration via a graphics processing unit or GPU. It also offers the ability to create deep neural networks

3.3.7.3 OpenCV

OpenCV is a popular open-source computer vision library. It provides common infrastructure for computer vision applications. It has thousands of optimized algorithms for both computer vision and machine learning. It would allow the ability to use computer vision algorithms and techniques to enable computer vision needed on Trash-E quickly and efficiently. It has C++, Python, and Java interfaces and supports most of the common platforms. These include Windows, Linux, Android, and MacOS. This library also works very well with real time computer vision applications which is essential for what Trash-E needs to accomplish.

3.3.7.4 LabelImg

LabelImg is a graphical image annotation tool. The tool is written in Python and is a popular way to label images to use in a dataset for object detection models. It will allow us to easily label our data and save it in a format that can be used in object detection models.

3.3.7.5 TensorRT

TensorRT is an SDK by Nvidia that optimizes inference performance of models for Nvidia GPUs. It is used to optimize trained models from a machine learning library so that it runs faster and more efficiently on an Nvidia Jetson Nano. When a model is finished training and ready to be deployed to a Jetson Nano, first the model or in other words graph is frozen. This essentially saves the model. Once the model graph is frozen, it can be optimized by TensorRT as shown in Figure 8.

Figure 8: The TensorRT Flow (Courtesy of Nvidia)

TensorRT will parse the model and apply optimizations to the graph where it is able to. When it detects a compatible subgraph, TensorRT replaces it with a TensorRT optimized node. First, layers within the TensorFlow graph that have unused output are destroyed so that unnecessary computation is avoided. Next, convolution, bias, and ReLU layers are merged to form a single layer. Further optimizations include layer aggregation which also improves performance. Most importantly the overall original computation of the graph or model is unchanged but it is restructured to optimally perform operations more efficiently and faster as shown in Figure 9.

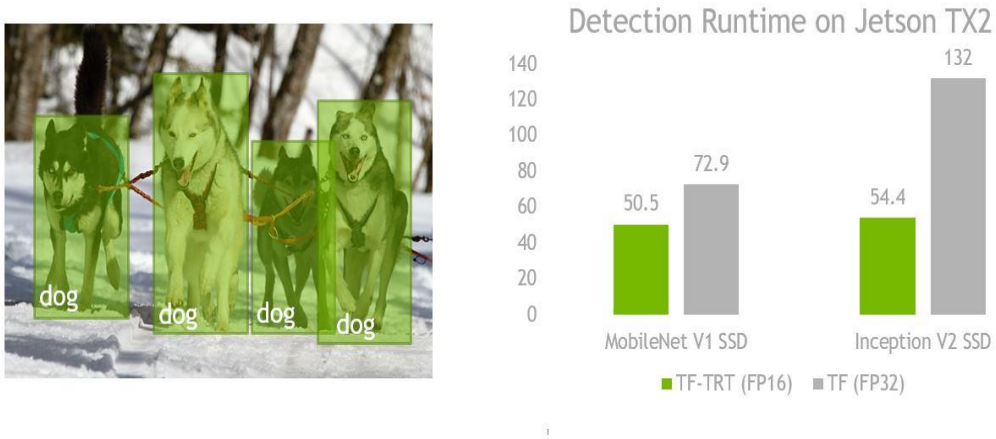


Figure 9: TensorRT Optimization Performance Graph (Courtesy of Nvidia)

3.3.8 Hardware Options for Machine Learning

Our robot will be using computer vision in real-time. To process the data and algorithms we need for computer vision and deep learning we would need a minicomputer on our robot capable of handling these tasks. These tasks include object detection, and classification. There are several out on the market such as the Nvidia Jetson Nano, Raspberry Pi 3, and Google Edge TPU. Figure 10shows benchmark comparisons for these products. The Nvidia Jetson Nano appears to drastically outperform the other two boards in this comparison and while using the object detection model architectures that we previously stated in our research on convolutional neural network architecture.

Model	Application	Framework	NVIDIA Jetson Nano	Raspberry Pi 3	Raspberry Pi 3 + Intel Neural Compute Stick 2	Google Edge TPU Dev Board
ResNet-50 (224×224)	Classification	TensorFlow	36 FPS	1.4 FPS	16 FPS	DNR
MobileNet-v2 (300×300)	Classification	TensorFlow	64 FPS	2.5 FPS	30 FPS	130 FPS
SSD ResNet-18 (960×544)	Object Detection	TensorFlow	5 FPS	DNR	DNR	DNR
SSD ResNet-18 (480×272)	Object Detection	TensorFlow	16 FPS	DNR	DNR	DNR
SSD ResNet-18 (300×300)	Object Detection	TensorFlow	18 FPS	DNR	DNR	DNR
SSD Mobilenet-V2 (960×544)	Object Detection	TensorFlow	8 FPS	DNR	1.8 FPS	DNR
SSD Mobilenet-V2 (480×272)	Object Detection	TensorFlow	27 FPS	DNR	7 FPS	DNR

Figure 10: Minicomputer Deep Learning Benchmarks (Courtesy of Nvidia)

3.4 Power

3.4.1 Power Supply

In order to determine the power supply necessary for the robot, the requirements of the components must be looked at. In Table 4, the possible components that will be needing power are listed along with their required specifications.

From table 4, most of the components should be able to be powered by a normal battery bank that is often used for phones. This is because most of these components are able to be powered through the USB port on a computer, which normally has a maximum supply of 5V, 0.5A. The maximum current and maximum power columns are the maximum, and thus the devices will not be drawing that much on regular use. The Blink Mini claims that it requires wall power on the amazon website, however with further investigation and after testing it, it should be able to be powered through a power supply. Some of the other cameras did not have readily available datasheets and without purchasing it, it will be hard to find the requirements to power them.

Table 4: Components Requiring Power

Component	Voltage Requirement	Maximum Current	Maximum Power
Jetson Nano	4.75V	4A	19W
Arduino Uno	7-12V	50mA	.35-.6W
Raspberry Pi 3	5V	2.5A	12.5W
Motor Driver	8-35V	1A	8-35W
MG996R 55g Metal Gear Torque Digital Servo Motor	5V	3A	15W
Stepper Motor	12V	1.2A	14.4W
AREBI Spy Camera Wireless Hidden WiFi Mini Camera HD	4.2V	300mA	1.26W
Blink Mini	100-240V	.15A	15-36W
Logitech C270 HD Webcam	5V	1A	5W
NexiGo N60 USB Computer Camera	5V	1A	5W
HC-SR04 ultrasonic sensor	5V	15mA	.075W

There are a few options for powering Trash-E. The first option and the least likely one will be a readily made battery bank that normally are used as backup batteries for phones. This option is the least likely, as we want to integrate our own design, from the batteries to the voltage regulation. The next few options that can be used are readily made batteries such as Li-Ion (Lithium Ion) batteries, Li-Poly (Lithium Polymer) batteries, or NiMH (Nickel-Metal Hydride) batteries. These three batteries

are the best options because while there are many more, these are inexpensive, and are not difficult to find or charge.

Table 5: Possible Battery Types (Courtesy Radek Jarema)

Battery type	**NiMH**	**Li-Ion/Li-Poly** high energy type	**Li-Ion/Li-Poly** high current type	**Li-Ion/Li-Poly** high safety type
Chemistry	NiMH	$LiCoO_2$ $LiNiMnCoO_2$	$LiMn_2O_4$	$LiFePO_4$
Nominal cell voltage	1.2V	3.6 - 3.7V	3.7 - 3.8V	3.2 - 3.3V
Operating cell voltage range	1.0 - 1.4V	3.0 - 4.2V	3.0 - 4.2V	2.5 - 3.65V
Max voltage for charging	1.4 - 1.6 V	4.2 - 4.3V	4.1 - 4.2V	3.65V
Max charging current*	0.1C or 1C (only with ΔV/ ΔT)	~1C	up to 3C	up to 4C
Max discharging current	1C - 30C	1C – 2C	5C - 30C	1C - 40C
Charging method	CC with timer or ΔV/ ΔT (faster)	2 stages: CC and then CV	2 stages: CC and then CV	2 stages: CC and then CV
Specific energy	40 - 120Wh/kg	150 - 250Wh/kg	100 - 150Wh/kg	90 - 120Wh/kg
Specific power	100 - 1000 W/kg	100 - 400W/kg	400 – 5000 W/kg	200 - 7000 W/kg
Internal series resistance for a single cell	5-50 mΩ (for 18650 size)	15-100 mΩ (for 18650 size)	10-50 mΩ (for 18650 size)	6-60 mΩ (for 18650 size)

The above table showcases the batteries that were outlined previously. From this table, it can be noted that the Li-Ion/Li-Poly batteries may be the best for our use case because they have a much higher voltage than the NiMH batteries, though NiMH have a better power-to-weight ratio and are safer than the Lithium batteries. The “C” in the current rows of the table is the capacity divided by hour. To understand the significance of “2C”, take an example battery capacity such as 4000mAh, and multiply by 2C and the result is 8000mA. Once all the parts are fully determined, we have to find the battery necessary to last 1 hour based off battery consumption of the different parts.

The batteries can also come in different constructions such as cylindrical, prismatic, or in a pouch. The Li-Ion batteries can come in cylinders or prismatic, but they require metal enclosures, whereas Li-Poly batteries can come in the previous or in a pouch as well. There are many cylindrical Li-Ion batteries, ranging in different diameters and lengths such as 14500, also known as AAs. These cylindrical batteries are a likely option, as battery packs can be constructed from them that we can use to power the Trash-E. The prismatic cells are unlikely to be useful in our application. Li-Poly pouches are another possibility, as they can be stacked and are often used for RC cars, drones, and other high-power

applications. However, the Li-Poly pouches must be secured safely within the robot and there must not be any sharp objects inside, because the Li-Poly batteries are much easier to be pierced than the Li-Ion ones.

Since our parts need to have a maximum of 12V, we can aim to create a 12V battery pack to power Trash-E. Using voltage regulators, we can down step the voltage to necessary voltages when needed such as for Jetson Nano.

3.4.2 Battery Requirements

Table 6: Battery Specifications

Requirement	Specification
Size	Less than 200cm^3
Weight	Less than 1kg
Nominal Voltage	10-12V
Maximum Discharge Current	10A
Capacity	Greater than 1250mAh

In table 6, the specifications of the battery can be found. The size of our battery pack needs to be small enough to fit on Trash-E while minimizing the space it takes. We hope that this size and weight will be sufficient. To find the capacity and maximum discharge current, we use the following equation.

$$Maximum\ Discharge\ Current = \frac{\sum P_{MAX\ COMP}}{V_{MIN}} = \frac{99.835\ W}{10\ V} = 9.985A = 10A$$

Thus, we need batteries that can handle 10A discharge current. To calculate the capacity, we use the following equation. We found the average A by adding the average current of the components together. We want to power the robot for at least 1 hour.

$$Capacity = A_{AVG} * h * 1000 = 1.2465 * 1 * 1000 = 1246.5mAh$$

3.4.3 Battery Options

Between the three batteries: NiMH, Li-Ion, Li-Poly, we will examine which one is the best. Since we will be requiring a lot of energy, Lithium based cells are a better option than NiMH.

Possible Li-Ion batteries that we can consider are the INR18650-35E 3500mAh batteries made by Samsung. The plan is to have 6 batteries, with 3 in series and those two rows in parallel. The table below shows the specifications of the batteries in this configuration. The batteries meet all of the criteria set in Table 7. The batteries are also less than $50 in total.

Table 7: INR18650 Li-Ion Batteries Specifications

Specification	Detail
Dimensions	67 x 57 x 38 mm
V_{NOM}	10.8V ($3.6V_{NOM}$ $4.2V_{MAX}$ Single Cell)
V_{MIN}	9V
Max Discharge Current	16A
Volume	145 cm^3
Weight	300g
Capacity	7000mAh

The Li-Poly batteries that we found are the LP616594 4700mAh batteries. The configuration is 3 batteries in series. Table 8 shows the battery specifications. The Li-Poly batteries in this configuration do not meet the maximum discharge current that we specified, but it should be sufficient because the robot will not be running at maximum current. Otherwise, the Li-Poly batteries meet the rest of the requirements.

Table 8: LP616594 Li-Poly Batteries Specifications

Specification	Detail
Dimensions	94 x 65 x 19 mm
V_{NOM}	10.8V
V_{MIN}	9V
Max Discharge Current	9.5A
Volume	113 cm^3
Weight	236g
Capacity	4700mAh

Out of the three batteries we considered, the Li-Ion batteries seem to be the best option. They meet all of the requirements set out for the robot.

3.4.4 Recharging

The batteries will need to be recharged. We can have two methods to recharge the batteries. The first method would be to use a DC power supply to fully charge the battery pack. With a DC power supply, we can limit the current flowing into the battery from the power supply. Figure 11 showcases a Li-Poly battery charging from a power supply. While it is a different battery from what we will be using, the concept is still the same. Another method would be to use a separate battery such as a 12V lead acid battery and use a Buck/Boost converter to step the voltage down so the batteries can charge properly. Figure 12 shows a possible configuration.

Figure 11: Battery Charging from a DC Power Supply

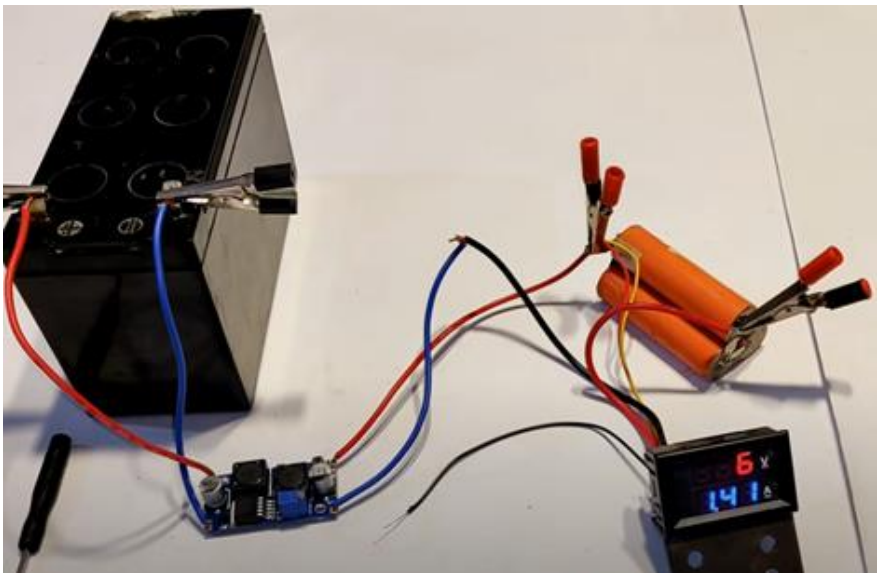


Figure 12: Battery Pack Charging with Buck/Boost Converter

Another option would be to design an AC to DC converter so that we can plug an AC adapter into the robot. The input AC adapter will be converted to DC and stepped down to a safe voltage so the batteries can safely charge.

3.4.5 Photovoltaic Cells

As a secondary goal, we hope to implement photovoltaic (PV) cells, or solar panels that can passively regenerate the batteries while Trash-E is operating. Things we have to consider for the photovoltaic cells are the size of the panels as compared to the size of the robot, the placement of the panels, and the recharge rate. Depending on the size of Trash-E, the implementation of photovoltaic cells may not be worthwhile, as they may not be able to provide any substantial energy at all.

The sun radiates photons, which contain varying energy, which varies based on the wavelength of sunlight. When the photons hit a PV cell, the cell attempts to absorb the photons, although all the photons are not fully absorbed, as some are reflected off. Once there is enough photon energy absorbed within the semiconductor material, the electrons inside the cell are free to move. When enough electrons have moved to the front of the PV cell, a voltage potential will have been created. Once the cell is connected to a load, such as a light bulb, electricity will flow. We can use this to help charge the battery while it is operating outside. We will have to make sure that the charge from the battery does not flow to the solar cells while the cells are not charging.

Photovoltaics have many advantages and disadvantages. PV cells are good for the environment because their energy generation releases no carbon emissions. This is beneficial for our robot because Trash-E will be able to work outdoors. Thus, we hope to be able to run Trash-E for longer periods of time when outside on a sunny day. Because PV cells have no mechanical parts, there will be little to no maintenance regarding them once they have been implemented.

3.4.5.1 Monocrystalline Silicon Cell

Monocrystalline Silicon Cells are generally more efficient than other types of PV cells. While they are more efficient, they also are much more expensive. As a result, we do not plan on using these types of cells, but they were considered in the preliminary stages. If we find low cost Monocrystalline PV cells, we may consider using them.

3.4.5.2 Polycrystalline Silicon Cell

Polycrystalline Silicon Cells are the cells that we will most likely use. They are cheap and abundant since they are the most popular types of photovoltaic cells. Section 6.2.9 further covers the types of solar cells that we will consider using in our robot design.

3.4.5.3 Thin Film Cells

It is highly unlikely that we will use Thin Film Cells because the flexibility and thinness of these cells are not necessary for our application. Furthermore, since they are less generally less efficient than the two previous cells, it is unhelpful to our design. In addition to the previous, some thin cells contain rare or toxic elements. These elements would be detrimental to our design because they would add unnecessary dangers to our robot. To make up for these dangers we may need to add potting to our circuits, which would add too much complexion that we do not need.

3.4.5.4 Miscellaneous Cells

These cells such as high efficiency cells are out of the scope of this project because they are either exceptionally expensive, or are still a new technology that is not fully developed.

3.4.6 Voltage Regulator

3.4.6.1 Linear Voltage Regulators

Each component within Trash-E requires certain voltages to operate correctly. By supplying 12V, each component should be able to be powered, either at 12V or stepped down to the required voltage. Certain components such as the ultrasonic sensor or the motors controlled by the Arduino will be taking power from the Arduino, thus it will not need to be stepped down. However, the Jetson Nano uses 5V to power, thus the 12V will need to be stepped down. The purpose of a voltage regulator is to keep a constant voltage output regardless of input voltage or current draw from the load. There are two types of voltage regulators, linear and switching, each with their own benefits and drawbacks. A linear regulator, which can be found in the figure below, is a simple circuit with low noise and few parts necessary externally. It uses the control circuit to monitor and change the output voltage. Linear voltage regulators are slower at changing the output voltage if there is a large change in the input voltage because it is using a feedback loop to control the output voltage. In our application there should not be huge drops or rises in our input voltage, so this should not be a problem. The linear voltage regulator often has poor efficiency between the input and output voltage conversion. The linear voltage regulator can also only be used as a buck converter. This is not an issue in our use case, as we only want to step down our voltage. It can also get hot easily, so temperature must be taken into account. This is because when stepping down voltage, the excess power has to go somewhere, and thus the voltage regulator expels it as heat. To calculate the power loss, the following equation is used. Figure 13 shows a basic Linear Voltage Regulator

$$P = (V_{IN} - V_{OUT}) * I_{LOAD}$$

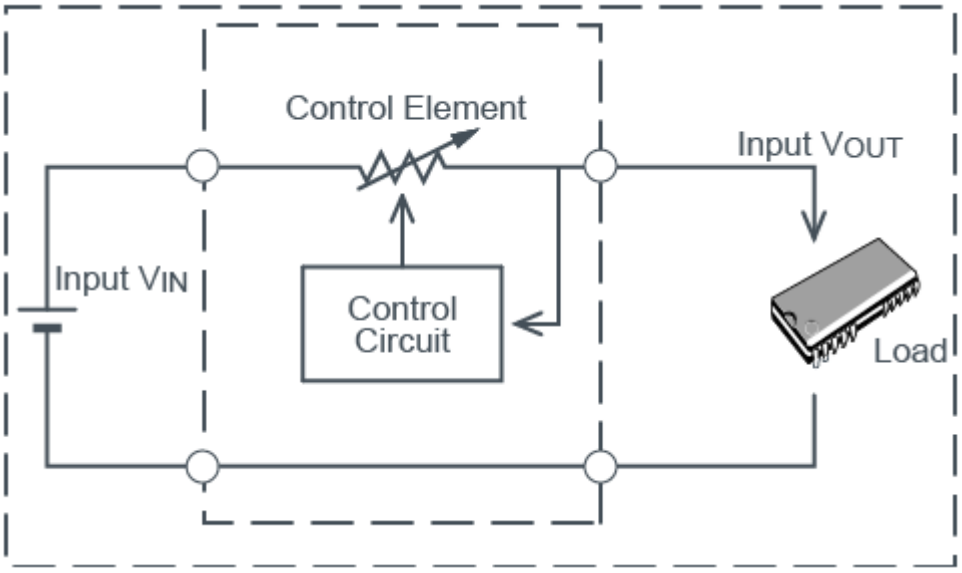


Figure 13: Linear Voltage Regulator (Courtesy Rohm)

3.4.6.1.1 Standard Voltage Regulator

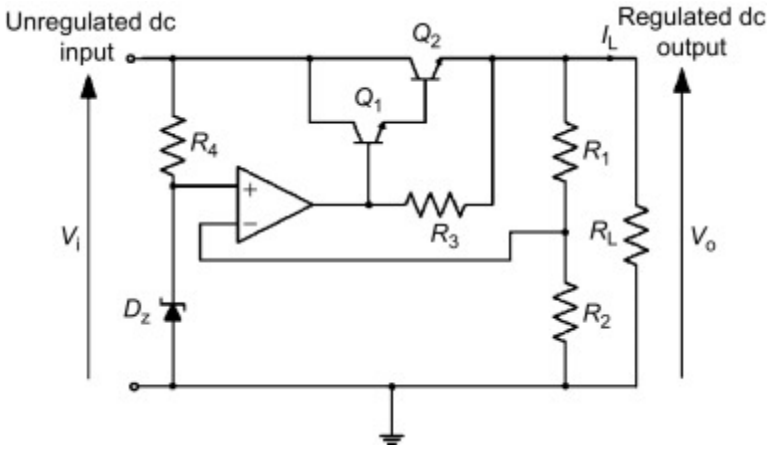


Figure 14: Standard Voltage Regulator

The standard voltage regulator in Figure 14, is a basic configuration using a Darlington pair of transistors. The Standard voltage regulator circuit can be replaced with an Integrated Circuit of a regulator. These options are later discussed in Section 6.28. Standard voltage regulators can have large voltage drops depending on the device specifications. Voltage dropouts for a standard regulator can vary between 1V and 2V. In cases where a regulator needs to drop from 120V to 12V, 1V voltage dropout is not a big issue. However, in a case where a voltage needs to be converted from 3.6V to 3.3V, the voltage dropout is a third of the input voltage. The output voltage must be less than the input voltage minus the dropout voltage, otherwise the regulator will be unable to function.

$$V_{OUT} < V_{IN} - V_{DROPOUT}$$

3.4.6.1.2 Low Dropout Regulator

Low Dropout Regulators (LDO) regulators are useful when needing small voltage drop amounts. Some LDO regulators can have drops of 100mV, this is useful for cases between 3.3V and 3V. Since we are dropping down 12V to 5V, and possibly 12V to 3.3V or 5V to 3.3V, we will not be needing a LDO regulator.

3.4.6.2 Switching Voltage Regulators

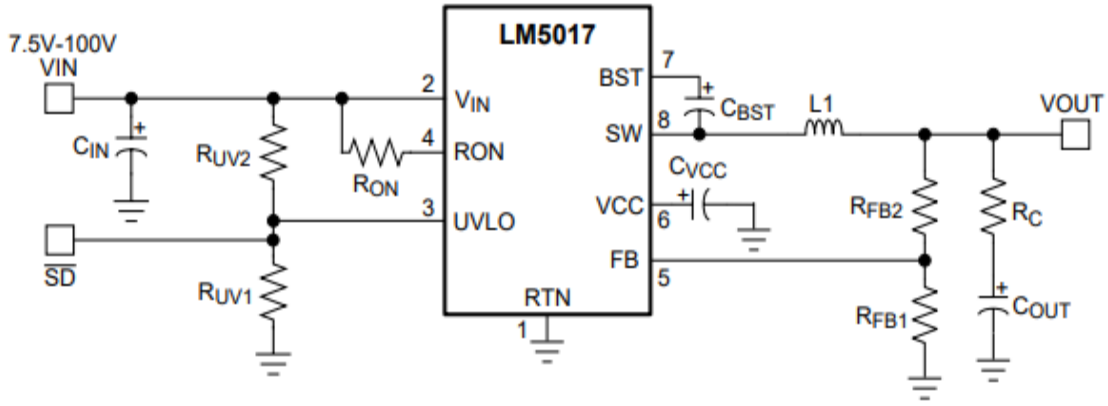


Figure 15: Typical Switching Voltage Regulator Circuit of a LM5017

A switching voltage regulator is a type of regulator that allows for both buck and boost of a voltage. This is possible by having a switching element that the circuit uses to change input power into a pulse. The voltage is smoothed out with the use of different capacitors and inductors, FETs, and other components. Figure 15 shows a typical circuit of the switching voltage regulator. It is more complex than the linear voltage regulator in Figure 13. The output power is set to the desired voltage, and once it reaches it, the switch is turned off. When the switch is off, there is no input power being supplied. By continuously doing this process at high speeds, the efficiency between the output voltage and input voltage is much higher than a linear regulator, which also results in lower temperatures because there is not as much power being dissipated as heat. Although the switching voltage regulator has these advantages, there are also several disadvantages such as the regulator being much more complex and requiring more external parts.

Within Trash-E we will not be requiring precise voltage drops with tight margins, we also want to keep costs down. As a result, we will end up using a Standard Linear Voltage Regulator circuit, as that should be sufficient.

3.5 Locomotion and Mapping

3.5.1 Different Types of Movement

There are a few options to how we can approach maneuvering Trash-E around on its own. As a recap, Trash-E needs to be able to maneuver any area to find trash, assuming it is physically capable of traversing the area given its physical limitations. Given Trash-E's physical limitations, Trash-E should be able to maneuver on any flat surface. However, this area or environment that Trash-E is placed into won't always be familiar and can be entirely new every time. So, there must be certain methods in our design that allow Trash-E to maneuver around an unknown environment and accomplish its tasks while being autonomous or without manual control via a controller.

One way of detecting obstacles in the robot's path is using bumper sensors. These are the least useful in terms of Trash-E since we have no way of determining where it is, where it's been, and where it will go. It is essentially random movement that is up to chance and the layout of the environment and can't guarantee every spot will be reached. The robot can also get stuck in an area depending on the configuration of the environment and the movement capabilities of the robot itself.

Facing some of the same challenges as the bumper sensors, this approach involves using ultrasonic sensors on all sides of Trash-E that will detect incoming obstacles in order for it to keep moving and avoid obstacles. If the sensors don't detect anything close to the chassis, then the robot would continue to move forward until a sensor has detected an obstacle that is too close. If the sensor detects an object in front, Trash-E will maneuver to the right or left depending if the sensors on those sides do not detect any obstacles. In the case where Trash-E leads itself into a dead end in which case the sensors on the front, left and right are triggered, then Trash-E would reverse out of that spot. However, there are a couple of downsides to this approach. There is a chance that Trash-E could get stuck in a loop and not be able to explore the whole area that we want it to clean. Another downside is that the movement would be completely random. This is bad because it would lead to a lot of repeated work since Trash-E would not know if it had traversed the area, it is currently traversing. This could lead to a much longer runtime to complete its cleaning task.

This approach we considered is a very simple approach to this problem but has some major downfalls. This approach involves Trash-E solely being guided by the computer vision algorithm and the objects that the camera will detect. In any case, when the robot detects an object of interest then it will approach it accordingly and then pick it up. Once it completed its task, it will then spin until it detects another object of interest. This method would have worked fine if all the objects are always right next to each other, however, this will usually not be the case. If there were objects scattered across a room, there is a chance that Trash-E would not be able

to detect an object either because it is too far away or there is an obstacle obstructing the view of that object.

Another way is with a camera. Visual detection is better than the bumpers since we can gather points of interest in the surrounding environment. It also allows us to keep track of the robot's position by using landmarks. The issue with visual detection is it is more sensitive to light and can throw off the calculations or blind the robot entirely.

One way to fix this issue is using a lidar sensor. These sensors are similar to an ultrasonic sensor except it uses light waves. "A typical lidar sensor emits pulsated light waves into the surrounding environment. These pulses bounce off surrounding objects and return to the sensor. The sensor uses the time it took for each pulse to return to the sensor to calculate the distance it traveled". [https://velodynelidar.com/what-is-lidar/] Sending out these pulses many times per second in a complete circle around the sensor achieves a real-time map of the immediate environment. This information can then be processed by an algorithm that makes a graphical representation of the surrounding area. lidar is a very valuable technology when generating detailed maps of the environment around a robot.

3.5.2 Simultaneous Localization and Mapping (SLAM)

The third approach is a fully autonomous approach and method that utilizes both localization and mapping which is called simultaneous localization and mapping. SLAM is a method that allows autonomous robots and vehicles to build a map of its surroundings and localize itself within that map at the same time. With this method an autonomous robot can use these algorithms to map out an unknown environment. At the same time, the robot is able to know where it is in the environment. With this map information, robots can use path planning and obstacle avoidance.

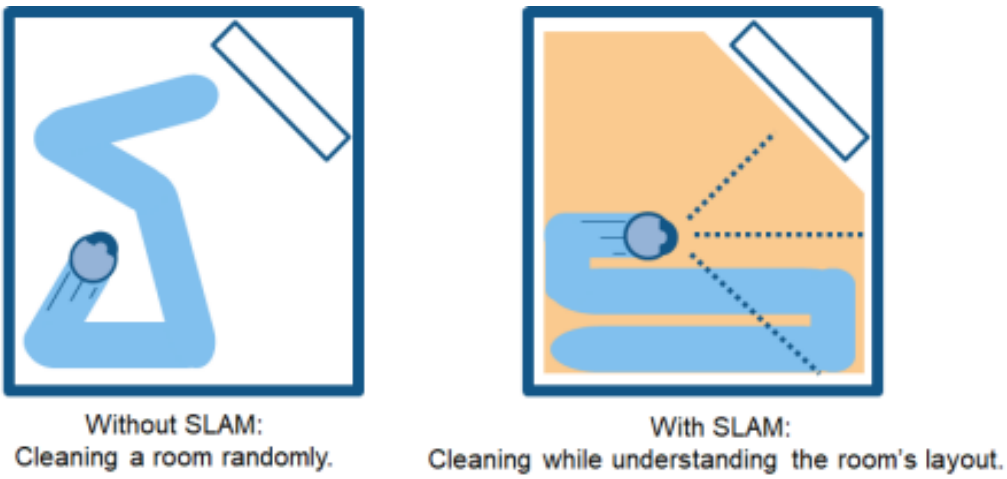


Figure 16: Comparison between no SLAM and SLAM (Courtesy of MathWorks)

A popular example of simultaneous localization and mapping in the real world is the home robot vacuum. These robot vacuums can navigate the floor of a home autonomously and figure out a path that can ensure it will vacuum every part of the floor. At the same time, these robot vacuums are in new environments and can create a map of the floorplan so that the path taken is the most efficient and avoids any obstacles or obstructions. In figure 16, we see the difference SLAM makes for the robot vacuums. This is very similar to the comparison of approach two and three for Trash-E. With our second approach we would move very randomly while in the third approach utilizing SLAM, our movement would be more defined and efficient for time and battery life.

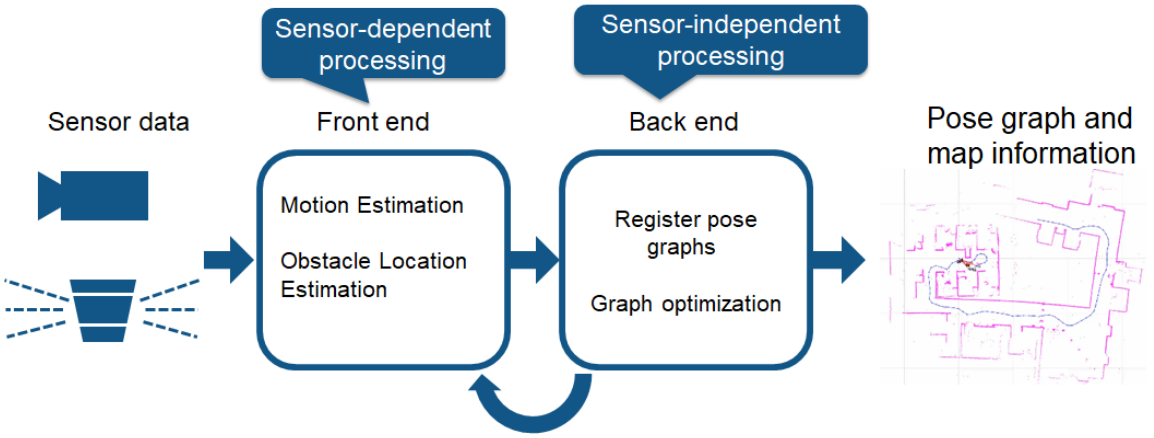


Figure 17: Flow of SLAM process (Courtesy of MathWorks)

There are two things that need to be done to achieve simultaneous localization and mapping. This includes the front end and back-end processing. The front-end processing is where sensor signal processing is done. The back-end processing is where pose-graph optimization is done. In figure 17 we can see the flow of the SLAM process, which goes from taking in sensor data to frontend processing, backend processing, and finally we get our map. SLAM uses different methods of gathering data such as from a camera, lidar device, odometer, wheel revolutions, or other imaging sensors to determine the amount of movement needed and its location in the map which is called localization.

There are also different versions of SLAM that have been developed. Two that we are considering for Trash-E are visual SLAM and LiDAR SLAM. Visual SLAM primarily uses images acquired from cameras and other image sensors. The cameras or sensors that are used can range from complex to simple and can be very expensive or inexpensive depending on the needs of accuracy. The next popular SLAM is LiDAR SLAM which uses a LiDAR device that is a laser sensor that have a 360 view. This method of SLAM is significantly more precise than visual SLAM.

For Trash-E it would be best to use LiDAR SLAM as this method is much more accurate and efficient. Therefore, we would need to place a LiDAR device on

Trash-E that will use 360 laser scans to detect the area around it. Trash-E will maneuver along an area and simultaneously create the map of it and localizing itself as well within that map to plan its path.

We have a couple of options for implementing SLAM on Trash-E. One is to use MATLAB's robotic systems tools that offer capabilities for implementing SLAM. MATLAB offers toolkits for implementing the SLAM onto Trash-E as well as for what comes after which is path planning for autonomous driving over that map. The downside with MATLAB however is that it is not free and in fact very expensive. We would need to spend approximately hundreds to use the toolkits from MATLAB on top of paying to use MATLAB in the first place. This is out of our budget range and doesn't make sense for us to use. However, we could use MATLAB on the computers located on UCF and work on SLAM at the UCF facilities. But in terms of personal use and working on the project at home, MATLAB is not the most feasible option.

The other option is to use an open-source SLAM library called BreezySLAM developed by Professor Simon Levy from Washington and Lee University. This package library gives us the ability to implement a LiDAR based SLAM on our robot at no cost and with Python or C++. Compared to using MATLAB, using this open-source library makes sense financially and allows us to develop at home. However, being that it is an open-source package created by an individual, it might not have all the features that are available on MATLAB for SLAM.

3.5.2.1 SLAM Implementation

When we initially place Trash-E in a new location, we will need to map the area that it will autonomously drive through. This is where SLAM will come into play. Trash-E will have a LiDAR on its body that will do a scan of the objects surrounding it to sense the distances and angles of obstacles around it. If needed, we can use the wheels on the body to determine the distance that has been driven by Trash-E and how it has turned. We can do this by calculating the rotations of our continuous servo motors that control the wheels with the circumference of them to get the distance traveled.

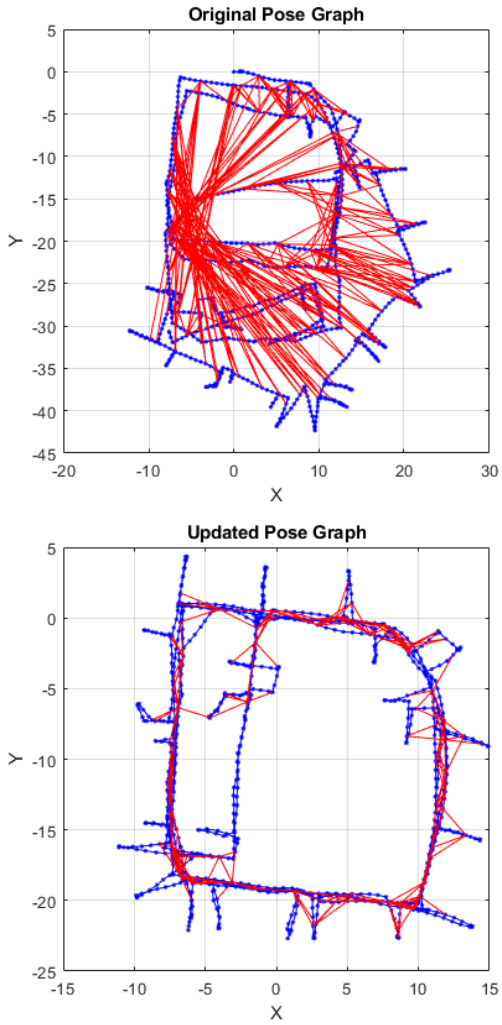


Figure 18: Example of pose graph optimization (Courtesy of MathWorks)

During this process we will be creating our map with pose graph optimization. Pose graph optimization helps fix the errors of positions and distances when using SLAM to create the map. Without pose graph optimization our map would likely look very inaccurate and have a lot of errors when relying solely on the sensors. Pose graph optimization will use nodes of poses (positions on the map) and constraints between the nodes which we can call edges. At some point in the process of SLAM, we will detect the same features once again with the sensors. This means that we can likely close the loop of our map traversal between these two nodes. Our pose graph optimization algorithm will pull these two nodes as close as possible until the features they detected match. During this process all other nodes' edges in the map experience "tension" and are pulled simultaneously as the original two nodes are being pulled together. After this is done the errors in the map have been mostly corrected and the is much more accurate than before the pose graph optimization. An example of this is optimization is shown in figure C where you can see the original map had many errors and very uncertain but after pose graph optimization the map is a lot cleaner and has less errors.

Once we have the map for our area, we can make a binary occupancy grid out of it which we can use to determine an optimal path to traverse this area/grid while avoiding any obstacles. For this we can use many shortest path algorithms and search algorithms. One that we can use is the A* search algorithm which is more efficient than normal graph search algorithms. We could also use RRT and RRT* (Rapidly Exploring Random Trees) algorithms which are sampling based search methods.

With the map and path planning made Trash-E will continuously and autonomously navigate the area which it has mapped using its path planning on the grid. While navigating autonomously through the area, our computer vision will be looking for the trash objects in its view. If while traversing Trash-E detects a trash object, priority will be given to the computer vision algorithm so that it can control the movement of it towards that piece of trash so that it can complete its task of picking it up and placing it in its bin. After it has been placed in it's been, control will be given back, and it will continuously keep searching the area for more trash.

3.5.3 Visual vs. Lidar

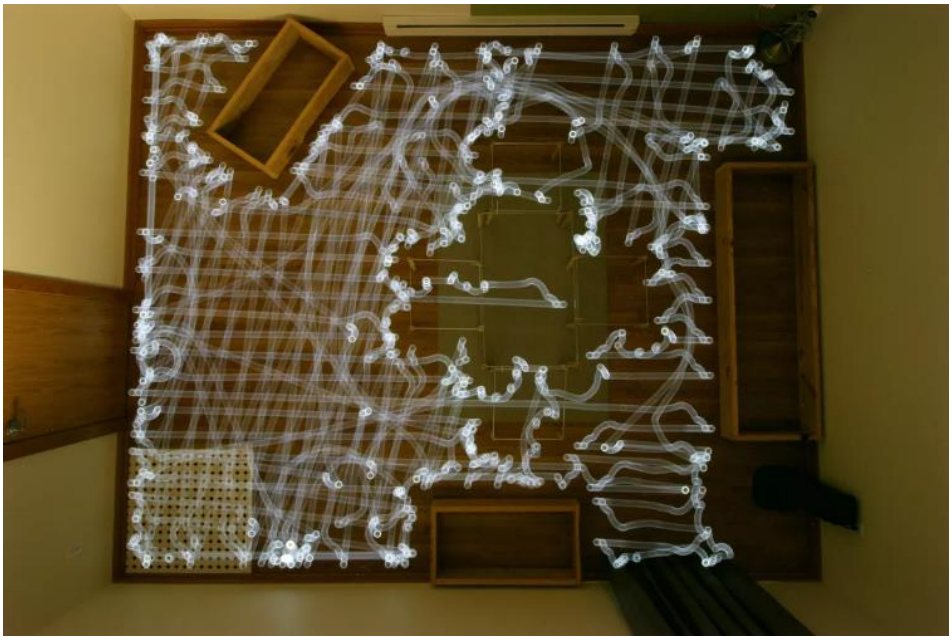


Figure 19: Robot Path Using VLSAM. (courtesy of Gianmarco Chumbe/CNET)

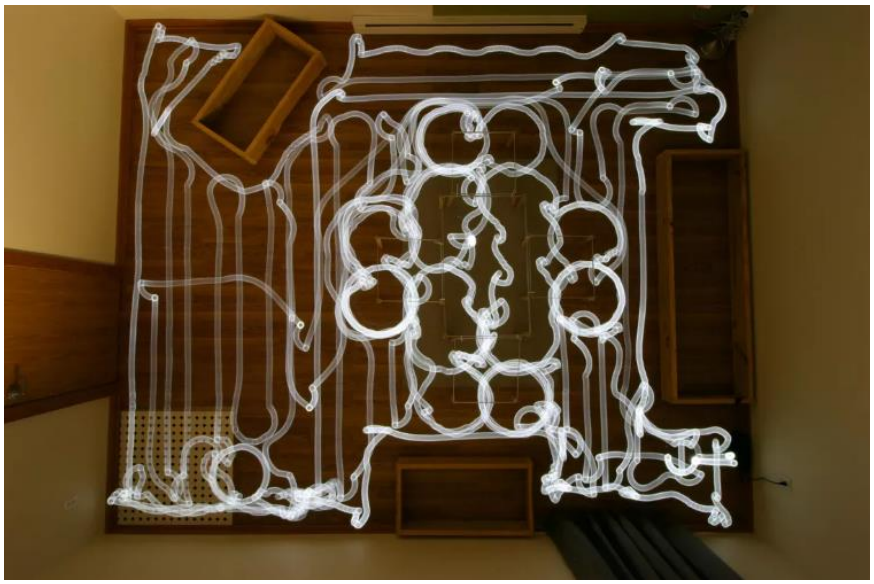


Figure 20: Robot Path Using SLAM with a Lidar Sensor (courtesy of Gianmarco Chumbe/CNET)

While utilizing visual locomotion can still complete the task, it is not very efficient as it has a lot of retracing, which can be seen above in Figure 19, due to only collecting points from in front of the robot at any given time. Lidar allows the same situation to be optimized and be more efficient which is why we want to utilize this technology. The highest efficiency and least amount of extra movement is necessary for Trash-E to keep power consumption to a minimum. When compared to VSLAM, Figure 20 shows significantly less retracing and a more optimized path.

3.5.4 Lidar Options

Table 9: Lidar Sensors

	Slamtec A1M8	MakerFocus YDLIDAR X2L	EAI YDLIDAR X4	getSurreal XV Lidar	Hokuyo URG-04LX-UG01
Price	$100	$70	$80	$150	$975
Availability	In Stock	In Stock	In Stock	In Stock	In Stock
Weight	370g	126g	180g	370g	160g
Input Power	5V	5V	5V	5V	5V
Power Consumption	500mA	500mA	500mA	500mA	500mA
Laser Safety	Class 1	Class 1	Class 1	Class 1	Class 1
Scan Radius	12m	8m	10m	6m	5.6m
Laser Range Scanning	360°	360°	360°	360°	240°
Accuracy	+/- 3.5%	+/- 3.5%	+/- 3.5%	+/- 3.5%	+/- 3%

Scan Rate	5.5 Hz (10Hz Max)	6 Hz	7 Hz	5 Hz	10 Hz
Ambient Illuminance	No Information	No Information	No Information	No Information	Florescent Max: 6,000 Lux
Communication	UART/USB	UART	UART	UART	Mini USB 2.0

3.5.4.1 Price

Since we are choosing to do a lidar based SLAM, we must purchase a sensor to gather the necessary data. Due to the nature of the technology, lidar can become quite expensive very quickly. Our first choice of sensor was the Hokuyo URG-04LX-UG01 due to it being tested by others using the Python library BreezySLAM that we will be using and knowing that there are no compatibility issues. The issue with this sensor for our use case is the price of $975 which is over double our total budget. Even though this is a very good sensor for education and researchers, we won't be able to use it. Instead, we did some searching for lower end, or hobbyist, sensors. The prices range from $70-$150 which are more realistic for our robot.

3.5.4.2 Weight

Weight is a large consideration for our robot when choosing hardware parts. The more the robot weighs, the more energy we need to expend to move it which depletes our batteries quicker. The goal for our sensor is to be as compact and lightweight as possible. The MakerFocus YDLIDAR X2L boasts its impressive weight of only 126g, while the Slamtec A1M8 is more than double at 370g, along with the getSurreal XVLidar. We want to keep our sensor below 200g as to minimize the total weight of our robot to prolong the up time we can pick up trash.

3.5.4.3 Power Specifications

Since lidar sensors spin around to send the laser signals, they need something that can accomplish this task. All the sensors we looked at utilize DC motors. Each DC motor has an input power of 5V and consumes a maximum current of 500mA while the motor is running. We will be able to supply the required 5V using the voltage regulator boards that were designed for Trash-E. The idle currents varied between them in the range of 200-300mA, but we must use the worst case where the motor is running all the time to spin the sensor. This gives us an accurate measurement of how long the robot can run at the minimum.

3.5.4.4 Laser Safety

Working with lasers of any kind requires certain safety specifications. Different safety procedures and PPE are required with different classes of laser safety.

According to the Environment, Health and Safety, Class 1 lasers are “eye-safe under all operating conditions. A Class 1 laser is safe for use under all reasonably anticipated conditions of use; in other words, it is not expected that the MPE can be exceeded”. [X] They also describe a Class 1 Product as “a laser product or device which may include lasers of a higher class whose beams are confined within a suitable enclosure so that access to laser radiation is physically prevented. Such products do not require a laser warning label on the exterior”. [X] The lidar sensors we are considering utilize an enclosure to ensure the laser radiation is physically prevented, making them a Class 1 Product.

3.5.4.5 Scan Radius

This specification of the sensor indicates how far from the center of the sensor the laser can accurately measure. The lowest radius in our price range is 6m. Given our robot will be used indoors, this minimum radius is sufficient. At any given point we will be within 6m of a wall for our robot to locate an obstacle of some sort, whether it be a wall or an unknown object.

3.5.4.6 Laser Range Scanning

Creating a full map of the environment is essential for Trash-E to traverse efficiently. If the map is not generated completely, there will be discrepancies with the path it should take since the information is not there. To generate a full and complete map, we will need the lidar sensor to be able to fully spin 360°. This will omit the possibility that obstacles weren’t detected due to the robot having not faced that direction. All the sensors we are considering are capable of rotating 360°.

3.5.4.7 Accuracy

Measurements of the environment also need to be accurate so the robot may traverse efficiently. Out of all the sensors we investigated, the lowest accuracy range is +/- 3% and the average is +/- 3.5%. With the 3% variance being a higher costing sensor, we must stick with the 3.5% variance. This will not affect our real-time measurements greatly and will be sufficient for the environment mapping since the robot will not be going that close to walls and obstacles to begin with.

3.5.4.8 Scan Rate

The scan rate determines how many full scans of the environment can be completed during one second. Given that our robot will be moving relatively slow to other autonomous mobile robots, like quadcopters, the scan rate is not too important for our decision making. Since we will also be using the Jetson Nano for our computation, the extra information that we would gain from having a higher scan rate won’t be properly utilized like it would if we were using a higher-powered CPU.

3.5.4.9 Ambient Illuminance

This specification is a very important one, although unfortunately most of the sensors did not have information regarding it on the manufacturer's websites or on their datasheets. Ambient illuminance tells us the brightness conditions that the lasers will work in without error for different lighting types. The only option that tells us this information is the Hokuyo URG-04LX-UG01 which is no longer under consideration. For this sensor, the maximum florescent max is 6,000 lux. According to Green Business Light UK[/], "the lux of artificial indoor lighting, however, is typically 1,000 lux or below…". They also point out that the lux of direct sunlight is a minimum of 32,000 lux and the minimum of ambient daylight is 10,000 lux. Given this information, even if the maximum ambient illuminance for the sensors that had no information is only 25% of the Hokuyo sensor, the robot will have a maximum of 1,500 lux and is still above the 1,000 typical lux. Sunlight is the only cause for concern when it comes to light. The robot will still be able to successfully complete the environment map without error if the shades are drawn to keep the sun out.

3.5.4.10 Communication

All sensors utilize UART at the minimum which is sufficient for one way communication from the sensor to the Jetson Nano. At least one sensor utilizes USB but this is not necessary to use as there is enough GPIO pins for us to use with the Jetson Nano.

3.5.4.11 Conclusion

Given all the considerations above, we are choosing the MakerFocus YDLIDAR X2L. The price point keeps us within our budget and the weight will keep power usage low. The other features that this sensor is lower in than the competitors are negligible for our use case.

4.0 Constraints

4.1 Description

This section covers the design constraints for Trash-E the litter picking up robot, and the associated standards with its design.

4.2 Economic

As the whole team consists of a group of students, it is to be expected that our capacity to spend resources is relatively small. Therefore, in order to complete the design in a cost efficient and on time manner the cost will be no more than four hundred dollars. The four hundred dollars allocated will be split amongst the four members of the group, which allows the burden of purchasing parts to be evenly distributed. Being mindful of what each member has spent will ensure that no conflict is had between the members. To reinforce this a bill of materials with who funded was implemented.

4.3 Environmental

Terrain was immediately taken into consideration when brainstorming ideas for the robot. Having a robot operating in several different kinds of terrains would take away from our main focus and consume more of our time and resources. For Trash-E, we mainly plan on operating on flat terrain such as tile floors, carpet, cement, or anything similar. With two wheels and a swivel wheel in a triangular configuration would not allow us to travel in any rough terrain. Implementing a design for rough terrain would be impractical for its intended use as well.

4.4 Social

The design of the robot will be mainly built around functionality as it is not intended to be used for anything other than picking up trash/litter, looks may be important later down the line. Therefore, in exchange for soft and aesthetic looks we can focus on functionality for the sake of development. Take for example iRobot®'s Roomba®, it's sleek and functional design allows it to do its job while not being an eyesore. As a stretch goal, a proper casing that is appealing may be developed.

4.5 Sustainability

In the case of sustainability, this robot would be fully sustainable as it will be 3D printed with polyethylene terephthalate glycol (PETG). The production of plastic is at an all-time high in the twenty-first century damaging the Oceans and polluting the environment around us. The majority of 3D plastics can be easily recycled back into its unused filament string form leading to less plastic ending up in the environment. Manufacturing metal parts specific to the project may lead to further

trash in the garbage heap when the robot is no longer operating or is not needed. To combat the issue of pollution, a shredder designed for cutting plastic along with a filament extruder should allow for the reuse of this plastic material.

4.6 Ethical

Concerning the job security of janitors and people whose job it is to clean up after public events or parties. This robot is designed in such a way that it should not put people in this occupation at risk as it was never intended to perform the entirety of their jobs in the first place.

4.7 Time

For this project we have two semesters to design, build, test, and present. This greatly impacts the sophistication of our robot as we have to make sure we can implement our idea in about 3 to 4 months. This can also affect the amount of primary and secondary features we get to. If something goes wrong or takes longer than expected, we will have to re-evaluate what we can get done in the remaining time. To combat this, work will be done in the first semester in making sure everything is researched and planned out as it will lead to a smooth development. Documentation as well as research and some testing should be done by December 2021. Having most of the research, testing, and documentation done by then should give enough time to make slight mistakes for the completion of the project by April 2022.

4.8 Safety

This robot is to autonomously operate in areas where human traffic is taking place; there must be multiple fail-safes as well as safety practices to prevent harm during operation. In the case of collision, Trash-E is plastic and light weight, the max voltage supplied to the motors is capped to ensure that the robot moves at a specific low speed. The gripper arm is designed in a way to avoid sharp edges and protrusion, this also goes for the chassis design. With the use of Ultrasonic, collision detection can be implemented to prevent the collision case mentioned earlier; on top of that, a camera for object detection can also be trained to not operate while a human is nearby. Electronics for the robot should all be grounded and hidden from direct contact from users. Stored inside the chassis, the electronics will be contained in a separate compartment to give easy access to developers and to protected users of the robot. Finally, an option for manual shutdown should be included in the case of an unforeseen action during runtime or if the robot is found to not be operating properly. Further elaboration on safety can be viewed in the standards section of the document.

4.9 Manufacturing

This robot being designed to operate indoors, operation outdoors is outside of the project scope at the moment. Furthermore, manufacturing costs can be saved since we do not need to deal with outdoor elements. Despite this the robot should still be reliable and durable enough to operate for several hours. Currently we are limited to the following methods for making parts for our robot:

1. 3D Printing: Using the 3D printer in the Innovation Lab or using a printer that a group member owns. Manufacturing of parts this way allows for greater creativity and less time for production. Using Autodesk can make for short work of chassis designs and moving components for the robot. This option is also relatively cheap if we provide our own plastic or use the schools.
2. Purchasing wood: Going to a home improvement store and getting the required wood to build into what we need. We also need access to a workshop that is provided by UCF. This would be one of the cheapest options, but it also requires the skills for woodwork as well as being able to design the specific measurements for schematics. Replacing parts would be cheap but would take some time, similar to 3D printing, to reproduce.
3. Purchasing metal: This approach would be potentially most expensive and difficult due to not having the correct tools. Similarly, we would be able to use the workshop provided by UCF, but working with metal is the hardest and, potentially, the most dangerous option. Replacing broken components on the chassis would take a great amount of time to do, but the likelihood of it happening in the first place would be low. Weight also has to be taken into consideration, as metal would be the heaviest out of all of the three options.

5.0 Standards

5.1 Lithium-Ion Battery Safety Standards

Several international/universal industry practices are used in upholding standards in lithium-ion battery safety, this also applies to regular lead acid batteries. Organizations such as IEEE, ICE, IECCEE, U.S based OSHA, NRT, ANSI, ISO/IEC, UN/DOT, UL, and many more have thoroughly created many standards for the regulation of lithium-ion batteries, all have the facilities and equipment to do so. For this project we will follow the *IEC 62133* (International Electrotechnical Commission) as they create non-profit standards internationally. The scope in this standard states that “IEC 62133 specifies requirements and tests for the safe operation of portable sealed secondary lithium cells and batteries containing non-acid electrolyte, under intended use and reasonably foreseeable misuse” (IEC). Several testing procedures, as well as maintenance requirements are recommended by this standard.

5.2 Standard SystemC ® Language Reference Manual Standard

The standard *IEEE 1666* 2012 lays out clear definitions on how to go about with syntax and proper procedure on developing certain aspects of C language including C++. Seeing as this project involves heavy usage of both software and hardware as well as the communication between the two, for example, serial data transmission from the Nvidia Jetson to the microcontroller that interprets data sent and act out instructions. In other words, it provides an extensive list of core language class definitions, predefined channel class definitions, system C data types, system C utilities, terminology, and simulation semantics. All of those listed previously will be in use during the development and documentation of our project.

As a side note, this standard uses the words “shall”[16], “should”[16], “may”[16], and “can”[16] that carry their own significance. Shall being the most important meaning that what is requested in the standard is mandatory. Should is mainly a recommendation and nothing more. Finally, can is used to imply that something is possible, or within the scope of operation. For example, shall is used when dealing with function definition and side effects in section 3.3.2 in the standard. The use of such is explicitly used throughout the standard like in this case: “Such functions shall not have any side-effects that would contradict the behavior explicitly mandated by this standard.”[16]. They clearly define what should be done throughout the standard with similar cases to the previous quote. Not following the advice indicated by the word “shall”[16] will typically cause issues within the C system you are designing.

Using this standard will “provide a C++-based standard for designers and architects who need to address complex systems that are a hybrid between hardware and software”[16]. Therefore, it will increase our options as well as

provide us with guidance for the solutions to our complex software and hardware systems.

5.3 Software and Systems Engineering – Software Testing

ISO/IEC/IEEE 29119 is a standard that takes multiple other standards and compiles them into one coherent standard. Developed by the International Organization for Standardization and the International Electrotechnical Commission, they attempt to make a worldwide standardization that could be adapted to work internationally.

Mainly, the concepts applied from this standard are the testing process, as well as the testing techniques. Outlining the testing process consists of splitting up and organizing several processes that need to be done. In our case, with four team members we can organize the software and hardware processes by assigning the preferred roles of them.

Test management will undoubtedly be the largest section as it is paramount that proper testing procedures are taken to ensure quality code and operation. First, coming up with a plan on how to execute a testing plan until its completion; this can consist of several techniques to accomplish this with liberty to adjust plans to meet design goals. For example, the test plan is created, testing starts and is monitored while providing needed updates, and finally test completion. In the test completion phase plans for further improvements or maintenance can be made, but it also serves as a final check if guidelines were followed before the release of the product.

Testing techniques include specification-based testing, structure-based testing, as well as experience-based testing. Each comes with its own approach to the testing process, and with their respective advantages and disadvantages. Specification-based testing is more about using previous information gathered such as documentation gathered from part manufacturers about specifications for operation. Furthermore, there are several ways to implement structure-based testing as there are many sources to pull from. Structure-based testing can pull from outside datasets, sample codes, models, and documentation to achieve design goals during testing; there are several ways to go about this. Experience-based testing relies on the testers previously gathered experience and knowledge. The tester in this case could create a model to aid in the structuring and development of code and the software, though it is slightly limited due to the fact of not relying on outside sources. This technique is also not as predictable since each developer/tester has varying skills in different fields. In this case, direct debugging and testing of code is utilized to develop features which would take more time, but it can lead to creative solutions. Errors encountered will also depend on the testers ability to predict the operation of written code as well as the ability to create unit tests to cover many different input cases.

Conforming to the standard as well as its shown practices will make it so that the structure of the software we develop will be able to apply to this standard. Although ISO/*IEC/IEEE 29119* provides many options for test management and testing techniques, many of them will be excluded from this robot's development as several of them provide enough guidance for a small development group. The testing techniques as well as the organizational procedures will be taken into consideration. With the combination of those two principles, proper planning, and adequate testing of each testing block will ensure proper adherence to the standard.

5.4 Programming language – C Standard

International standard *ISO/IEC 9899* intends to specify: "the representation of C programs", "the syntax and constraints of the C language", "the semantic rules for interpreting C programs", "the representation of input data to be processed by C programs", "the representation of output data produced by C programs", and "the restriction and limits imposed by a conforming implementation of C" [19]. This is what we will be using for the majority of the embedded software design for the project.

Within the standard document, the language section includes notation, concepts, conversion, lexical elements, (constant) expressions, declarations, statements and blocks, external definitions, preprocessing directives, and future language directions. Typical concepts for programming languages like syntax, data type identifiers, and more are included under annex A. Following this is further information on several libraries that aid with specific operations, for example, the math.h or string.h libraries that will be very useful during development. Before the creation of the C standards, a large amount of functionality may have been difficult to know about.

Previously mentioned aspects of the standard will aid in the development of drivers on the embedded side of Trash-E the litter cleaning robot. Communication between the Nvidia Jetson and the microcontroller will use a serial communication protocol dealing with parsing through strings. For example, the Nvidia Jetson sends a compressed string of instructions to the microcontroller for motor control; the way to interpret this string is to make an algorithm and use functions given to us by libraries to do so. We are doing a Python to C conversion as well, so data types will also be important to keep track of. While testing we must keep in mind what data type is being sent. An example of this would be sending a string from python and having to use a conversion to make it a long int or unsigned float for interpretation. Pulse width modulation will also need to be calculated for the motor controls, so the math library will be of great use for handling the work required. Without the use of this standard, much of the functionality for the embedded/hardware side would be mediocre in efficiency at best, as the saying goes "don't reinvent the wheel". Having a fast and efficient system is essential to operating in real time to improve the responsiveness of the

robot. Coincidentally, next to assembly, C language is one of the fastest languages to choose from.

5.5 Robot Systems – Safety Requirements Standard

The scope for the standard *ANSI/RIA R15.06* states that “this safety standard applies to the manufacture, remanufacture, rebuild, installation, safeguarding, maintenance, testing and start-up, and training requirements for industrial robots and robot systems” [20]. A general overview of the sections provided by the standard: definitions, hazards to personnel, actuating controls, Installation of robot systems, safeguarding personnel, safeguarding devices, and maintenance. The purpose of this standard in our case is to avoid potential setbacks and damages in the development of Trash-E. It also provides several propositions for certain designs for power systems and other features. Some of these suggestions include designing reliable circuitry for controls, robot stopping circuits and emergency stop, grounding requirements, and much more.

To avoid any injury to users of the robot we are following several of the pieces of advice given by *ANSI/RIA R15.06.* Circuitry being implemented for the power systems need to be safe to avoid electrical shocks and shorting of the system. Section 6.10 encourages the grounding of any electrical system within the robot; this also includes limiting access to the electronics during use. Since Trash-E will be interacting with its surrounding environment, it's important to include an emergency stop for unforeseen actions by the robot. Developing reliable circuitry with minimal interference from outside sources will also be essential to the robot’s operation, because if the motor controls and power supply DC to DC converter are not reliable unforeseen operations may happen.

In the case of our alternate design of having an articulate arm, rather than a stiff one directional one, *ANSI/RIA R15.06* also provides safety standards for this. The standard suggests defining a maximum, restricted, and operating space for articulate robot arms. Shown in Figure 16 below is a graphical representation of this concept.

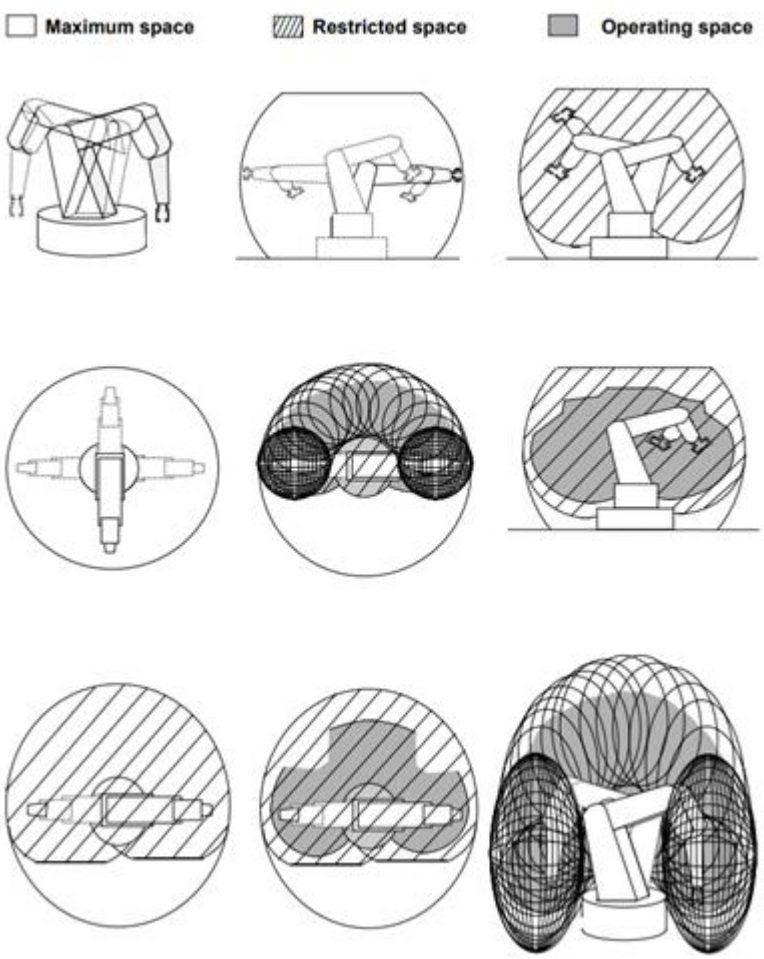


Figure 21: Use of Maximum, Restricted, and Operating Space

Maximum space, as the name suggests, the complete reach of the articulate arm to show the potential reach of it. This is useful in the case of estimating the safe range a user or bystander can be in during operation. Restricted space indicates the areas where the articulate arm should not move to. In the case of Trash-E, the arm would have a 180-degree arc of restriction behind, because if it would rotate into that range, it would hit the electronics as well as the chassis. The operating space in front of it, also a 180-degree arc, will be its operating space to pick up trash. For throwing away the trash after it had been picked up, we would use the case of dynamic restricted space for the arm to be able to bend into the restricted zone and drop the garbage into the garbage can. The definition for dynamic restricted space is as follows: “the safeguarding interlocking logic may be such that the restricted space is redefined as the robot performs its tasks”[20]. The stiff arm design would not require as many restrictions due to its two dimensional plane of movement.

6.0 System Design

6.1 Software Design

In this section we will be going over how the Trash-E software will be designed. The following subsections will split the information for the software design on the three main software platforms. These will involve design explanations of the various features and algorithms that will be used on the microcontroller, Jetson Nano, and computer vision.

6.1.1 Software Overview

Trash-E should be able to maneuver and spot trash and pick it up on its own. Trash-E will be roaming on its own until it finds a piece of trash. Trash-E will be constantly using computer vision to be able to recognize these trash items and maneuver its way towards each object. Once a trash item has been detected, Trash-E will move towards it until it gets a certain distance close to it. Trash-E will have an arm with pincers that it will use to pick up the trash. It will need to be able to decide how it will approach the pickup of the item. It should be able to precisely grab the item and put it into its trash bin.

6.1.2 Computer Vision

6.1.2.1 Functionality

Trash-E will have a camera connected to its main computer on the Jetson Nano. A camera will be used to capture images of what is in front of Trash-E. The camera will be capturing video and our computer vision software will be analyzing each frame. In each frame our algorithm will perform object detection and look for the trash items of interest. If there are multiple items in front of Trash-E that are of interest, the software will decide to follow the item that is closest to Trash-E. The Jetson Nano will be powerful enough to process the images so that Trash-E can scan and identify trash objects in its view in real time. Once Trash-E has decided which trash object is detected it will move towards that object. The software will be sending data to the microcontroller through serial communication in order to determine a PWM signal that will control Trash-E's direction of movement. Once Trash-E is close enough to the object, the software will stop accelerating Trash-E and bring it to a complete stop so that it can now pick up the trash. Once the item is in Trash-E's bin, the computer vision software will initiate once and again and begin to look for an object. If there is no object in view, Trash-E will rotate until one is detected or a certain amount of time has passed in order to conserve power.

6.1.2.2 Development Environment and Platforms

6.1.2.2.1 Programming Language for Computer Vision

We are going to primarily use Python to develop the computer vision and machine learning software that we will be using on Trash-E. Although not as performant as languages like C++ due the nature of it being compiled at runtime, Python is a very powerful language, has a lot of machine learning libraries, and the code syntax is very easy to read.

With Python we will worry less about the syntax of the code and its semantics since it has no types, pointers, and everything is handled for you in easily readable code while still having all the powerful data structures and object-oriented functionalities that C++ provides. Leaving all the focus on the implementation of our machine learning and computer vision algorithms for our application. If we would have gone with C++ as our primary language, there would have been a lot of nuances in the language that we would have to deal with aside from the machine learning and computer vision implementation. C++ has things like types and pointers that could possibly complicate our program that are handled behind the scenes in python. However, C++ is a faster language and is very popular for robotics programming.

Python is already supported with many machine learning and computer vision libraries that we can use as well as many other frameworks, and extensions that provide a lot of functionality. Python is platform independent meaning that we could develop and implement our computer vision code on our desktop using the Windows operating system and pass on our code to a Linux operating system and it would still work as intended. This makes implementation of what Trash-E needs a lot more simple and more efficient.

6.1.2.2.2 Development Environment

For this project the plan is to use an IDE to develop our code for computer vision and machine learning such as PyCharm. Using an IDE like PyCharm will give us the best development environment to be able write our code with great debuggers. PyCharm is also directed towards use for writing code in Python and offers a lot of support for doing so. We will be developing code on a Windows operating system since it is the current operating system that we own and the libraries and tools we need to develop our machine learning computer vision platform are mostly cross-platform in terms of the operating system.

We will be installing another necessary tool and platform for our development environment called Anaconda. This is specifically to configure our development environment for machine learning and computer vision development in Python. It is an open source Python distribution platform that acts as a data science toolkit. Anaconda offers a quick way to install and use thousands of data science and machine learning packages for Python that include many tools and libraries using an easy to use desktop GUI. These include but are not limited to TensorFlow,

PyTorch, NumPy, SciPy, PyCharm. Extra packages and libraries not included in the original install of Anaconda will be very easy to acquire using the Conda environment and command console. Anaconda also allows the ability for us to have more than one environment setup that can be run and maintained separately from each other. Having Anaconda provides us the boilerplate environment for our machine learning software development, and will allow us to start coding and testing our machine learning models quicker and skip the tedious development environment setup.

The computer vision software that we develop will end up being transferred and run on the Nvidia Jetson Nano. The Jetson Nano runs on a Linux operating system and has a RAM capacity of 2GB. Our software will be able to run on this system as an inference model meaning it will not be training on the Jetson Nano. The training of the machine learning model will be done on a desktop PC using a dedicated GPU to process the training. This will save lots of time for development and ease the stress on the Jetson Nano RAM and processing power. The machine learning object detection model will also be optimized by a proprietary Nvidia tool called TensorRT that will optimize our model so that it can perform only necessary computations and save performance on the Jetson Nano while still ensuring the same results as if it were unoptimized.

6.1.2.2.3 Libraries

There are many ways to go about creating computer vision applications using the extensive amount of libraries that are available to use. Using these libraries will allow us to use state of the art algorithms and architectures already created by AI researchers. This cuts down the development time and overall will give us a more efficient performing product. Python comes supported by many machine learning libraries as well as some that are tailored toward computer vision.

One route that we could go with designing our machine learning software is to use the more recent PyTorch library. This is Facebook's open source machine learning framework that was released in 2016 and is relatively new to the industry and is primarily used by researchers and people who want a more pythonic framework. In comparison to TensorFlow, PyTorch is a bit more simple to read and is more intuitive since it is more like python making it easier to learn than TensorFlow. This allows people to make quicker prototypes and get projects going much quicker too. Debugging with PyTorch is also more simple to do with common tools compared to TensorFlow which requires you to use another tool for debugging. Using PyTorch would involve similar processes as if we were using TensorFlow. We could use a pretrained model such as Faster R-CNN that is offered by PyTorch and attempt to leverage it for transfer learning to be able to train it to our custom dataset a lot quicker and potentially get better accuracy than training from scratch. If we ultimately decide to write our own CNN architecture instead of using a researched model during prototyping, PyTorch makes building our neural network a lot more simpler than on TensorFlow. This is because PyTorch uses dynamic computational graphs which allows us to change behaviour of our model at runtime

which makes optimizing models much easier. Since PyTorch is newer than TensorFlow, that means that it is not as extensive. However, for our use case in designing this computer vision application that should not be an issue.

On the other hand the other route to developing our computer vision software is using TensorFlow which is the most popular machine learning framework in the industry for production. The reason we would want to use TensorFlow is because it will allow us to use a bigger selection of famous state of the art pretrained models and give us the option to train our own custom object detection models using our custom objects just like we would be able to with PyTorch. TensorFlow is backed by Google and has frequent updates and support. It is also open-source so we don't have to spend a dime in order to use it like PyTorch. TensorFlow is packed with many built-in functions for machine learning that will make training and testing our models a lot quicker and testing more efficient than from scratch. TensorFlow also includes TensorBoard integration which can help us in fine tuning our model by showing us our testing evaluation metrics. One downside for TensorFlow is that in order to train your model on a graphics processing unit or GPU it must be manufactured by Nvidia and is only supported with Python. However, this will not be a problem for us since we will be using an Nvidia GPU that we already own to train our model. TensorFlow also has a much steeper learning curve than PyTorch.

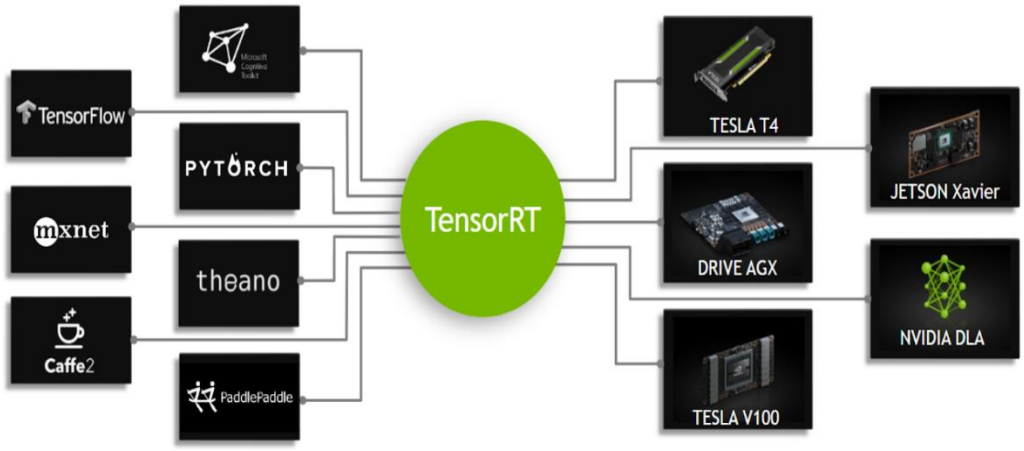


Figure 22: Nvidia GPU Optimized Models (Courtesy of Nvidia)

Both PyTorch and TensorFlow are supported by Nvidia TensorRT. This is an SDK by Nvidia that is written in C++ that takes a trained model from libraries like TensorFlow and PyTorch and converts to a more optimized model for Nvidia GPUs as shown in figure 17 while maintaining the same results which includes the Jetson Nanos GPU. This will drastically increase performance on the Jetson Nano while using our inference model on it.

There are a couple of options of how we will run the model on our Jetson Nano. With PyTorch we would convert the model to ONNX format and convert it straight to TensorRT to run on the Jetson Nano. With TensorFlow, we could either use the

Tensorflow-TensorRT integration on TensorFlow to be able to still use unsupported parts of the model on TensorFlow on runtime while everything in the model that is compatible will be using TensorRT converted computations. The last option will offer the best performance for the Jetson Nano which is to convert the TensorFlow model to UFF format and convert it straight to a TensorRT model. This would be the most optimized way of going about it.

For our decision on which major library will be primarily used for deep learning, we'll be using TensorFlow. The reason is that TensorFlow has a lot more support available online to help us accomplish what we want to do for Trash-E, even though PyTorch is catching up to where TensorFlow is in terms of community and support. TensorFlow also has a much wider selection of pre-trained models that we can use than PyTorch has. PyTorch has about only five models to choose from. Using a pretrained model from these libraries will allow us to get our software working a lot quicker. If for some reason we decide that the TensorFlow library isnt working out for what we want during prototyping, switching over to PyTorch wouldn't be a difficult task since in the big picture they are very similar and work to achieve the same task.

OpenCV will be used towards the end of our software implementation to connect the camera on Trash-E and send the video feed into the inference model on the Jetson Nano for real time object detection. It comes with many builtin functions and capabilities that will make camera connectivity and image capture a lot more simple and we will use a specific function to access our system's camera and use it as the input for our object detection model.

Other libraries that we will be using to assist the main computer vision implementation are PySerial and LabelImg. PySerial is a python library that encapsulates the access for the serial port. It provides backends to python that will automatically be configured for the platform we will make a serial connection to. The serial connection we have to make is by UART to the Jetson Nano. With this library we will initialize that connection so that the computer vision software can guide Trash-E to the trash items. Computer vision models can give results in bounding boxes, these coordinates from these boxes will be sent to the microcontroller via serial connection on PySerial so that it can guide Trash-E’s movements with a PWM signal.

LabelImg will be used to create the labels and annotations for the images in our training dataset. The reason we want to use this is so that the labeling process for our image training dataset is much more efficient and is done well. It will also help save development time in the most tedious step of the process which is creating and labeling our dataset.

6.1.2.3 Object Detection Model Architecture

The algorithm that we need in order to achieve good object detection is a convolutional neural network. As mentioned before, both Pytorch and TensorFlow

offer many state of the art pretrained models that are based on convolutional neural networks and have very good results in object detection. These models are already trained with very good weights which allows us to leverage transfer learning for quicker and efficient training on new objects.

We will be using a pretrained model from the TensorFlow Model Zoo located on their GitHub [21]. These models are high quality researched architectures or models that are provided by Google's TensorFlow GitHub. Using a pretrained model gives us the advantage of utilizing transfer learning and could ultimately make our training more efficient and more accurate in the end. The models available in the model zoo have been previously trained on a dataset with hundreds of thousands of images and have already been trained to have the best weights to detect very common objects. Leveraging the technique of transfer learning will enable us to train the final layers with our new images and classes in much less time since the weights from previous training are already very good and it will be accurate at detecting our new classes of objects as well. These models also offer the option to be trained from scratch. The TensorFlow model zoo offers a lot of options for pretrained models. Some of the object detection choices we have include SSD MobileNet v2, SSD ResNet50 v1, Faster R-CNN ResNet, and Mask R-CNN.

Mask R-CNN offers normal object detection such that it uses detection boxes. However, a main key feature that differentiates this model from the others is that it offers masks as well. These masks essentially wrap the object instead of just placing a box around the detected object. This feature comes with a heavy cost however. The performance runtime of this model can take as long as 301 ms. This number could likely be worse if we were to run it on the Jetson Nano. This model also has a high mAP accuracy but comes with a great performance cost. For the purposes of our project this model would be overkill, and the masks are an unnecessary feature and would be extremely inefficient for Trash-E.

The Faster R-CNN is another high accuracy model but has better performance than the mask R-CNN. This model only uses detection boxes for identifying objects and has a much better average runtime of the range 53 - 236 ms depending on the choice of resolution and the ResNet architecture.

SSD ResNet50 v1 performs very similarly to the Faster R-CNN models. At the lowest resolution it offers a faster runtime and also gives a slightly higher average accuracy for the model. However when we compare this model with the SSD MobileNet v2, it is surpassed in speed.

The SSD MobileNet v2 model option offers us the best performing runtime for object detection. At the lowest resolution it offers object detection in 19 ms, surpassing all the previously mentioned models. However, this increase in speed does come with a tradeoff of accuracy. The accuracy for the fastest version of

MobileNet is averaged at 20.2 mAP. Compared to all the previous models this is the lowest average accuracy.

An alternative option in our design would be instead of using TensorFlow models, we use PyTorch instead for our implementation. If we were to switch to using this alternate library for any reason we still have a wide selection of pretrained models that we could use from the PyTorch library that offer similar performance. Another alternative option is to use pretrained models that come from a library called YOLO which offers another good selection of object detection models. Lastly, if for some reason none of these models give us satisfactory results both TensorFlow and PyTorch offer us the tools to create our own neural networks or object detection models to use for our project.

After considering all our options for the object detection models available in the TensorFlow Model Zoo. The model we will specifically be using from the TensorFlow Model Zoo is the SSD MobileNet v2 320x320 model. This is a single stage object detection model. This model has been previously trained on the COCO 2017 dataset which was a large-scale dataset with hundreds of thousands of images that include many common objects in the real world. We will train the model to be able to detect our own custom objects only, which in our case are cups. However, this custom dataset can be easily expanded upon in the future.

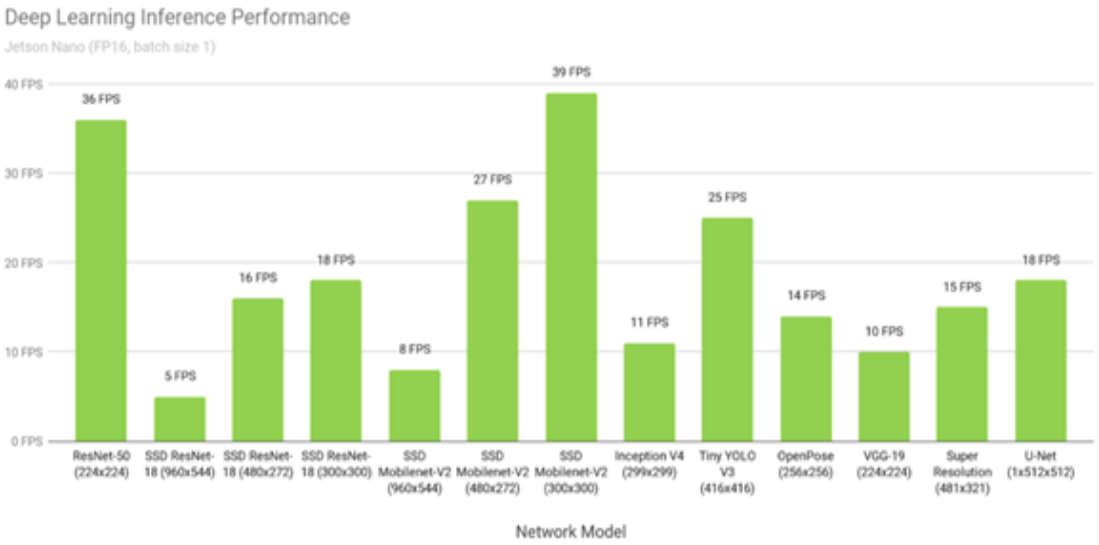


Figure 23: Object Detection Model Performance on Jetson Nano (Courtesy of Nvidia)

The SSD MobileNet v2 320x320 model shows a 320x320 resolution in its name. There are a couple of reasons for choosing this specific model, one being that it had very high performance compared to the other models as shown in Figure 18, which is very important for our application since we are running the inference model on a Jetson Nano in real time. One of the advantages of using this model is that it will preprocess the images we feed into it in a smaller resolution and in this

case, they will be 320x320. That will make the model more efficient in terms of speed and performance but we trade off some accuracy.

Since our model will be running on the Jetson Nano, we should optimize for performance and efficiency for the sake of hardware capabilities so therefore we are going with a lower resolution model. The RAM that is available on our Nvidia Jetson Nano is 2 GB, the main operating system on the Jetson Nano already consumes a decent portion of the RAM so it would be critical that our design uses a performant algorithm with lower computational cost so that we don't run into issues of crashing or overheating our Jetson Nano which would render our product useless. Our dataset and objective does not require the most precise and most accurate model to detect trash objects.

Therefore, it is best to go with performance over accuracy for our convolutional neural network architecture or object detection model. As stated previously, the SSD MobileNet v2 model runs a low resolution and consequently is less taxing computationally on the Jetson Nano. The SSD MobileNet v2 model runs very well on the Jetson Nano around this resolution as can be seen in Figure 18. When we take a look at the SSD MobileNet v2 model with 960x544 resolution, the performance drops drastically from 39 frames per second to 8 frames per second.

6.1.2.4 Creating The Dataset

The first step in every computer vision task is to gather the data that we will use to train our model for computer vision. For our project, we need to gather photos of all the objects that we want Trash-E to detect. We can take pictures using the camera that we will buy to use on Trash-E or we could even just take pictures with our smartphones. In the end it doesn't matter as the images will be preprocessed automatically before entering our model into the lower resolution.

There are techniques involving scripts that we could write to automatically take pictures from a webcam attached to our desktop computer. This script can automatically take pictures for the appropriate classes. The script will loop through each class that we want to detect and take a certain number of pictures accordingly until we've completed taking pictures of all classes. This method would be great if we were only creating computer vision software that would only run from a webcam on top of a desktop inside a normal room. Such as signing into your account by face detection or placing filters on peoples background. However, for our project this would not be ideal since Trash-E will be operating in many different conditions and not just one room in place.

The approach we will have to go with is to manually take these photos for our dataset. These photos need to have to show the items in many orientations, lighting conditions, colors, and distances. It is important that the pictures are done in all these ways so that our algorithm can recognize them from any position in any condition that Trash-E can operate in. If we did not take these steps to consider

the different conditions in our images then we would get a very inaccurate model with many false positives as well as false negatives.

We will need at least 100 photos per class to have a good enough training on it and luckily with transfer learning the accuracy will be good even with the new small dataset since the pretrained models weights were already very good. Each class is attached to an object we are trying to find.

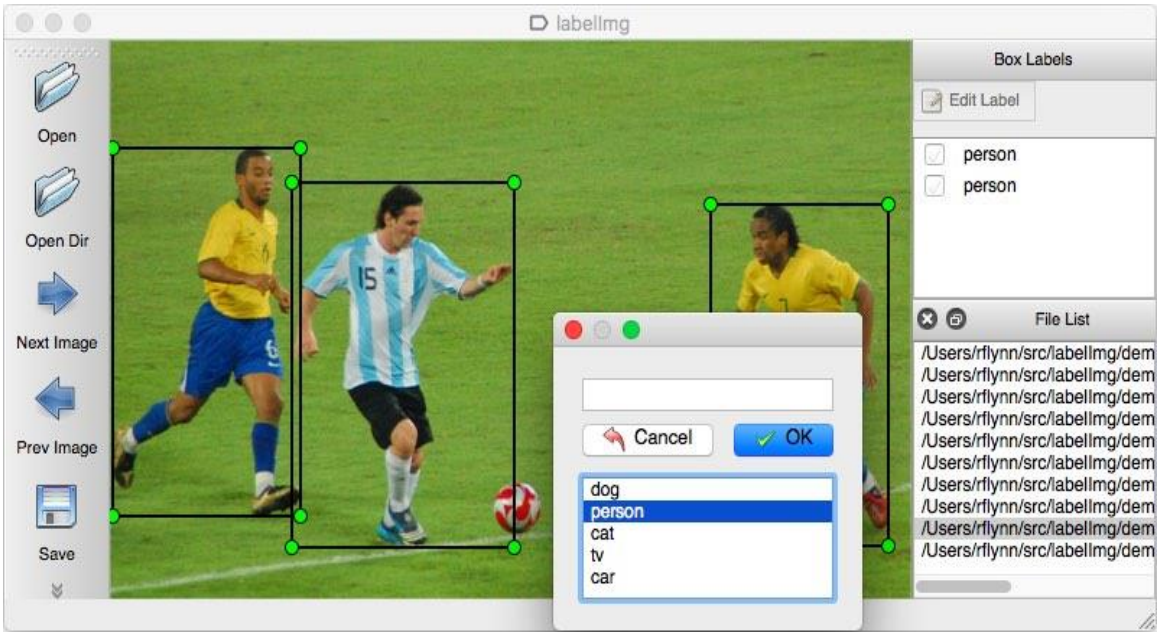


Figure 24: Labeling the Dataset With LabelImg Tool (Courtesy of LabelImg GitHub)

Once we have gathered these images, we will label the data based on the object it is and what we want our network to classify it as. We are going to use a library called LabelImg from python that allows us to easily select the objects in our images that we want to label. These labels that we put on our images must be as tight as possible as shown in Figure 19 so that we ensure our model learns that object better.

We also will need to create a label map for our dataset. This map data structure will hold all the labels for our dataset including the label name as well as a unique identifier for that label in the map.

We also want to create our TensorFlow records. TensorFlow records are a binary file format for storing data and using them will help speed up the training for our object detection model by converting our label annotations and images into a file format that our model can use.

6.1.2.5 Training The Object Detection Model

We will be training our model using the TensorFlow library for Python. The training will be done on a desktop using a GPU or graphics processing unit rather than on

the Jetson Nano. Training on a dedicated GPU on a desktop will make training go a lot faster than it would on the Jetson Nano. In order to be able to do that we need to install both CUDA and cuDNN to our desktop, so that TensorFlow can utilize our desktop's graphics card.

TensorFlow comes with an object detection API, which we can utilize to easily perform functions on our model. The object detection API also comes with a training script designed for the specific model that we chose from the model zoo. This script is modifiable and we can change some parameters. One of the parameters we will be changing a bit is the number of epochs the model will train for or the amount of training iterations it makes. The model will train for about 5000 epochs at first. If we feel that the accuracy is not good, we can train it for longer or increase the amount of images in our dataset for training.

Once our model is trained, we can use the OpenCV library to access a camera connected to our computer and feed live video to our object detection model. Then our object detection model will examine each frame and detect our custom objects that are in them. Using our object detection API, we will be able to draw boxes around these objects in each frame to show the location of the object on the image that the model predicted as well as return the values of the coordinates in the detection boxes that will come as a list of bounding boxes.

6.1.2.6 Moving our Trained Model to Jetson Nano

Once we are satisfied with the accuracy of our model, we will move it onto the Jetson Nano. Nvidia offers tools that will allow our model to run efficiently on the Jetson Nano. We will need to freeze our TensorFlow model or in other words freezing the graph. This is essentially saving our model so that we can use it in another instance. We can use the TensorFlow TensorRT API to do this and the following steps. After freezing the graph into a savedModel format, we will convert the frozen graph to a TensorRT optimized model. Then we will call an API for TensorRT object detection that will build our optimized TensorRT graph which creates a TensorRT execution engine. This will allow for better performance on the inference graph than just using the converted graph. However, we must build this execution engine on the Jetson Nano since it is required to build it on the same GPU that the inference model will be executed on, even if both of the graphics cards are by Nvidia. In our case, we are using an Nvidia GTX 1080 Ti for training our model on our desktop, and the Jetson Nano is using an Nvidia Maxwell GPU. With this TensorRT optimized model we can run our trained object detection model on our Jetson Nano more efficiently than just the native TensorFlow model.

6.1.2.7 Serial Communication with Microcontroller

One of the most important aspects of our software design is the connection between the computer vision software and the microcontrollers software. The microcontroller is in charge of maneuvering Trash-E as well as controlling the arm in which it will use to pick up trash. However, there is no way that the

microcontroller would know where a trash object is on its own. Therefore, the computer vision software must gather necessary data that it can send to the microcontroller via serial communication so that it can determine what to do. So, the main two problems we must solve for Trash-E's vision and maneuverability decision making are how will Trash-E know which trash object to approach in a scene as well as how will Trash-E know how to maneuver itself to that particular trash object. Then finally, how will it send that information between the Jetson Nano computer vision software and the microcontrollers software which controls all the motors.

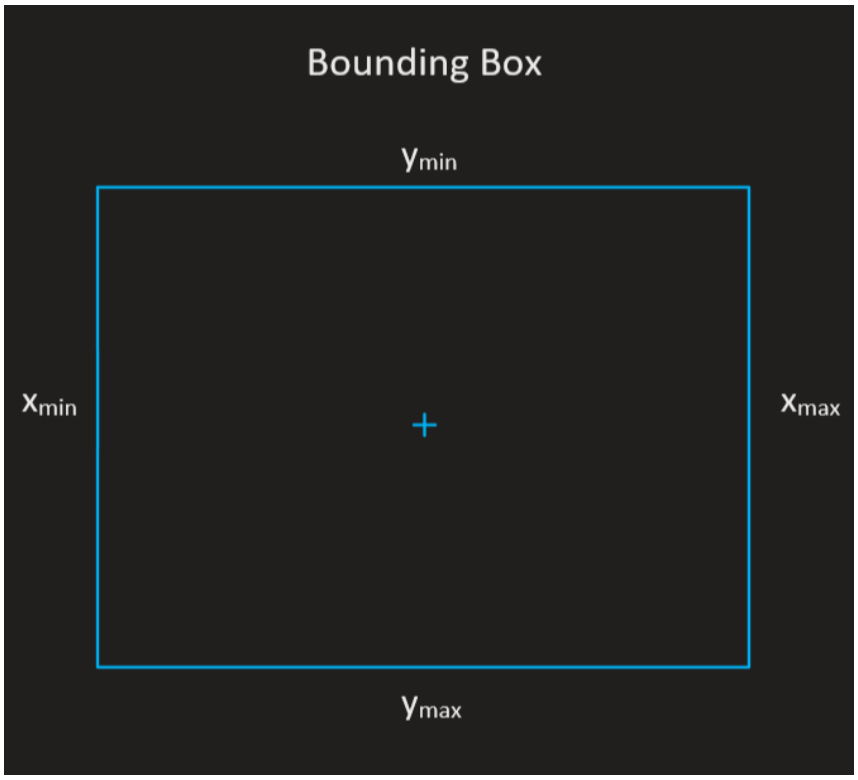


Figure 25: Object Detection Bounding Box Coordinates

TensorFlow's object detection API already offers bounding box coordinates that surround all the objects of interest in the algorithm's view. These coordinates in each bounding box include the x_{min}, x_{max}, y_{min}, and y_{max} as shown in figure 20. This essentially gives us the coordinates in the image that this object was found in and creates a tight box around it. With these coordinates we can determine many interesting bits of information that we can use to eventually guide Trash-E.

These coordinates can be used to determine the area of each bounding box that is detected by our camera. Our software will sort the areas of each object's bounding box that it has detected in decreasing order of area. In other words, the biggest area detection bounding box will be in the front of the sorted list of bounding boxes. Why is this necessary for Trash-E? With these bounding box areas sorted, we now have a way that Trash-E can decide which object in its view it should approach. A bigger detection box area will mean that the object is closer, and

Trash-E will approach the specific object or biggest bounding box. For testing purposes later on, we will draw a green circle outline around the closest object in the program window that will appear when we run the model.

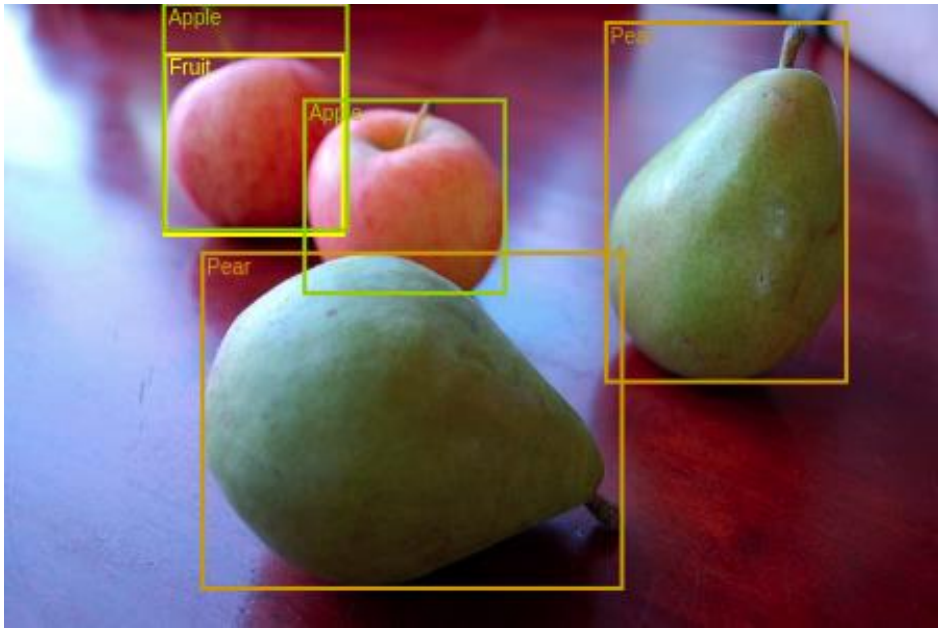


Figure 26: Object Detection Bounding Boxes (Courtesy of Algorithmia)

For example, let us say our object detection model was tracking fruits. In figure 21 we see that the closest pear has the largest bounding box area. In this case Trash-E would approach that pear since it has the largest area and will continue to be the largest since as we get closer the area can only increase. In our real case of trash objects, which are red solo cups, they will always be of the same or very similar size. Therefore, the edge case of a huge object in the background being mistaken as the closest object compared to a smaller object that is closer will be very rare.

Trash-E must eventually stop the approach towards the object when it gets close enough for pickup. A method that we have designed to solve this problem is to have a sensor towards the front of Trash-E that will detect the presence of an object in front of it. The computer vision software will keep signaling Trash-E's microcontroller to move forward until the sensor detects the object is close enough to grab with its arm for trash removal. Once at that point, the computer vision software will be overridden and the microcontroller will take control of moving the robot's arm to place the item in its trash bin and ignore incoming data from the Jetson Nano's computer vision software.

This would all work great if Trash-E was always in a straight path to the object. However, that will rarely be the case so there is another aspect of Trash-E's maneuvering that must be solved. An object that is detected and is closest can be anywhere in Trash-E's camera view on the x-plane. In order to turn Trash-E so that it turns and moves straight towards the object, we can use the coordinates to determine that maneuver.

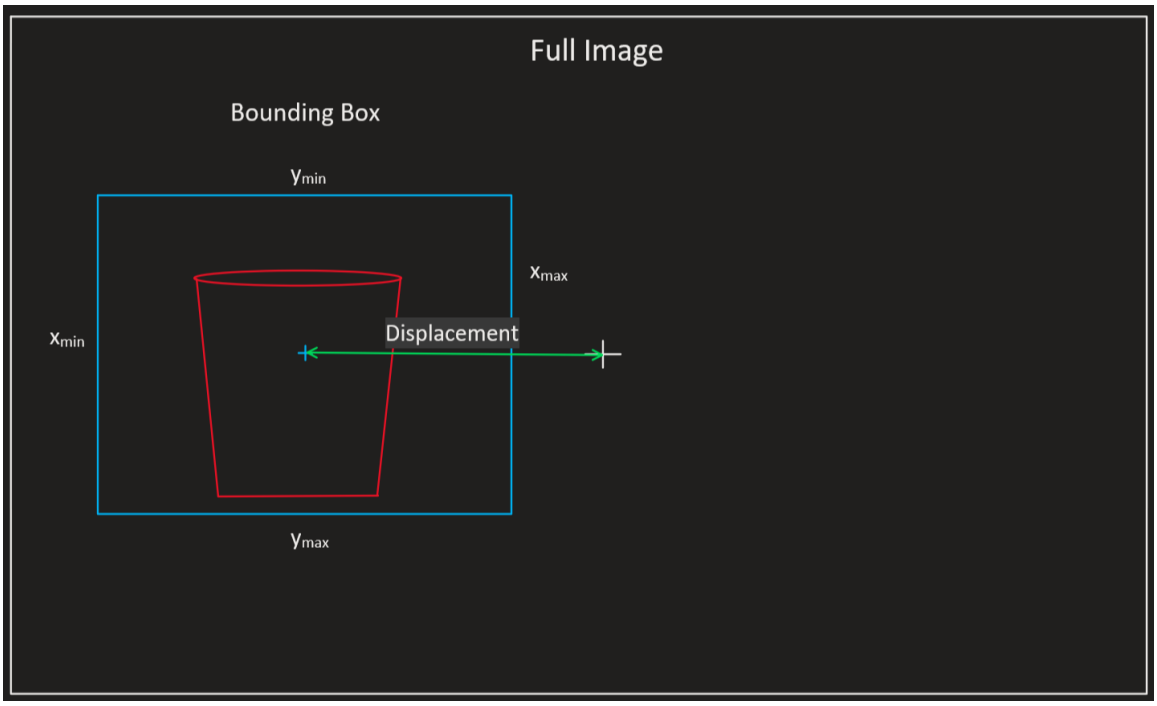


Figure 27: Detection Bounding Box Displacement From Image Center

With the coordinates from the closest bounding box, we can determine the center of that particular bounding box. We can calculate the center of the bounding box by taking the midpoint of x minimum and maximum and the midpoint y minimum and maximum. We would then do the same for the overall image size to get the center of our screen or image. With both the coordinates of the center of the bounding box and the center of our image we can determine the displacement between these two points as shown in figure 22 as well as the direction it is from the center origin of the image.

Since in our use case Trash-E will only ever need to turn right or left or go straight, only the x-plane is of significance to us. Therefore the displacement calculation between our bounding box's center and our image center will only need the x-coordinates and will be the difference between the bounding box's x-coordinate and the image's center x-coordinate. If that displacement is negative, that means that the object is to the left of our origin and Trash-E should turn left. Otherwise if the displacement is positive, then Trash-E should turn right. Trash-E will continue to turn until the image center and the bounding box's center displacement has reached a certain threshold from zero. The reason we don't want the Trash-E to turn until the displacement hits exactly zero is because that would lead to an extremely fidgety movement. Due to real world limitations and scenarios Trash-E would constantly try to correct itself because it will overshoot zero from the negative and positive side. Having the small buffer threshold around zero would eliminate this mediation issue.

Now we have our way of determining which direction Trash-E should turn and which object it should move towards using the data that we receive from our object detection model. The only part left is to design a way that we can pass this information to our microcontroller that ultimately controls these movements based on the information it receives from the Jetson Nano. We will have a Python script that will be able to send that data in a UART method to the microcontroller. The Jetson Nano will never need information from the microcontroller so the communication will be one-directional. Through this python script we will initialize a connection over UART with the microcontroller. There is a library that we will use to make this process simple and it is called PySerial and it has support for serial support access on many platforms.

Once our computer vision software has determined which direction Trash-E needs to turn after the previous mentioned steps in our design, we will send a value over UART that the microcontroller will interpret to perform the corresponding maneuvers. We only have three decisions to make on which turn to make, which are left, right, or forward. Therefore, we can hardcode three values to send over UART that the microcontroller can easily translate. Each value sent over UART will be a hexadecimal number. If the displacement calculations return a 0 value then 0x1 will be sent over UART which corresponds to going straight. If it returns a negative number, 0x2 will be sent over UART which corresponds to turning left. If it returns a positive number then 0x3 will be sent over UART which corresponds to turning right. If in this case our object detection model does not detect any objects that we are looking for, our calculations will return a null value and we will send a value of 0x0 over UART.

6.1.3 Microcontroller Software Design

The movement of Trash-E will be controlled by the microcontroller using the Cortex-M4 processor. The main tasks of the microcontroller will be to: move the robot using servos on the wheels, determine when the trash is close enough to be picked up, lower and raise the arm of the robot with a stepper motor to put the trash into the bucket on the chassis, and to grip the trash with the gripper using a servo. The software will be written using Texas Instruments' Code Composer Studio IDE since the microcontroller is also made by TI and we are familiar with using the IDE.

6.1.3.1 Flowchart

The overall structure of the software will be implemented using a finite state machine (FSM). Since the overall processes that the robot will do is linear and needs to be completed in order, the FSM is perfect for this application. The overall logic that the microcontroller software will follow is shown in Figure 23 below.

6.1.3.2 Wheel movement

To move Trash-E, there will be two servo motors attached to two of the four wheels. These motors will be attached diagonally from each other, for example, one in the front left and the other in the back right. Having the motors attached in this way will allow us to spin the robot without moving too much forward or backward. The microcontroller will generate a PWM signal on the GPIO pin that is connected to each servo. For the wheels we have chosen pins 13 and 14 to generate the PWM signals. To move the robot straight, equal duty cycles will be generated to keep both sides of the robot moving at the same speed. To turn left, the right servo will be given a higher duty cycle and/or the left servo will be given a lower duty cycle. The opposite is true to turn right where the left side will have a higher duty cycle.

6.1.3.3 Baud rate

The decision on whether to move straight or to turn will be decided by the Jetson Nano and sent to the microcontroller using UART on pins 15 and 16. A baud rate of 9600 will be chosen to send the information. We don't need a high amount of bits as too much information could result in the robot over-correcting or potentially under-correcting with the PWM signal generation being overwritten too quickly. To achieve this 9600 baud, we need to alter the registers shown in Table 10.

Table 10: UART Baud Rate Register Configuration

Name	Description	Value
UARTIBRD	UART Integer Baud-Rate Divisor	Determined by formula below
UARTFBRD	UART Fractional Baud-Rate Divisor	Determined by formula below
UARTLCRH	UART Line Control	0x00
UARTLCTL bit 5	HSE of UART Control	1'b0

The values for the integer and fraction portions of the BRD can be found using this formula:

$$BRD = \frac{UARTSysClk}{(ClkDiv * Baud\ Rate)}$$

The PIOSC will be used for the UARTSysClk and the ClkDiv is determined by a bit in UARTCTL. This bit will be set to 0 to achieve the divide by 16 we need for our regular speed operation.

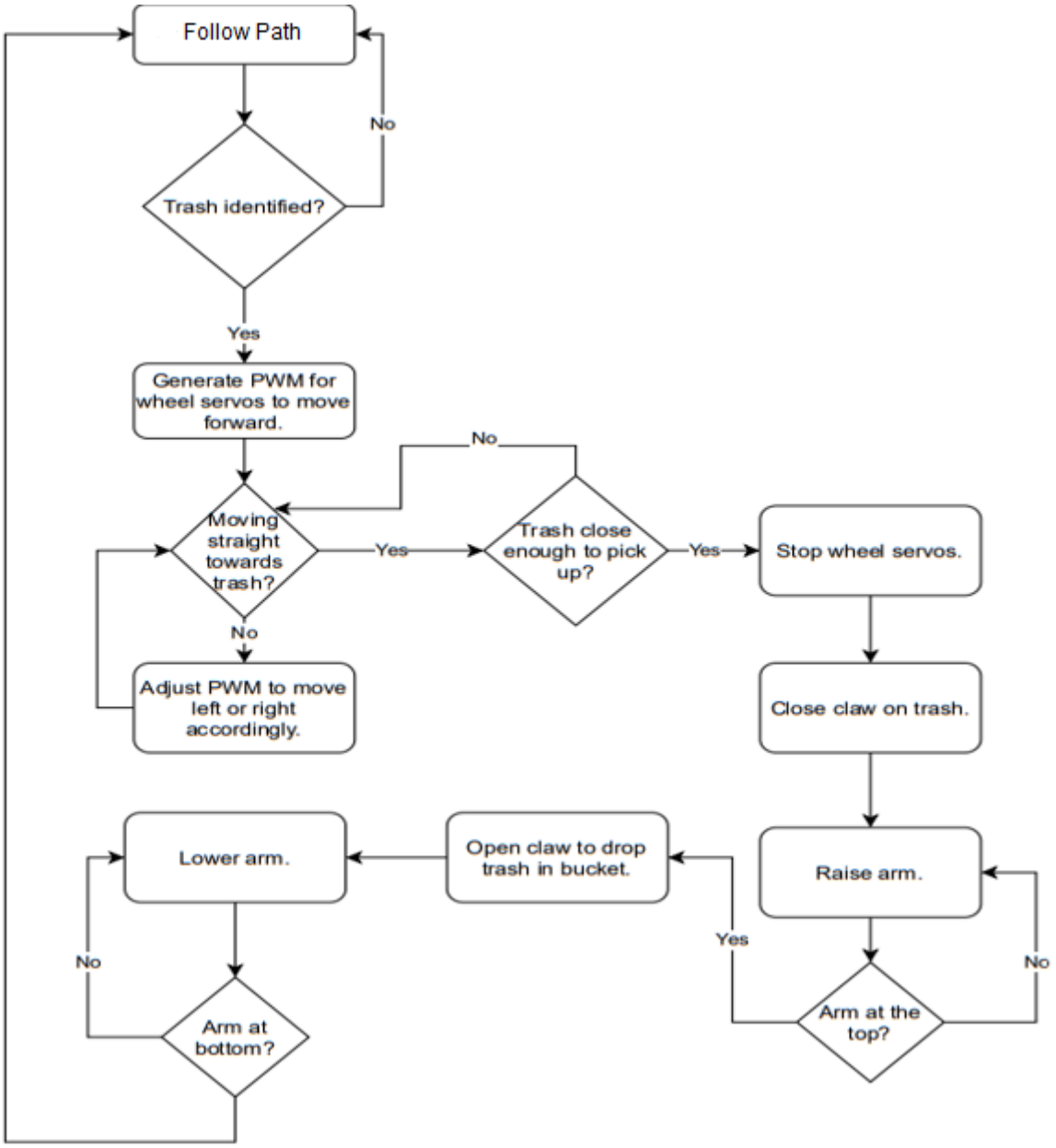


Figure 28: MCU Software Flowchart

6.1.3.4 Command handling

While the robot is in this movement state, it will be continuously listening to the Jetson Nano for instructions. There are three different commands that can be sent to the microcontroller: steer left, steer right, or continue straight. With the small amount of commands we are going to implement, the amount of bits that need to be sent from the Jetson Nano to the microcontroller can also be kept low. We will be utilizing the lowest amount of data bits that the UART interface allows us to send, five data bits, to send a single hexadecimal character. If a value of 0x0 is parsed from the Jetson Nano, the PWM of the two servos will not be altered and

the robot will continue to move forward. If 0x1 is sent it means we need to turn left. If 0x2 is sent it means we need to turn right.

6.1.3.5 PWM Signal Generation

The PWM signals for the motors need to be generated using the timers in the microcontroller. For each servo a separate PWM will need to be used. We chose pins 13, 14, 43, 44, 61, 62, 63, and 64 for the PWM signals since they are all 32/64 bit counters which will give us the most flexibility in timing. To set the timers to PWM mode, the registers in Table 11 need to be altered in each GPTM block for the corresponding timer. The timer period is set in GPTMTnILR and the match value is set in GPTMTnMATCHR. The signal will stay high while the counter is increasing, then goes low after the value is the same as the match register. This allows us to set any duty cycle that we want and can be unique and individually controlled for each motor.

Table 11: PWM Register Configuration

Name	Description	Value
GPTMCFG	GPTM Configuration	0x4
GPTMTnMR	GPTM Timer A/B Mode	0x006
GPTMCTL bit 14	GPTM Control	1'b0
GPTMTnILR	GPTM Timer A/B Interval Load	0xFFFFFFFF
GPTMTnMATCHR	GPTM Timer A/B Match	Determined by what duty cycle is required

6.1.3.6 Wheel Stopping

As the robot gets closer to the trash that it is going to pick up, the ultrasonic sensor will start sending response signals to the microcontroller indicating how far away the object is. The sensor needs a PWM signal as input to trigger the detection, and the response will be sent back to the microcontroller on a GPIO pin. Pin 43 will be used to send the PWM to the sensor. The microcontroller will then sample how long the response is high which will indicate how far away the object is. The response will be sampled on pin 44. Pin 43 will be set according to Table 10. Interrupts will be used to sample the signal from the ultrasonic sensor. The interrupt will trigger whenever the value is high and a flag will be set to indicate the start of a reading. If the flag is set and another interrupt is enabled, the counter will be incremented. A separate interrupt will occur when the flag is set and the

incoming signal is set to low. This will calculate the distance based on the counter then set both the flag and counter to zero.

Since the Jetson Nano will be communicating with the microcontroller to direct it towards the trash, we need a way to have the robot stop when it's close enough to pick it up. The ultrasonic sensor will be attached to the end of the arm where it will have a good view of the area in front of the robot and won't be obstructed by other pieces of equipment. Once the sensor indicates that the object is about one inch away, an interrupt will occur to set the duty cycle of the wheel servos to 0% and move the state to pick up the trash.

6.1.3.7 Grabbing Trash

A smaller servo will be attached to the end of the arm to handle opening and closing the robot arm's claw mechanism. By utilizing the servo we will always know what position the claw is in and can adjust it accordingly. This servo will be connected to pins 61 and 62 set to PWM mode. With the motor starting out at 180°, it will be rotated to 0° by altering the value in the corresponding GPTMTnMATCHR register to clamp onto the trash. The process will be reversed to let go of the trash at the top of the arm movement over the bucket.

6.1.3.8 Raising/Lowering the Arm

Once the trash has been picked up, the robot must move it to the bucket on its back. The microcontroller will be interfacing with an A4988 motor controller to drive the stepper motor. The input on the A4988 will be hooked up to pin 64 which will be set up in PWM mode. The microcontroller will continue to step the motor upwards until a certain amount of steps has been achieved that is going to be determined during the prototyping phase. We can use a single value to move the motor up and down since the arm will always have to travel a set distance up and down.

6.1.3.9 Function Descriptions

This section will describe the overall steps that happen in each state the robot can be in. There will be three states total. After the third state, the microcontroller will return to the first state which acts as an idle state.

6.1.3.9.1 Discover Trash Function

The goal of this function is to find trash that is on the ground.

- START
- Generate 50% duty cycle PWM to rotate the robot.
- If an interrupt is triggered by the signal 0xF being sent to the microcontroller
  - Start moving forward
- END

6.1.3.9.2 Acquire Trash Function

The goal of this function is to move Trash-E towards the trash based on the Jetson Nano's commands.

- START
- Keep moving forward until the ultrasonic sensor reports the trash is one inch away from the claw.
  - Read input from Jetson Nano. Change PWMs accordingly for hexadecimal inputs.
- Set duty cycle to 0% for wheel motors.
- Generate 50% duty cycle for servo at the end of the arm until it has reached 0°.
- END

6.1.3.9.3 Move Trash to Bucket Function

The goal of this function is to move the grabbed trash to the bucket on the back of Trash-E.

- START
- Set the DIR pin connected to the motor controller high.
- Generate 25% duty cycle PWM and increment counter on each pulse.
- Once the counter is at the specified value, generate 0% duty PWM.
- Generate 50% duty cycle for servo at the end of the arm until it has reached 180°.
- Generate 25% duty cycle PWM and decrement counter on each pulse until it's zero.
- END

6.1.4 3D Modeling Software

There are many options when it comes to choosing a piece of 3D modeling software. Software that was under consideration: Tinkercad, Solidworks, AutoCAD, FreeCAD, Fusion 360, and OpenSCAD. Each has varying features and learning curves, and some may be more appropriate for the project than others. Depending on which software will take the least amount of time to learn, provides an adequate number of features, and is free would be the best for this project.

TinkerCAD offers a simple user interface along with fewer features than other modeling software. The number one thing about TinkerCAD is it's learning

curve. Testing the software itself, it walks you through several tutorials to help you get familiar with the interface as well as how to use all of its tools (there's not many). Due to its simple design STL file for 3D printing can be made relatively fast, but if you plan on adding any detail to the model it's not for you. After working with it for about an hour I was able to create a simple model based off the initial design for the robot shown in figure 24 below. The cherry on top would be that this software is completely free and no download is needed.

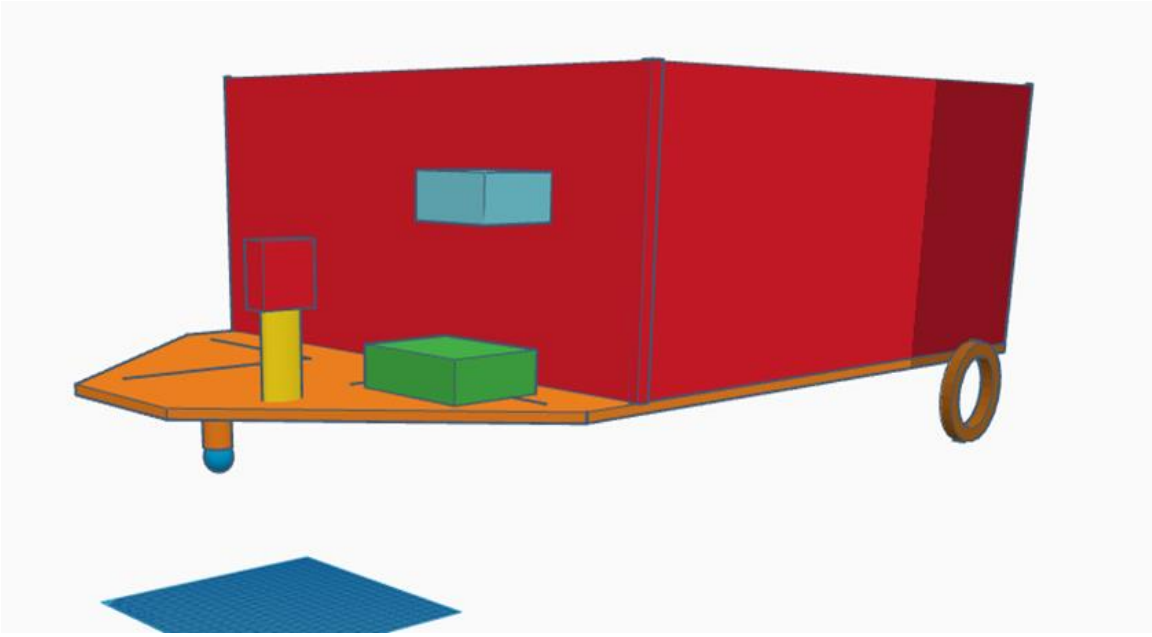


Figure 29: Three Wheel Design Created in TinkerCAD

SOLIDWORKS offers a 3D CAD software free for students while having a code given by my.cecs.ucf.edu. This truly is a professional piece of software that takes many hours of training/practice to get the hang of. It offers many tools to get the job done, and it even lets you simulate the movements of models you are making. Despite that, the first time you open it AUTODESK recommends reading through hundreds of pages of documentation on how each tool works and so forth. Of course, our group consists only of computer and electrical engineers, no one has ever worked with a software on this kind of level before, so the documentation was very overwhelming. Instead, opting for a YouTube tutorial was able to give a good introduction to the software and how to make basic shapes and such, but it wasn't enough to make a robot chassis. If one were to train with SOLIDWORKS for a year undoubtedly great designs would be made, but the time is of the essence and spending too much trying to develop a chassis with complex software would not be efficient. All in all, it's a great free package, but it's too much of a time sink to learn what we're trying to accomplish.

Being one of the most used AutoCAD undoubtedly one of the most powerful 3D CAD software on the market. Reviewing its features, you can create detailed designs while being able to collaborate with other people while you work. It provides many visualization tools to aid in the production of 3D models. Essentially,

AutoCAD is SOLIDWORKS for students, but with twice the number of features and tools to learn. Knowing this, the large number of tools and features is overwhelming to a beginner with limited time and without direct guidance. This suffers from the same issue SOLIDWORKS does, on top of that a 30-day free trial is offered before a subscription is needed.

FreeCAD is a step up from TinkerCAD since it's capable of much more such as configuring settings, it has more than quadruple the number of tools, clear and descriptive UI, and it's able to turn a two-dimensional schematic into a 3D model. In terms of complexity, it is a decent amount above TinkerCAD and a bit below both AutoCAD and SOLIDWORKS. FreeCAD is at a decent middle ground. If a more complex model is needed FreeCAD would be a good choice. There are plenty of videos that showcase its tools and features in a manner that covers all bases and is easy to follow. Overall, its open-source platform allows it to compete with larger paid software's like the two previously mentioned while still being free. Fusion 360 is another solid choice and slightly better than FreeCAD in terms of an easily navigable user interface while still maintaining the same number of features. 2D design schematics can be made and transformed into 3D models. Eagle can also be used in tandem with Fusion 360 to seamlessly integrate the CAD and PCB software to give a more accurate representation of the orientation of components after printing the Chassis. This extra feature would be useful, but it doesn't have the same collaboration features AutoCAD has. We would have to complete our designs separately and merge them together at the end. Though it has great compatibility with several popular slicing products, making 3D printing easier by reducing errors in the STL file. Compared to the top end software like AUTODESK and AutoCAD it has nearly the same number of features, but with a friendlier looking UI along with a package that lets you port over your PCB designs.

OpenSCAD is a nearly limitless 3D modeling software that relies mainly on a scripting language to generate models. Out of all the choices OpenSCAD has the largest learning curve, but if you're able to code it OpenSCAD can make it. It has little to no interactive UI making it very unfriendly to new users. Much time and effort is needed to become efficient because a new language must be learned. To make matters worse, taking the time to code together models is a slow and tedious process compared to predesigned tools in other user interfaces. There is no chance OpenSCAD will be used for this project, the complexity is just too high.

Obviously, TinkerCAD would be the safest option as the interface and tools are minimal and easy to understand. As mentioned before, experimenting with it for the first time I was able to make a rough model of the chassis. For comparison, I spent three hours attempting to learn AUTODESK and at most I could turn a 2D shape into a 3D shape. Building the complete chassis in TinkerCAD then disassembling it into individual pieces should allow for easy printability. The build plate volume of the Prusa i3 MK3S+ is 9.84 x 8.3 x 8.3 inches (250 x 210 x 210 mm), and if the disassembled piece is greater than that volume it can be split to two separate pieces and glued together.

6.1.5 3D Printing Software

Typically, 3D printing software, or slicers, can take several different kinds of 3D modeling file types such as 3MF, STL, OBJ, AMF, and sometimes unique file types that contain special information. Depending on what brand or version of a 3D printer will determine the possible software's that are compatible with it. Some slicers are more capable and provide more features than others. Printer brand and the way each machine generates g code (instructions for 3D printer) can also contribute to the quality of a print. Several 3D printers available on campus are open for use for a fee, to save money and have more convenience we are using a team owned Prusa i3 MK3S+ for printing parts for Trash-E. For the software our options are Cura, Simplify3D, Slic3r, KISSlicer, Tinkerine Suite, Prusa Slicer, Repetier, OctoPrint, an SelfCAD.

Cura is the most widely used 3D slicing software out on the internet. Part of its success is from its free price tag along with being open source. Of course, Cura is specifically designed for Ultimaker 3D printer users, but it offers compatibility with several others. Unlike most printer software, this software has three different stages of processing during the process: in the first phase you can configure printing settings and decide how you're going to slice the model, the second scans the model after generating the g-code finding any areas in need of structural support or that could potentially fail, and in the last stage its possible to what your prints progress live and even remotely.

Simplify3D is probably one of the most powerful and far-reaching slicers. Its greatest strength would be its ability to easily implement detachable supports, this is a category most slicers struggle in. It allows for configuration of the material and support thickness which no other slicer provides. By having effective supports it ends up leaving a better surface finish due to its supports being able to cleanly detach. It ends up leaving less of a clean up job for post processing resulting in better looking prints. Its pre-print simulations are even better than Cura's because of how accurate its error detection system is. Out of all slicers Simplify3D has the most accurate and precise calibration system for tuning retraction, infill settings, cooling fans, and brims. There is no comparison in terms of quality in any other slicer software. Despite this there is a price point of 150 dollars making it too expensive for the scope of this project.

Slic3r, while being relatively old, created in 2011, is probably one of the best open source 3D slicer. Initially, it was released as a non-profit project and it ended up beng one of the greatest 3D model slicer on the internet due to its massive community on github with more than a 1000 people contributing to the project. It's a great all rounder having the ability to display a preview of your print, and it can even do so with multi extruder 3D printers that allow different support materials to be used to make removing supports easy. It's also a lightweight piece of software requiring no dependencies. Other features include brim, microlayering, bridge detection, command line slicing, variable layer heights, sequential printing,

honeycomb infill, mesh cutting, object splitting into parts, AMF support, perimeter avoidance, and different extrusion lengths. Slic3r may beat Cura in terms of its functionality, but it doesn't have a user interface.

KISSlicer seems to be like every other slicer with a more detail oriented setup. Some of the options in KISSlicer are settings no casual 3D printer would mess with , this is clearly for experienced engineers and 3D printer hobbyists. This slicer is only able to work with single extruder 3D printing, while the dual extruder version will cost an extra 42 dollar cost with it. There is a premium option that has a 82 dollar fee that allows you to combine multiple STL files and print them out at once. Compared to other slicers KISSlicer seems a bit lackluster for its cost. Though if the free version is used, it still has access to every content update that adds new mesh topologies, filaments, types of 3D printer, and print styles. Finally, the user interface is not that great compared to other slicers that are free, so in our case KISSlicer is a no go.

Tinkerine Suite is very similar to TinkerCAD, it's a great introductory piece of slicer software for people new to 3D printing. The barrier to entry is nothing since all you need to do is create an account and you can log on the website and start slicing. Originally it was designed for teaching children about 3D printing, but it has enough features like descriptions on how each setting change will effect the print, or how long a print will take to finish, as well as indicators for unsupported bridges and weak points in the print. Although it's a great learning tool, most slicing technology isn't that hard to get a grasp of. As a result, after reviewing the slicers it's a bit too simplistic for what we need to ensure in the design of our parts.

Prusa Slicer takes advantage of Slic3r's open source software and reimagines it into something more specialized. It's main selling point is the attention to detail and the ability to tune almost every aspect of a print. Part of the reason why this slicer is so popular is due to it's great software features that improve upon every aspect of Slic3r as well as the quality of the Prusa printers themselves. Furthermore, it's specifically tuned to enhance the printing quality of Prusa printers making their printers even more appealing. On the other hand, Prusa slicer is able to work with several other non-Prusa printers and over 50 different 3D printer filaments, it even works with resin printers. Just like Slic3r, Prusa Slicer is open source, so it's easily modifiable for anything a user might need to accomplish. A member of our group owns a Prusa printer so this is most likely going to be the slicer software we use unless we need a specific feature from another.

These next two slicers fit within the same category since they both allow for remote printing, but with their own pros and cons. OctoPrint and Repetier Host both set out to accomplish the same goal of allowing users to print remotely. Octo print isn't so much of a slicer as it is a platform for monitoring 3D prints remotely. Even though it doesn't offer much in terms of slicing it's still able to do

so, but it’s remote monitoring abilities are the best out there as of today. You can even add a temperature sensor for monitoring and adjustment, and can stop printing from any location as long as you’re connected to the internet. Repetier Host has a better slicing system than Octoprint, and it allows for larger scale remote printing services. For what we need Repetier Host is too much, Octoprint may turn out to be useful for cutting down on prototyping time.

SelfCAD is probably the most well rounded compared to the rest of the selections for slicer software. It’s more of an all-in-one tool that allows you to create 3D models from scratch like CAD softwares, but then you can import that model within the same system and use slicing software to prepare it for printing. The streamlined and simplistic UI makes it easy to learn SelfCAD. No download is needed since it’s entirely a cloud-based service, but you need an internet connection to work with it. For modeling it uses a system like FreeCAD that is integrated within the software itself. After modeling, SelfCAD provides a few options for slicing, but it’s not as in depth as some of the slicers previously mentioned. Furthermore, it is compatible with almost all fused deposition modeling printers. There are two downsides to SelfCAD and that would be it’s monthly subscription of 14.99 a month and it’s lack of slicing features; free slicers have more functionality than it.

As a final verdict, taking into consideration that the team has access to a personal Prusa i3 MK3S+ it would be best to use the software designed for it, Prusa Slicer. Although, it should be noted that slicers like Cura and Slic3r may have better support options if any overhangs need support while printing. Octoprint integrated into the Prusa printer will allow for less time wasted on failed prints since monitoring it live gives us the option to cancel the print before any time is wasted. The best results will be achieved by using several slicing softwares for their strengths.

6.2 Hardware Design

6.2.1 Robot Design

To have Trash-E pick up cups, it must have a chassis, an arm to pick up and grip the cups, a place to store them, and a way to move around. This section will discuss the possible designs that Trash-E can utilize to complete the task.

6.2.2 Design Overview

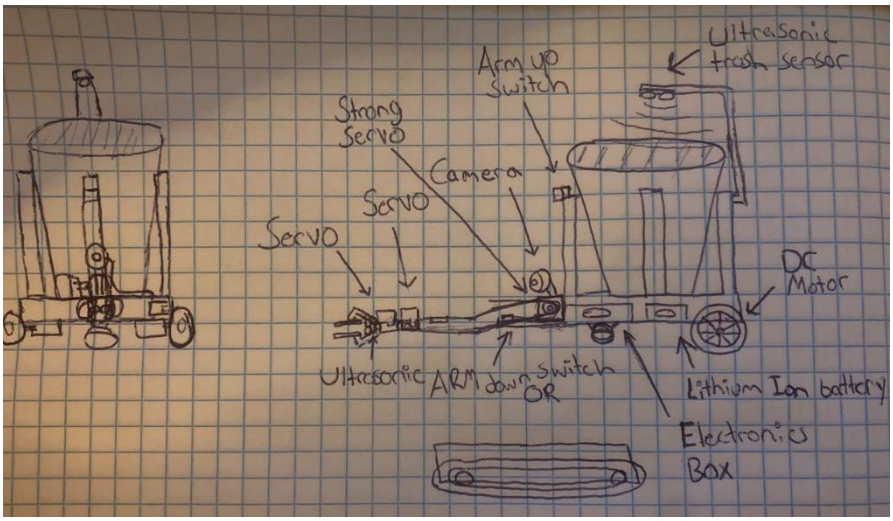


Figure 30: Project Illustration by Alex Rizk

6.2.2.1 Arm and Gripper Design 1

As shown in Figure 25, Design 1 will utilize a straight arm powered by a stepper motor that will drive the arm vertically until it hovers above the garbage bin. At the end of the arm will be a gripping device utilizing a ball and socket joint that can pick up a plastic cup in any position after Trash-E drives up to it. After driving up to the cup the open gripper, using the gear system, will close around the cup with the action of a miniature servo. Also, at the end of the arm will be an ultrasonic sensor to aid in figuring out the distance of the trash in front of the gripper, this way knowing when to close the gripper will be easy to determine.

6.2.2.2 Arm and Gripper Design 2

Design 2 differs with the arm implementation. Instead of one long arm, it will be broken up into two segments with a motor controlling each segment. At the end of the arm will be the gripper. Two motors will control the gripper: one to open and close and one to rotate the pincers. This will allow the arm to center itself to the middle of the cup and grab it based on the orientation of the cup. This design is a stretch goal as it requires more hardware, using more motors, and software development to figure out how it should orient itself.

6.2.2.3 Arm and Gripper Design 3

Despite being a little bit more experimental, design 3 will have a soft robotics themed gripper. Using soft robotics, the main advantage over traditional servo-gear based robotic grippers is its flexibility. This gripper will consist of two appendages with hollow cores that allow for air to be pumped into and out, this causes a closure and release motion. Direction of movement is determined by ridges on the back of it that push it in an inward motion when inflated. As mentioned

before, when the core is filled with air the appendage will move in an inward motion and conform to the object it is grabbing shown in figure 26. With a textured grip adhesive grip, it could potentially grab any object we set out for it; it would allow for greater operability later down the line.

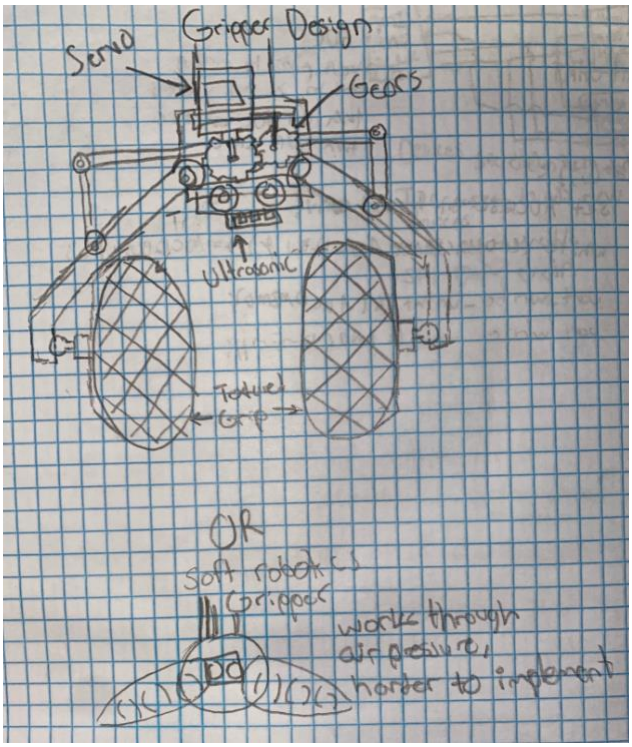


Figure 31: Prototype designs for textured gripper and soft robotics gripper for the purpose of picking up litter

Components and tools needed to create the mold: cardboard, box cutter, hot glue, scotch tape, and gloves. Though, using cardboard would be the cheapest option, but 3D printing would be available for a reusable mold; the downside to this is that it makes prototyping time consuming since we would need to print a new model every time, so we wanted to change the design. Furthermore, to make the gripper itself: Smooth on Ecoflex 00-30 (rubber), scissors, printer paper, a nail, water bottle with lid that is at least one liter, 1/8 inch outside diameter pneumatic tubing, and a curling ribbon.

First, to set up the cardboard mold we fashion two small rectangles out of 3 x .5-inch pieces of cardboard by stacking two of them and scotch taping them together then covering with a thin layer of hot glue, these are put aside for later use. To make the walls of the mold four pieces of rectangular cardboard 4 x .75 inches are cut and the edges are taped and the entirety of the cardboard is covered in a thin layer of hot glue to smooth it out. Taking a 9 x 9-inch plane of cardboard and drawing a dot in the center then hot gluing and placing the previously made cardboard blocks ¾ inches away from it at 180 degrees and -180 degrees mirroring each other. Next, place the walls and draw some lines that are ¼ inches away from the blocks previously glued down, and then place the walls on those lines and glue it. Between the two walls at each end will be a ¼ inch gap which should be filled

by an appropriately sized piece of cardboard matching the height of the previously placed walls. Finishing the air chambers, connect the two rectangular blocks with a generous channel of glue, avoiding the walls, and keep applying layers of glue until half the height of the block. Finally, seal any remaining cracks/gaps in the walls of the mold to make sure the rubber mixture doesn't leak out later down the line, and the mold for the top part of the gripper is done.

Following this, the rubber pouring mix needs uncured Ecoflex 00-30, which is a mild skin irritant, so as a safety precaution, gloves and safety goggles are needed. Pour the mold very slowly into the mold until the air chamber blocks are submerged by at least 1/8 inches of the rubber mix while keeping an eye out for potential leaks. In the case of a leak a paper towel should be placed over the area to seal the gap, and if the mixture seems uneven some small object should be placed underneath the cardboard to level the mixture. It should take around 4 hours for the mixture to completely cure. Once the mix has finished curing it should be pulled out by its outside edges towards the center until the mold is removed entirely.

Now for the second mold, A trace of the first mold made of hot glue should be made with a space of ¼ inches from the newly made rubber gripper; two to three layers of glue should make walls high enough for the next mold. Similarly, take the recently made appendages and trace them on a piece of paper. Making a smaller new batch of Ecoflex, use it to cover just the bottom of the new mold, then place the paper in the center of the mold and fill the rest of it with the remaining Ecoflex. After both bottom and top pieces are made, check for imperfections, and if there are any such as gaps or holes, fill them with some more rubber and spread it evenly. To put the two pieces together, place the thinner piece back into its mold and put some more Ecoflex evenly across it, then, place the larger piece to seal them together ensuring that there is still an air chamber. Finally, after waiting another four hours for the rubber to cure, the two pieces will be melded together to form one cohesive soft robotics gripper.

With the completion of the gripper the air pump needs to be made, for this to be done hands free it needs a small electric air pump or a servo that controls a liter sized syringe. To hook up the pump to the gripper we will need the components mentioned earlier. Connecting the tubing by using hot glue along with some shrink wrap, or with other adhesive along with a pneumatic air seal. Going back to the gripper, pierce the center of the gripper ensuring it lines up with the central air cavity and insert the tubing, blow air into the gripper to test inflation. After ensuring air can cleanly enter and leave the gripper, take it out. Taking two strips of about 20 inches of curling ribbon wrap it around up one of the appendages counter clockwise with the first strip, and with the second strip wrap it clockwise up the same appendage ensuring they overlap on the top and cross on the bottom. When done wrapping that appendage, tie up the ends and remove the excess ribbon; repeat the process for the other side. When the wrapping is done, take the end of the tubing that connects to the gripper, cover it with a layer of Ecoflex keeping it away from the hole, and reinsert it back into the hole previously made to let it cure.

Once finished curing, we inflate the gripper to test how the curling ribbon interacts and ensure that a pinching motion occurs, if not, then testing with different ribbon configurations is needed until the desired result is reached. Now, curling ribbons tend to slip around when force is applied, so a friction layer is needed on the end picking up objects. Taking out the mold for the small layer, fill it with a thin layer of Ecoflex and place the end picking up object in it to cover the curling ribbons. After waiting for it to cure for another 4 hours, the robotic gripper is done and finally able to be used.

Overall, this is a low cost and effective way to make an entry level soft robotics gripper. Despite the several hours this takes to develop, it saves a considerable amount of time compared to designing a new gripper and waiting hours for it to print.

6.2.2.4 Unique Materials and Gripper Design 4

The fourth gripper design, and open-source project by Marc Schömann [22], is a hybrid between designs three and one. It takes the advantages of both designs and combines them into one gripper. From design one it pulls the ease of manufacturing because it can be 3D printed, and from two it somewhat takes the flexibility of a entierly soft robotics gripper. It is composed of two parts: the solid layer which controls the contractions of the limbs and the flexible layer that allows the limbs to return to their original position. As a result, two different plastic filaments need to be used to realize the design; the flexible one being either TPE or TPU and the solid one being PETG or nylon (Talked about under the materials sections).

As can be seen in Figure 32, the three-prong design is flat when the servo is not actuated. However, in Figure 33, the gripper bends and can easily grip the object. We believe that a design like this can help solve our issue of needing to pick up more than just red solo cups and picking up things at different angles.

Figure 32: Flexible gripper at rest (Courtesy Layershift)

Figure 33: Flexible Gripper Actuating (Courtesy Layershift)

To continue, TPE (thermoplastic elastomer) filament, which stands for thermoplastic elastomer filament, is hard plastic blended with rubber. Its elasticity can vary greatly depending on its specific composition, different versions of TPE serve different purposes. For example, one variation of TPE may have a hardness suitable for high impact and friction while the other may have more of a stretchy characteristic like rubber products. Furthermore, its rubbery like nature also makes it great for a gripper limb, allowing for a better grip on objects. Rigidity (ability to return to its original shape) of TPE isn't the best, TPU is better in this category, but depending on the type used it still has some presence. Due to its very flexible nature TPE happens to be difficult to print. It needs temperatures of around 230ºC for the extruder head, a print bed temperature of 110ºC (very hot for print bed temps) and must be printed very slowly making hard to prototype with. Luckily, the

Prusa i3 MK3S+ 3D printer we will be using has a direct drive extruder which can handle TPE well enough to print without jams.

TPU (thermoplastic polyurethane) filament is a category of TPE that has several major differences to standard TPE. TPU tends to be harder than TPE, meaning it can resist surface deformities better than TPE. Its shore hardness classifies it as being a medium hard rubber and hard runner which is like a tire head or shopping wheel care respectively. Despite its hardness it still manages to be very elastic which gives it a wider range of applications. Mentioned before, TPU has a greater rigidity compared TPE allowing to recover from deformations better, for the soft robotics gripper this can come in handy when we need to retract the limbs. Though, TPU tends to have a smoother texture which would lead to possible troubles when it comes to gripping objects. TPU also has a higher durability compared to similar TPEs because it shrinks at a slower rate. Due to its stiffness, TPU is much easier to print, but not as easy as non-flexible plastic filaments. Printing properties are like TPE, but slightly more manageable with lower temperatures. It still needs to be printed slowly to ensure print quality is up to snuff.

The hybrid gripper would work with either thermoplastic, so other factors must be taken into consideration to figure out which plastic would fit better into the scope of this project. A comparison of TPE and TPU prices shows that, in general, a roll of TPE is 10 to 20 dollars cheaper than most rolls TPU. The effort of printing is very similar so in this way it does not matter. Durability of the soft part of the gripper is not a concern, so the main advantages of TPU don't seem that appealing, while the rubber like grip of TPE would benefit us more. Overall, TPE would seem to be ideal filament to use in the soft part of the gripper shown below in Figure 34 along with its dimensions in Figure 35.

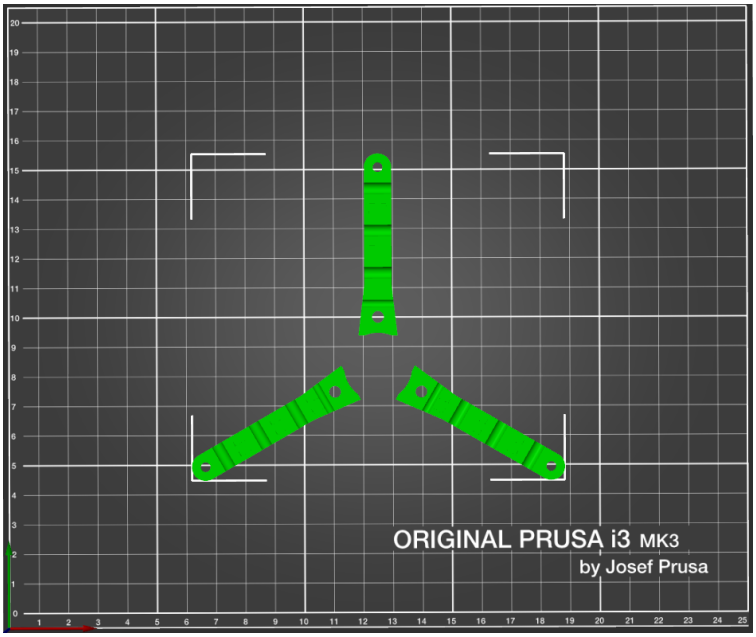


Figure 34: 3D Model of the Soft Portion of the Gripper

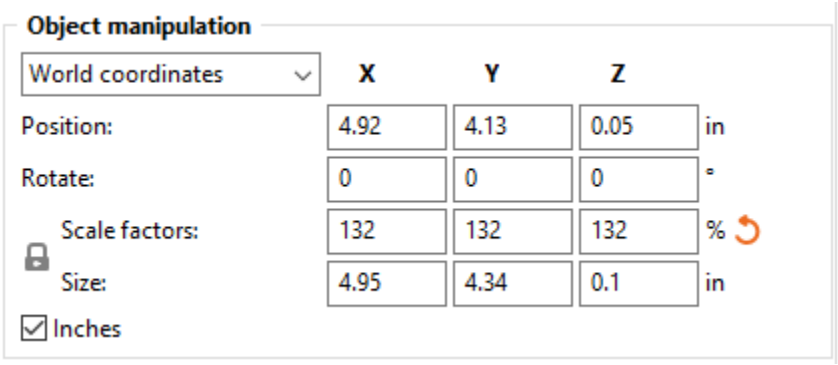


Figure 35: 3D Model Dimensions of the Soft Portion of the Gripper

6.2.2.5 Chassis Considerations for all Designs

Two different designs were taken into consideration for the chassis of Trash-E. The first design consists of two wheels towards the back of the chassis while one swivel wheel is positioned in the front forming a triangular shape. In this case, there would be a servo on each rear wheel for movement left, right, and forward. The second design has more of a car shape with four wheels and a compartment below the operating plate to store the electronics. Placement of the driving servos can be placed in two ways with this design: one servo driving the left rear wheel and the other driving the right front wheel, or vice versa (this allows for a swivel movement like the triangular design).

Weight is a big consideration for the design of the chassis, as it would cut down on power consumption by reducing the watts needed for the motors providing movement. Without having to create a separate compartment for the electronics we can place everything on the front plate; this gives us easy access to the components and makes sufficient airflow to the Nvidia Jetson easy to achieve. Furthermore, it saves on plastic, money, and time since we would need to take the time to figure out a compartment system and use up more plastic trying to print it. On the other hand, its greatest disadvantage is its stability. Leaving the front part of the chassis reliant on a swivel wheel may introduce some wiggle to the movement of the robot. Having this unnecessary movement could lead to further power consumption due to making corrections during navigation. Calibration of the servos may be difficult since the triangular wheel orientation may introduce unpredictable movements.

On the other hand, the four-wheel design, though using a bit more power, comes with its own advantages. The first advantage of this design would be its clean design which would protect the components in its specially made compartment. As mentioned before, there would only be a design issue having to figure out how to achieve enough airflow for the jetson to not overheat during operation. This could be remedied by adding some holes near the jetson for intake as well as some for the expulsion of hot air. Unlike the triangular design that is unstable, the four-wheel

design, shown in figure 27 below, can maintain a relatively stable movement during its operation. Due to having a wheel on each side, each opposing wheel acts as a sort of counterbalance when rotating. Whereas, with the triangular design it may wiggle. In turn, the more stable design would make it easier to calibrate the motors, as we don't have to worry about unpredictable movements during operation.

As a side note, the bucket design, although simple, needs some attention to ensure it's able to contain what we are picking up. To formulate a proper design, we need to take into consideration the largest item we plan on picking up, a red solo cup (though this may change later down the line). A red solo cups dimension is irregular since the rim of the cup is larger in diameter than the base, height is also a big concern. The dimension of the rim is 3 5/8", height is 4 5/8", and the base is 2 1/4", to determine the length and width of the bucket we need to specify how many cups need to be picked up. For the scope of this project, we're not going to be picking up hundreds of cups, more of a proof of concept, we should account for around 12 cups taking the height and rim to simplify measurements. The cups will not be stacked since they'll essentially be dropped into the bucket, so we can get a rough estimate of the dimension of the bucket. Schematics for the bucket have been drawn to give guidance for 3D modeling it shown in figures 36 and 37.

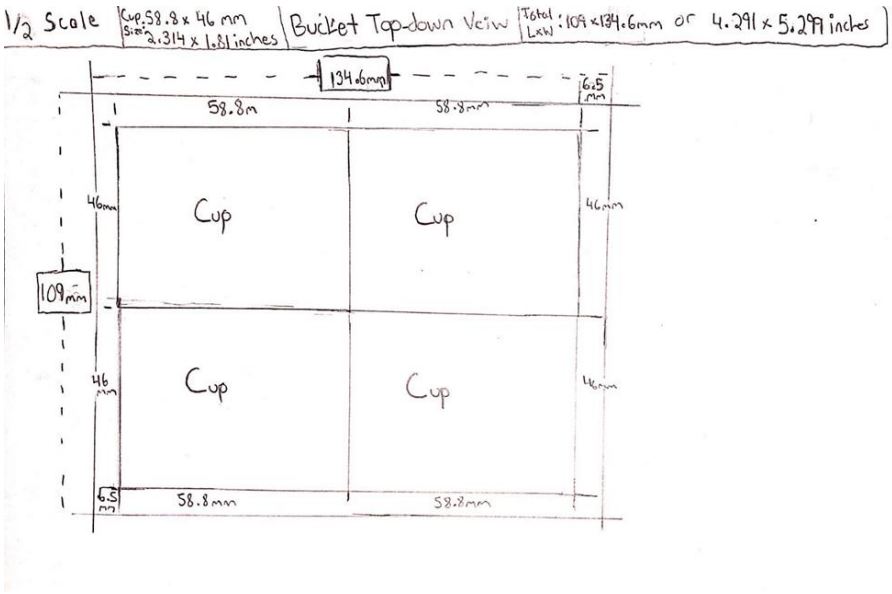


Figure 36: Top-down view schematic for trash bucket

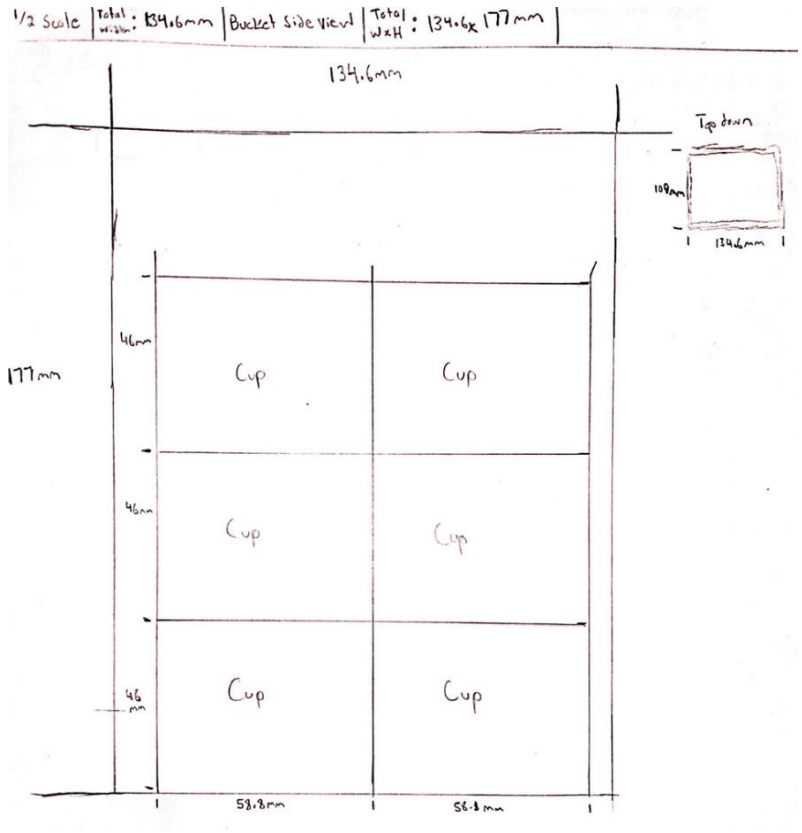


Figure 37: Side view schematic for bucket

6.2.2.6 Final Arm Design

The biggest flaw in previous arm designs mentioned before is that they don't allow for tweaking of the shape and length of the arm. Rather than having to print several versions of the arm we can just create a fully modular one. Like Legos the pieces of the arm shown in figure 38 will interlock. As a result, it forms a tight seal that resists vertical forces while somewhat resisting horizontal ones. More specifically, the three forces we need to account for when designing these joints: Friction, Tension, and Shear. Furthermore, using PETG for the choice of plastic for each of these blocks will ensure a durable design.

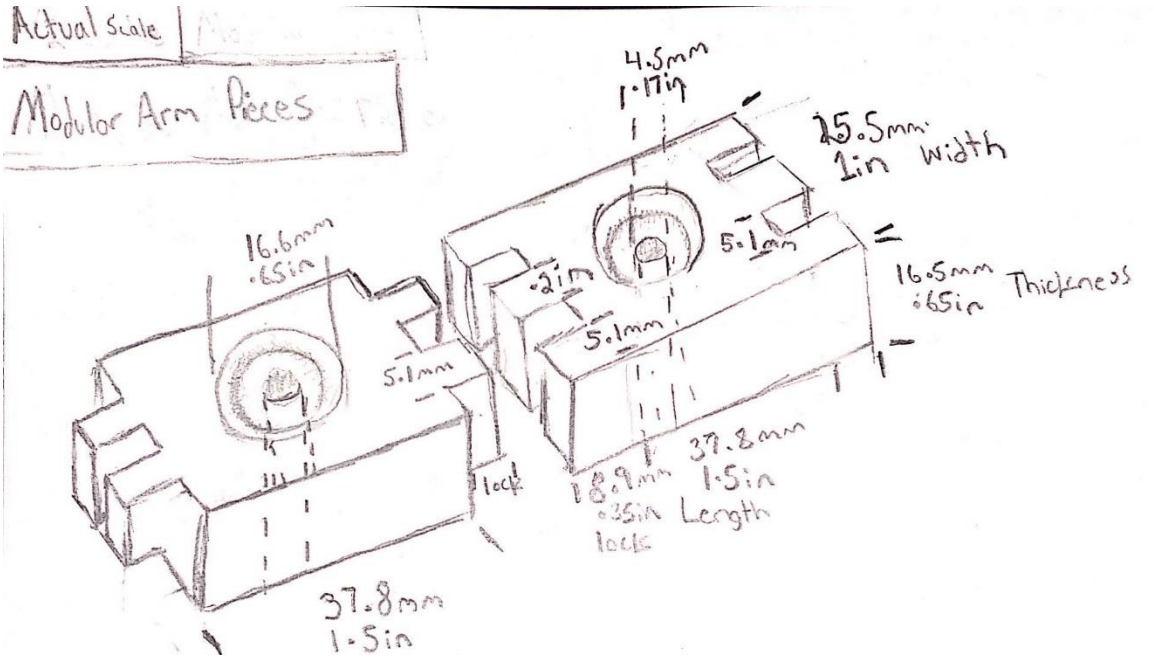


Figure 38: Illustration of modular arm pieces

Length of the arm can be increased or decreased based on the number of pieces interlocked shown in figure 39. Attaching each piece can easily be done with one bolt, two washers to distribute force evenly, and one hex nut to tighten it all. In the center, the screw holes open several configuration and reinforcement possibilities that can also be seen in the figure. For the arm to operate successfully the gripper has to be hovering over the bucket to ensure that the litter can be dropped without issue. The arm will need various tweaks to be in the proper position. Testing that follows would be to start with a base arm size, check if it's above the trash bucket, and if it is no adjustment is needed, otherwise adjust arm length and orientation.

Price wise, this arm is inexpensive since PETG is relatively cheap and easy to work with. The greatest issue would be the time it would take to print each individual piece one by one, or in batches. Dimensions being 1.5 x 1 x .65 inches, the estimated print time on each piece should be around 15 minutes. If each piece takes 15 minutes and we need to print 20 pieces, it will take around 5 hours (granted there are no issues printing within those 5 hours). Although it will take 5 hours it will be worth it since the design is modular and it would save time compared to other designs.

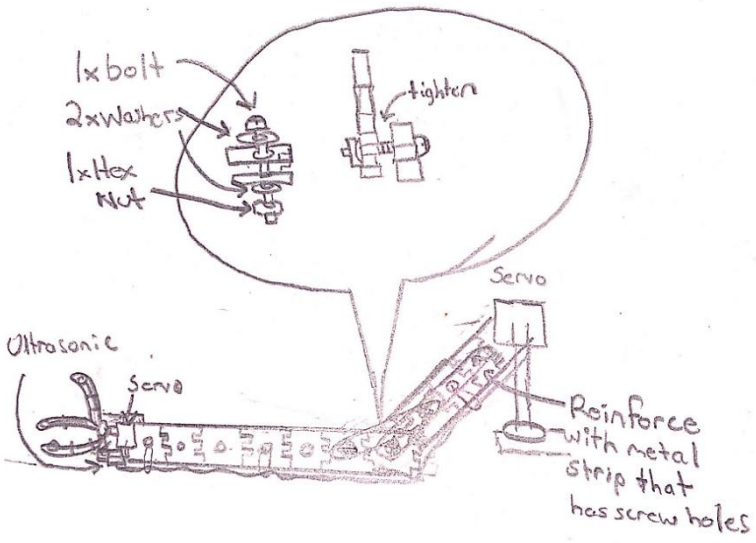


Figure 39: Illustration of modular arm as one piece

When the final length and configuration is determined adhesives can be used to further solidify the connections between the pieces. Ideally, plastic bonding glue would be used to ensure that the plastic is permanently bonded at a molecular level. Other glues will work such as super glue, polyurethane, hot glue, and epoxies. Overall, this design saves time and money in the case changes occur in other components. For this to be achievable, attention to print settings is paramount since each piece must ensure a snug fit, otherwise the design may fall apart. .Several configurations for the Prusa i3 MK3S+ are available online to prevent the hassle of tweaking the settings related to this.

6.2.2.7 Material Considerations

There is a plethora of plastics available on the market and can be easily found on several websites for a reasonable price. Here is a list of the most used plastics available: ABS, PLA, ASA, PET, PETG, Polycarbonate (PC), high performance materials (PEEK, PEKK, ULTEM, etc.), PP, Nylon, composite material, hybrid material, Alumide, and resins. Research was done for each of these plastics to see which one fit the best into the scope of the project. As a side note, no person on the team has experience with materials or mechanical engineering so careful consideration into each of these materials had to be made.

To start, acrylonitrile butadiene styrene, or ABS for short, is one of the most used plastics used in 3D printing. Its usages can be seen in appliances, mobile phone cases, and car bodywork. Being a thermoplastic, it is resistant to drops/shocks and is not brittle making it bendable, in turn, reducing the chances of cracking and breakage. In terms of recyclability ABS is easily reusable when run through a shredder and filament extruder, and it can also be welded together with other pieces of ABS with chemicals like alcohol and acetone. This plastic can even

withstand temperatures between -20ºC (-4ºF) to 80ºC (176ºF). Though, this plastic is not biodegradable and shrinks while in contact with open air causing warping during printing. This can be prevented by taking the following precautions: having a chamber with hot ambient air temperatures, complete restriction of airflow to the outside, a heated build platform, and a nozzle temperature of 230ºC (446ºF) and 260ºC (500ºF). for printing. It's also important to keep in mind that ABS while heated/printing has one of the heavier particle emissions of microplastics out of all plastics, so an enclosed printing space is essential. Even though ABS is durable and checks all the requirements for the components of Trash-E it just requires too much to manufacture. To add, equipment for safe and easy ABS printing is not available to us, we would have to risk printing on a standard open air 3D printer.

Polylactic acid or PLA's greatest strength is its environmentally friendly properties and printability, but it stops there. Unlike ABS, PLA is biodegradable as well as easily recyclable, it is more ethical to print with. Moreover, it is one of the easiest plastics to print with as it doesn't require a heated build plate or as many restrictions as ABS. It prints at much lower temperatures between 190ºC (374ºF) to 230ºC (446ºF), which is virtually possible on all 3D printers. In terms of manipulation, PLA is very difficult to meld due to cooling and solidifying very quickly, but in our case, this is not an issue. When in contact with water it deteriorates very slowly over time, and in the case of Florida weathers year-round humidity would not see long term use. More of a decorative plastic, PLA comes in many colors, but is on the lower end of durability when it comes to 3D printable plastics.

Acrylonitrile styrene acrylate (ASA) is extremely similar to ABS in its properties with the benefit of UV resistance. This plastic would be great for use outdoors with the durability and heat resistance of ABS. Despite having all these benefits, its production cost is even higher than ABS due to a component added to grant its UV resistance. Styrene and microplastics are emitted during printing which can cause symptoms of styrene poisoning if one neglects to print it in an enclosed space. This plastic would be a great choice if we had planned Trash-E to operate outdoors, but the proper equipment to work with ASA is not available to us.

Polyethylene terephthalate (PET) like PLA is easy to work with but lacks the biodegradability. PET is somewhat rigid making it good for pieces that are not exposed to constant movement or collisions. It has great resistance to various chemicals making it good for contact with food, it can be seen in use with water bottles, synthetic fibers, and similar products. Unlike ABS it releases a minuscule amount of plastic during printing, as well as being odorless it is very safe to print in any 3D printer. Its biggest downside is its overall brittleness and fragility, it cannot handle high temperatures or impacts. Based off the previous statement, Trash-E being an autonomous robot, may encounter collisions during testing, so PET would not be the best choice since we want something durable and reusable. Luckily, its cousin glycolized polyester (PETG) is able to make up for its weakness while still retaining the same safety. It combines the durability of ABS and the

simplicity of PLA. The glycol added improves the ductility, chemical resistance, transparency, hardness, and impact resistance. Though it does require a heated build plate along with extrusion temperatures of 220ºC (428ºF) to 260ºC (500ºF), it's nothing most standard 3D printers can't accomplish. PETG is one of the easiest and durable 3D printable plastics and it will most likely be used for the entirety of the chassis as it is durable, easily printable, and affordable.

Polycarbonate (PC) would be one of the greatest plastics to use for our application, but it has many pitfalls if not managed properly. This plastic is extremely durable, lightweight, as well as being able to withstand temperatures of 150ºC (302ºF). It's so durable that it's used in the production of bulletproof glass and other glass products. Although the durability is great, production and safety are just too taxing. It releases bisphenol A (BPA) particles which can have several negative side effects. It is sensitive to humidity and UV rays making it practically unusable outdoors. Troubles during printing include trouble sticking to the build plate resulting in print failures, warping (peeling) from the build plate, and pretty much all the difficulties of printing ABS. High temperatures are needed not only for the nozzle, 260ºC (500ºF) to 310ºC (590º), but also for the build plate that would have to reach temps of 80ºC (176ºF) to 120ºC (248ºF). On top of this, a sealed chamber is required if you want the optimal and safe printing results. Overall, this plastic is very far out of reach to work with and would be extremely overdeveloped if we were to implement this plastic for Trash-E.

Several high-performance polymers like polyaryletherketones (PAEK) and polyetherimides (PEI) are great choices as it is one of most durable and multipurpose plastics out there. In terms of physical and temperature resistance it can be higher than PC, and in most cases it is. Mostly found in the medical, aerospace, automotive, and military sectors it's almost the end all be all industrial plastics. Despite the plastic being an amazing all rounder it is just not meant to be used by the average person as expensive equipment is needed to work with it. To print PEI/PAEK nozzle temperatures need to reach temperatures over 350°C (660°F) along with build plate temperatures needing to reach 230°C (450°F). Even more, an enclosed chamber is needed to properly balance the temperature within, needing very capable cooling systems. Being one of the best plastics out there the price is also high (for good reason) with prices of PEEK reaching 195 dollars per 250 grams, which is possibly one of the most expensive options. Over time the barrier of entry for these kinds of plastics have lowered, but it is not at the point where a group of students can afford the cost or facilities to work with this plastic unless sponsored and given access to the proper equipment. Hence, high-performance polymers are completely infeasible for use with Trash-E.

An alternative to PETG, Polypropylene (PP) has similar properties, but it has great interlayer adhesion allowing for it to stretch before breaking. Its overall cohesion allows it to be a better version of PETG with the ability to resist abrasions and shocks while still maintaining good rigidity. Much of the time it's used in the automotive industry but is used in much of our everyday objects since it's non-toxic

and poses no risk from using it. Printing with it is easier than with PETG with print temperatures of 220°C (428°F) to 240°C (464°F) and can even be printed without a heat bed (it helps though). It's hard to find any downsides to this plastic as it's easily accessible and printable through normal means, this is a great contender instead of PETG. Given that price is a known constraint, a spool of PP (40$) is almost double the price of a spool of PETG(20$). Despite the great properties, PETG is still the number one choice for the chassis.

Nylon finds a good middle ground between user friendly and durable, as it has a crystalline structure consisting of carbon. Alternatively, it is much easier to work with than PC, it removes the hassle of having to deal with the absurdly high temperatures and safety risks during printing while still maintaining a durability that rivals PP. Because nylon is composed of carbon it has amazing temperature resistant properties being better than PC at 180°C (356°F). It's also environmentally friendly since it's bio sourced from castor oil. Overall, it's a highly stable material with one weakness, and that would be its high propensity to absorb humidity from the surrounding air and a heated chamber of at least 40°C is needed for a successful print. This one downside removes it from outdoor applications, but for a lot of companies nylon is the go to plastic for high end prototyping. The extra hassle from having to store nylon in a dry box and having a heated chamber isn't worth it, PETG seems to still be the best option so far. Although, it may be considered for the internal structure of the hybrid soft robotics gripper in figure 40 since it's very flexible when printed thinly.

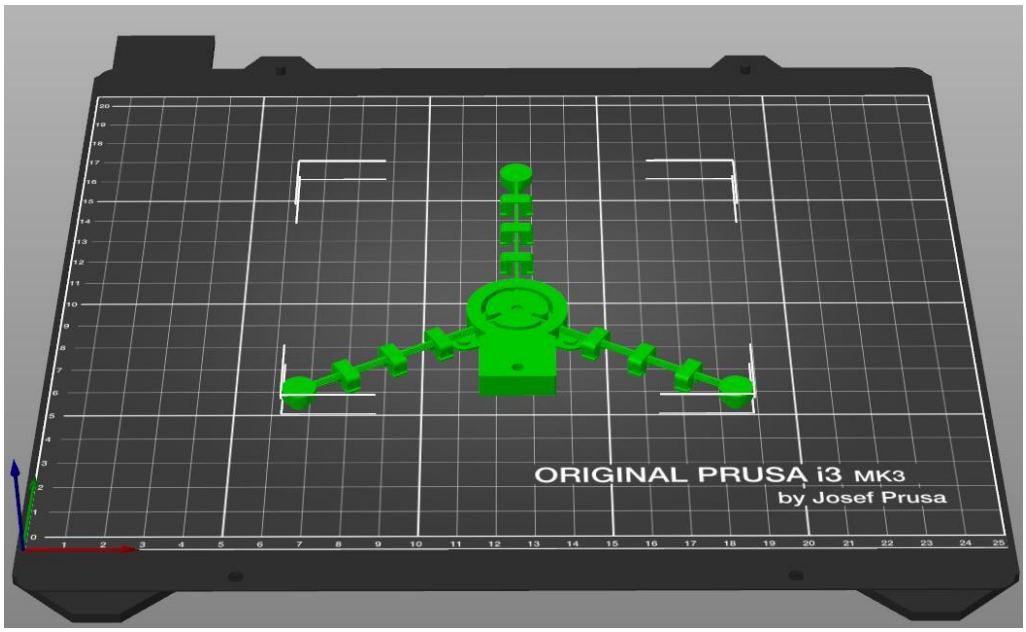


Figure 40: 3D model of the solid component of hybrid gripper

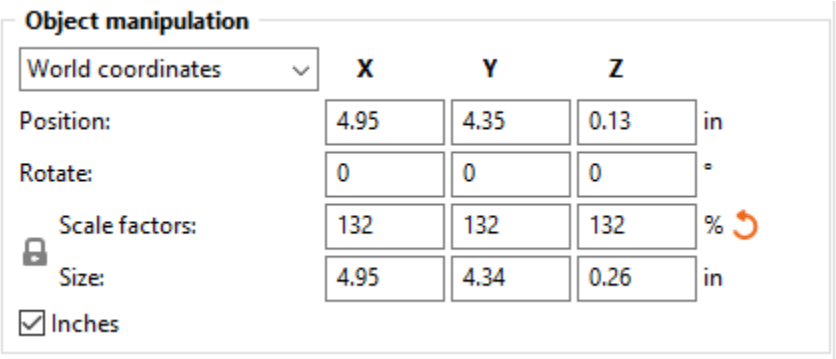


Figure 41: Dimensions of hybrid gripper

Composite material consists of various plastics like PLA, ABS, or nylon that are mixed with short fibers of (in most cases) carbon fiber or various other materials to achieve certain unique properties. This category is just too expansive to delve into, there are just too many combinations that could be made with composite materials. There may be one material out there that has the properties we need, but the majority of composite materials are priced a bit heavier than their non composite counterparts. Besides, carbon fibers mixed into any of the aforementioned plastics can deteriorate the nozzle of a 3D printer, starching it as its extruded. Taking into consideration money and time it's not worth considering as we just need a material that is relatively durable while still being able to easily work with and print.

Delving into hybrid materials, they suffer from the same issue as composite materials. Many hybrid filaments, or might I say the most popular, are typically composed of PLA mixed with various materials to achieve a certain look or mechanical property. For example, PLA can be mix with several wood products like wood dust, oak, mahogany, etc. to achieve a look that is like wood but retains the properties of PLA. Metal like copper or brass can also be mixed in to make a print have conductive properties or make it look like either metal. Hybrid filaments can also cause damage to nozzles, so special reinforced nozzles are needed to print this material. Like before, adding extra material to filament incurs extra costs and requirements to print, so to remove unnecessary complexity from the project we will avoid hybrid materials.

Alumide would be a decent alternative to almost everything on this list as it shares the properties of aluminum. Its temperature resistant and is great for use on small models that require a lot of detail, great for use in creating replacement parts. Though, unlike every other material in this section it is not printable through normal means. A selective laser sintering (SLS) machine is needed to even work with it. On top of this, it's not purchasable through Amazon and seems to be only available to the manufacturing industry. Basically, this material is inaccessible to average students and not to even mention the expensive equipment needed. Alumide is unusable for Trash-E.

The last considered material is resins, the best way to describe this would be to say it has the same properties as ABS with half the benefits. It can only be used in

special printers that utilize UV light to harden the resin into whatever shape needed. The greatest advantage is the amount of detail achievable by resin, the results are comparable to injection molding. Resin printers are cheap, cheaper than some extruder printers, but working with them is a hassle. There are several kinds of resins that can be used for many kinds of applications such as dentistry and various hobbies, but there really isn't a use case for this project.

In summation, after running through the available 3D printable plastics such as ABS, PLA, ASA, PET, PETG, PC, high performance materials, PP, Nylon, composite material, hybrid material, Alumide, and resins I now have a greater understanding of 3D printing. Considering the various pros and cons of all the mentioned materials PETG offers the best middle ground in terms of price, strength, accessibility, and printability. PETG will be the final decision for the plastic used in the prototyping, build, and testing sections. It came close between PP and Nylon because they we're the best affordable options when it came to what we were looking for, but the main deciding factors among these options was price. In this case, PETG is 20 dollars, PP is 40 dollars, and nylon is 30 dollars; when we only have 400, minimizing our expenses is paramount.

6.2.2.8 Overall Design

In the end, the four-wheel design the prototype four-wheel design shown in figure 27 will most likely be the final design for Trash-E. Not shown in the figure is the canopy holding the Lidar sensor positioned above the box shaped trash bucket, this feature may be implemented during the development phase of the robot (low priority). The gripper will be the hybrid design option since it offers the greatest amount of flexibility when it comes to picking up various items. Last, the gripper arm will be a modular and adjustable in the case that modification need to be made to improve the functionality of Trash-E. Furthermore, the final model of the gripper in figure 43 will cover all bases. Considerations for weight distribution of components will also be considered to have adequate maneuverability.

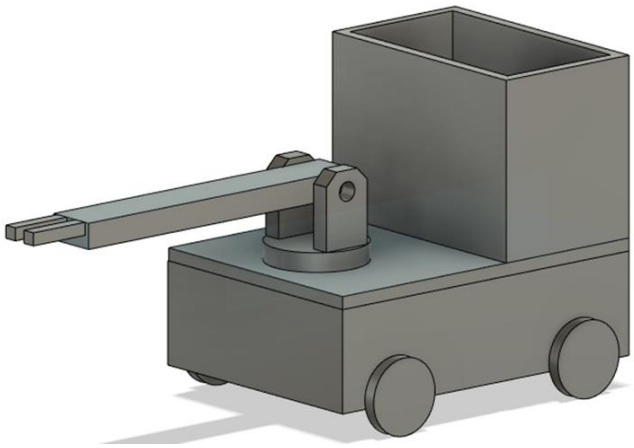


Figure 42: Four Wheel Design for Trash-E

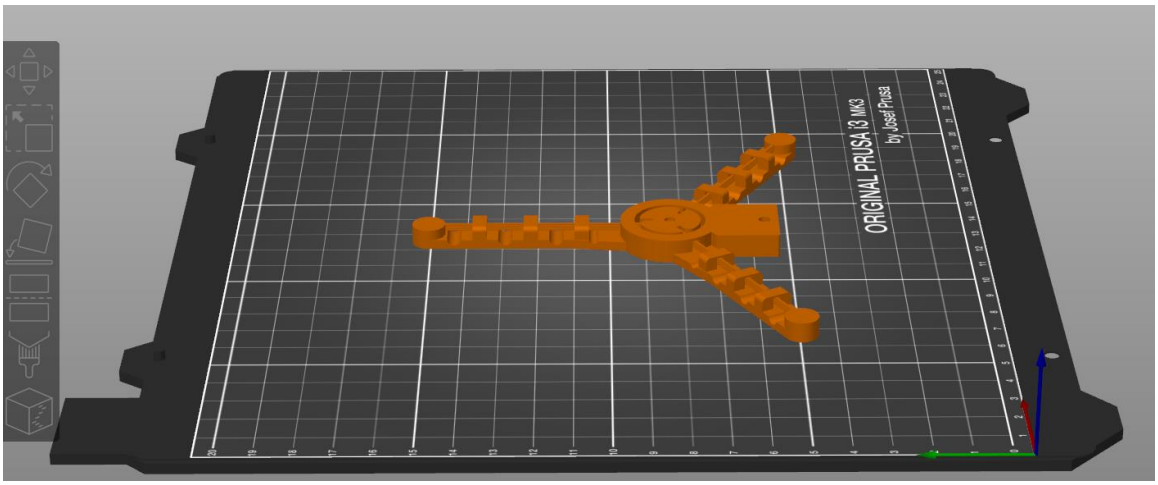


Figure 43: Full design of the hybrid gripper

6.2.3 Motors

6.2.3.1 Stepper Motors

Stepper motors are very useful for moving in precise increments while also having high torque at low power. It can achieve these precise movements because each stepper motor has a specific step angle which it turns every time the motor moves one step. The Twotrees Nema 17 motor has a step angle of 1.8°. Using the formula

$$Steps\ per\ revolution = \frac{360}{Step\ angle}$$

we can rotate the motor 200 times until it has completed one full revolution. For the tradeoff of torque, we can increase the number of total steps by dividing the step angle even further. The movement will be more precise, but the max weight we can lift will be reduced. To calculate the microstep we use the following formula:

$$Microstep = \frac{Step\ Angle}{Step\ Divisor}$$

If we wanted to divide the current step angle by a step divisor of 16, we would have a new step angle of 0.1125° and achieve 3,200 total steps instead of the original 200. These motors best fit the application of moving the arm vertically when it has picked up a cup and then when it needs to return to rest. We will know how many steps it has moved since being at rest so it can be returned exactly to the same place.

6.2.3.2 Servo Motors

Two types of servos will be utilized in Trash-E: positional and continuous. Positional servos allow the user to control the position of the servo using a potentiometer driven by a pulse-width modulation (PWM). Based on how long PWM is high, the motor can be all the way to the left, right, or somewhere in-

between. This type of servo will be used for the gripper at the end of the arm to grab the cup and release it.

Continuous servos allow the control of speed and direction but lose the positioning information. Altering the PWM signal will change the speed and direction of the servo rotation. This will be utilized in the movement of Trash-E to move it forward, backward, and/or turn.

6.2.4 Motor Driver

The output power of the microcontroller is too small to activate the stepper motors. This requires the use of a motor driver. Motor drivers allow a signal to still be sent from a microcontroller on how it should move, but the motor will be powered by an external source. Figure 44 depicts the typical wiring for the A4988 stepper motor driver we will be using. The motor power supply will be powered by the onboard battery.

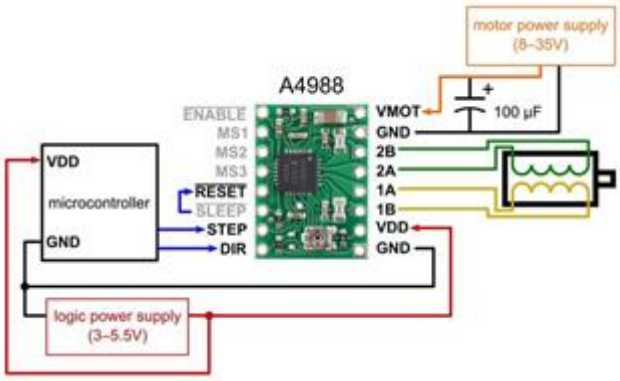


Figure 44: Wiring Diagram for A4988 Motor Driver (Courtesy Polulu)

6.2.5 Ultrasonic Sensor

Determining how far away the cup is from the grabber is necessary for picking it up. If the cup isn't close enough or is too far away, the gripper won't be in the correct position leading to the cup not being picked up. The computer vision will guide the robot left and right to go straight into the cup. Once the ultrasonic sensor starts getting input from the distance to the cup, the microcontroller will take over the forward movement. Once the ultrasonic sensor determines the cup is a set distance away, Trash-E will stop and proceed to pick up the cup.

6.2.6 3D Printing

After looking online for a pre-made chassis we could utilize for the base of this project, we could only find options out of our budget that met the size requirements. We will be utilizing 3D printing for the chassis and the bucket that sits on the back. Printing of the arm and gripper will also be performed.

6.2.7 Power Supply

6.2.7.1 Battery Options

Table 12: Battery Options

Part #	Manufacturer	Availability	Price/Unit ($)	Capacity (mAh)	Discharge Max Current (A)
35E 18650	Samsung	☑	$7.99	3500	8
ICR18650-2600-F	PKCELL	☑	$6.00000	2600	3.9
LION-1865-26	Dantona Industries	☑	$4.99000	2600	?
ICR18650-2200-F	PKCELL	☑	$5.00000	2200	3.3
ICR14430-650-F	PKCELL	☑	$3.00000	650	?
PRT-12895	SparkFun Electronics	☑	$5.95000	2600	3.9
ASR00050	TinyCircuits	☑	$5.95000	2500	?
LI18650JL PROTECTED	Jauch Quartz	☑	$13.05000	3250	4.875
MJ1 18650	LG	☑	$6.99	3500	10
NCR 18650B Protected	Panasonic	☑	$9.99	3400	4.9?
Epoch 18650 Protected	Epoch	☑	$9.99	3500	8
35E 18650 - Protected Button Top Battery	Samsung	☒	$6.99	3500mAh	8

Table 12 showcases several batteries that we are considering using. The highlighted batteries are batteries that have battery management systems built into them. For our use case, we believe that 18650 batteries are the best bang for our

buck. They can have high maximum discharge current, and can be used to create a battery pack with our desired voltage output. The batteries with capacities over 3000 mAh are the most expensive from the ones put in our table. The batteries that have a question mark under the Discharge Max Current column are ones that we had trouble finding the datasheet for. The specs they have are shown on the product page, but for some reason or another the datasheets were unavailable and the specs page did not show the discharge current.

We will most likely use batteries that are above 3000 mAh. The batteries in the 2000 mAh or less range were considered because they are cheaper, but to get the same output, we would end up using more batteries, which would cost more. For example, to get 7000 mAh using the ICR18650-2200-F, with the same max discharge that we calculated in Section 3.4, we would need 15 batteries. The total cost would be 75$, while with the Samsung 35E unprotected, the price is 42$.

Another decision we have to make is whether or not to use batteries with built in Battery Management System (BMS), buy separate BMS circuits that we can implement, or create our own that we can use. The benefits of having built in BMS in our batteries is that we will not have to worry as much about incorrectly recharging the batteries. We also will not need to worry about designing our own BMS or finding a third party BMS. However, the price is much steeper when the batteries have built-in BMS. Comparing the Samsung 35E and the Epoch Protected battery, the price is 2$ more. If we are buying 6 batteries, the price will end up being 12$ more. We may be able to find a third party BMS that costs less than 12$, or even design our own for less.

Ideally, we would want to use the Samsung 35E 18650 3500mAh 8A - Protected Button Top Battery because it is cheap, with a large capacity, and is protected. However, due to supply chain issues, this battery will not be in stock for the foreseeable future. Therefore, we have to assume we will not be able to get these batteries at all. If we decide to use batteries that have BMS built in, we will likely use the Epoch 18650 Protected batteries. The NCR 18650B Protected batteries have good specs, but no datasheet was able to be found for them, so it might be hard to work with the batteries in the future. The LI18650JL PROTECTED batteries are usable, but they are very expensive. For batteries that do not have BMS built in, the Samsung 35E 18650 3500mAh is the best battery that we could find. As stated above, the other non protected circuits do not meet the requirements that we need for our use case.

6.2.7.2 Battery Management System (BMS)

Table 13: BMS Board Options

Part Name	Price
2Pcs 3S 11.1V 12.6V 25A W/Balance 18650 Li ion Lithium Battery PCB Protection Board	$9.99
5S 20A 18V 21V Li-Ion Lithium Battery Pack Battery Charger Protection Board Circuit	$8.88
Anmbest Balancer 4S 16.8V 30A 18650 Charger PCB BMS Protection Board	$9.49

For the 3 possible BMS boards found in Table 13, we are not confident in using any of them. This is because many of the reviews found for these boards said that the boards were not able to handle the rated currents, and some got obscenely hot even at low current. Furthermore, there was little to no information on the technical specifications of the boards. No datasheets could be found for these boards.

6.2.7.3 Battery Test Plan

In the end, we believe that it would be best to buy the batteries with BMS protection. Buying a third party board to connect will add unnecessary bulk to the interior of our robot. Furthermore, out of the ones that we found, the reviews seemed to indicate that the boards had heat problems, which would cause a large problem within our robot. Creating our own circuit may add more complexion to our robot, because we will need to have an esp32 and create more code to help keep track of the voltage and current.

6.2.7.3.1 Procedure

We can run tests by fully discharging and fully charging the batteries to make sure the capacities and max discharge currents are correct. We can further look at the discharge curve to make sure that the batteries are discharging at a steady rate.

1. Connect battery pack to voltage recording device such as an 34970A Data Acquisition / Data Logger Switch Unit
2. Connect battery to power supply and set power supply to 4.2V
3. Allow battery to reach Nominal Voltage at 4.2V
    1. If we decide to get batteries without BMS, we need to keep careful watch of the batteries when they are charging and discharging because they can very easily catch fire. The batteries with BMS will still need to be monitored regardless.
4. Record time taken to reach maximum charge
5. Connect battery to load (Such as DC Electronic Load) and set discharge rate to expected current draw

6. Record periodic voltages and current with Agilent until battery is depleted (3.0 V)
7. Graph output voltage of the battery over time to make sure battery discharge is sufficient
8. Current should be constant and voltage drop should be constant

6.2.8 Voltage Regulator

For our use, we will be using 12V input from the power supply that we make. We will then use voltage regulators to step down the 12V input down to 5V, and 3.3V. The different output voltages will be used to power the different components on the robot such as the webcam, servos, sensors, and microcontrollers. Below are possible configurations using the TPS52903RPJ regulator from Texas Instruments

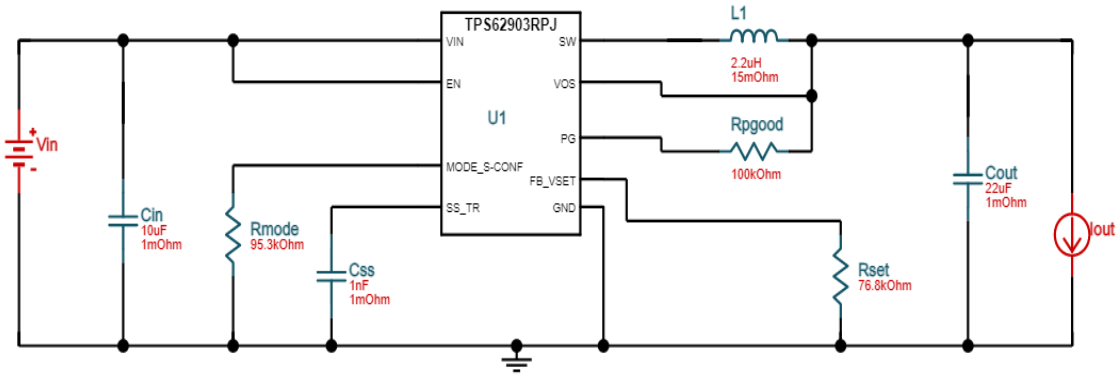


Figure 45: 12V to 5V Buck TPS52903RPJ Voltage Regulator

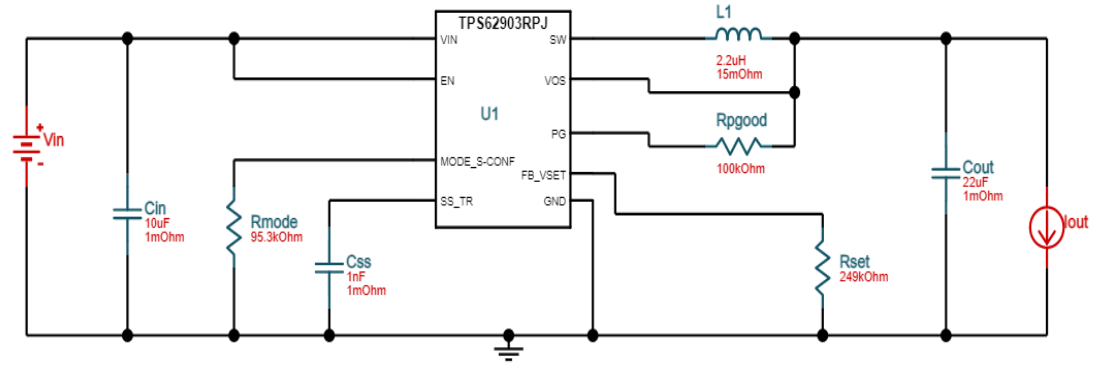


Figure 46: 12V to 3.3V TPS52903RPJ Voltage Regulator

One of the parts that we are considering to use for the Voltage Regulator is the TPS62903RPJR from Texas Instruments as shown in Figure 29. We believe that this is a good part because it is low cost and has high efficiency at our load of 5V. Furthermore, as seen in Figure 45 and 46, the circuits between the 12V to 5V and the 12V to 3V are almost identical. By changing the resistance of Rset, we can easily change the output voltage. This is beneficial because we can reduce the

variety of different parts that we order. We can also save money by buying the same components aside from Rset.

While we want to use the part TPS62903RPJR for a voltage regulator, due to the supply chain limitations from COVID, this part is currently out of stock on all known websites, including TI's, the original manufacturer. For the moment, we will proceed as if this part will always be out of stock. However, if this part comes back into stock, we will consider ordering it along with different regulators to test the efficiency, in case this part ends up working better than the new parts.

After further investigation, most, if not all of the voltage regulators from Texas Instruments that we planned to use are out of stock for the foreseeable future. Therefore, we have to look at other manufacturers. Table 1 shows a compilation of voltage regulators that we plan to use if they come into stock. This stock is based off the stock available on Digikey. We aim to have at least 5 different voltage regulators in case the stock suddenly changes, so we can have multiple layers of backup. We want to minimize the cost of the unit, while being within the specs of the robot. We know that the max current draw of the whole unit will be 10 A, but the robot should never be running anywhere close to that maximum. Realistically, it will be more likely that the max current will be at 5A, while the typical current draw should be less than 3A. The regulator AP62150Z6-7 is the cheapest price/unit regulator that we have on the table, but it has a current output of 1.5A. It may be sufficient most of the time, but it is cutting close to the maximum expected current.

Table 14: Possible Voltage Regulators

Part #	Manufacturer	Availability	Price/Unit	Current (A)
TPS62903RPJR	Texas Instruments (TI)	☒	$2.04000	3
TPS566238RQFR	TI	☒	$2.330	6
TPS564208DDCR	TI	☒	$0.788	4
BD86120EFJ-E2	Rohm Semiconductor (RS)	☑	$2.19000	5
NR111E	Sanken	☑	$1.69000	4
LM22673MR	TI	☑	$6.04000	3
AP62150Z6-7	Diodes Incorporated (DI)	☑	$0.54000	1.5

LMR14030SSQDDAQ1	TI	☑	$3.94000	3.5
SC4524FSETRT	Semtech Corporation	☑	$1.56000	2

From Table 14, we decided that the voltage regulators NR111E or SC4524FSETRT are the best cost performing price/unit for our case. NR111E has much more room for error with a higher maximum current output. The voltage regulator LM22673MR is very expensive compared to the other units, and expensive in general for our budget, because if we order 10 for testing, it will be 60$, which is a large portion of our budget. The voltage regulator LMR14030SSQDDAQ1 is a possible regulator, but is more on the expensive side. We will keep this one in mind, but prefer not to use this or the previously discussed one. TPS566238RQFR is a good regulator because it has a high current ceiling of 6A. It is in the middle in terms of pricing for all of the prices in our table. However, it is out of stock for the foreseeable future. TPS564208DDCR is cheap, and has good room for error in regards to current, but it is also out of stock. The regulator BD86120EFJ-E2 is a possible candidate, as it has high current output, but begins to encroach on the expensive territory. The top 3 candidates are: NR111E, SC4524FSETRT, BD86120EFJ-E2.

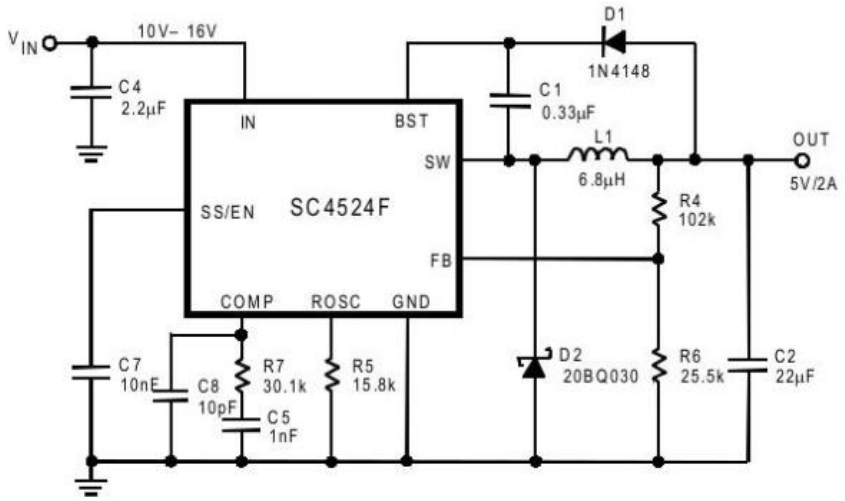


Figure 47: 12V to 5V Buck SC4524F Voltage Regulator Circuit

Using the voltage regulator SC4524F, Figure 47 shows a possible circuit that we can use to drop the 12V input from the battery down to the 5V output to power the different devices such as the Jetson Nano. Furthermore, after dropping the voltage down to 5V, we can add another SC4524F voltage regulator circuit after, to drop the 5V even further down to 3.3V for the other components that require it. This circuit can be found in Figure 48.

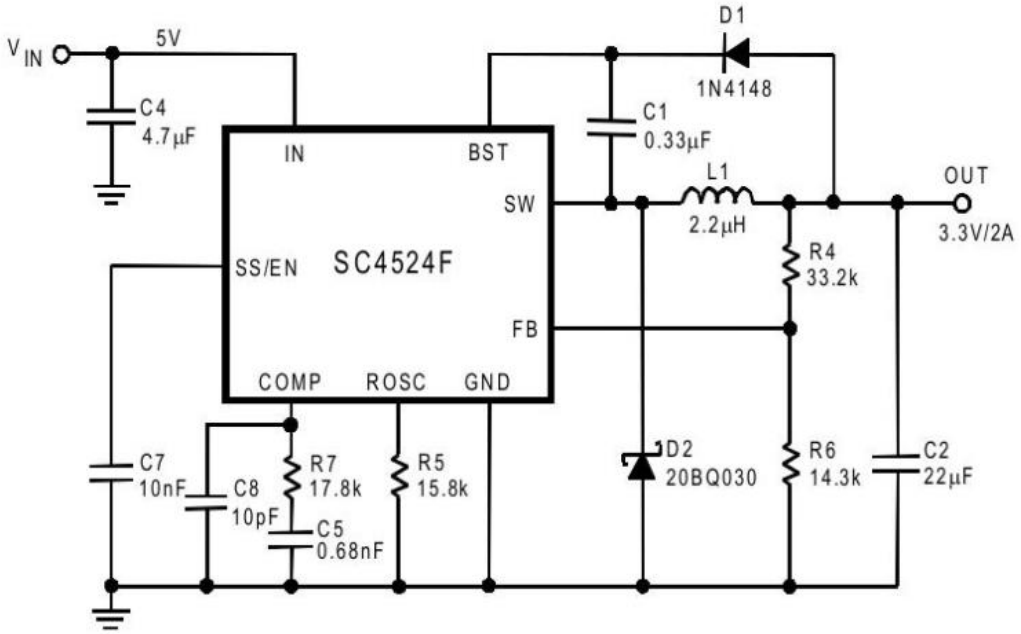
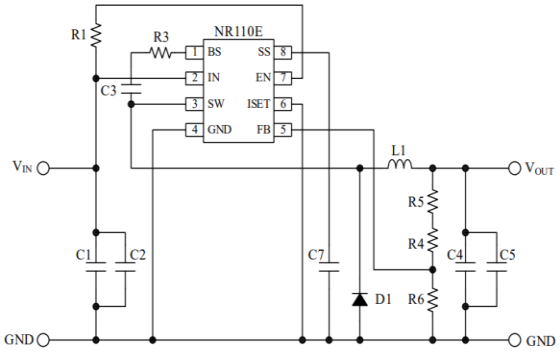


Figure 48: 5V to 3.3V Buck SC4524F Voltage Regulator Circuit

For the NR110E voltage regulator circuit, Figure 49 showcases the configuration for 5V output. According to the table, Vo is controlled by changing the R5 resistor.



Symbol	Ratings	Symbol	Ratings
C1	10 µF / 35 V	R1	510 kΩ
C2	10 µF / 35 V	R3	22 Ω
C3	0.1 µF	R4	18 kΩ
C4	22 µF / 16 V	R5	2.7 kΩ (Vo = 5.0 V)
C5	22 µF / 16 V	R6	3.9 kΩ
C7	0.1 µF	L1	10 µH
		D1	40 V, 5 A (Schottky diode)

Figure 49: 12V to 5V Buck NR110E Voltage Regulator Circuit

From the figures above, it is likely that we will be using the SC4524F voltage regulator made by the Semtech Corporation. While we may be using the SC4524F regulator, it may be a good idea to still get the top 3 candidates, and run testing on them and compare the results.

Once we have gathered the required components for the Buck Circuit in Figure 45, we can test the circuit using a breadboard, before physically making the circuit on

a PCB. During testing, we want to test to make sure the output voltage is 5V, and that the maximum current is 2A. This can be done by measuring with a DMM, and using a DC Electronic Load to vary the current. We also want to make sure the regulator does not have bad efficiency and thus does not heat up too much.

Table 15: Components Needed for Regulator Circuits

Component	Value	Quantity (for 1 board)
Capacitor	2.2µF	1
	0.33µF	2
	10nF	2
	10pF	2
	1nF	1
	22µF	2
	4.7µF	1
	0.68nF	1
Resistor	102k	1
	25.5k	1
	15.8k	2
	30.1k	1
	17.8k	1
	14.3k	1
	33.2k	1
Inductor	6.8µH	1
	2.2µH	1
Diode	1N4148	2

Zener Diode	20BQ030	2
SC4524F	N/A	2

The above table shows the materials needed to implement the circuits from Figures 31 and 31 onto a PCB. The table shows the minimum number of components to make just one board, so if we wanted to create several boards to test, more components would be required.

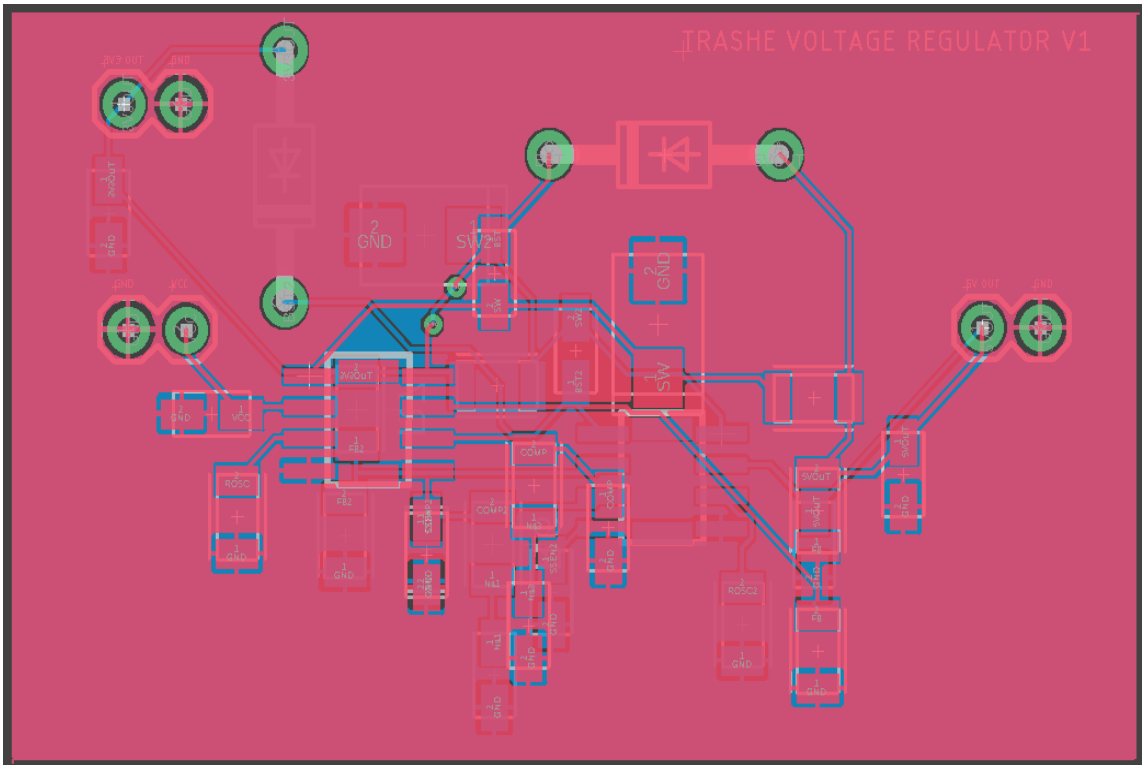


Figure 50: Voltage Regulator PCB

The PCB above is the voltage regulator design for Trash-E. The PCB includes both the buck converters for the 12V-5V step down and the 5V-3.3V step down converters. The 12V input from the battery is VCC+ on the left. The 5V output is on the right and the 3.3V output is top left. This PCB should be able to handle all the voltage regulation that we need done on the robot. If we need more output ports, we can add more headers later after testing.

6.2.9 Solar Panels

Table 16: Possible Solar Panels

Part #	Manufacturer	Voltage @ mpp (V)	PV Cell Type	Price/Unit ($)
SM500K12TF	ANYSOLAR Ltd	6.7	Monocrystalline	$6.26000
SP3-37	PowerFilm Inc.	3	?	$2.99000
10Pcs 5V 60mA Epoxy Solar Panel	SUNYIMA	5	Polycrystalline	$15.99/10
2 Pieces 2.5W 5V/500mAh Solar Panel	ALLPOWERS	5	Polycrystalline	$12.99/2

Table 16 shows the solar panels that we found that are not too expensive. Since the panels are not 12V, we can have 2 or 3 panels, depending on the Voltage at mpp, in series to create a 12V output. The SM500K12TF panels are monocrystalline, and claim to be highly efficient. We can test this following the Solar Panel Test Plan outlined in the next section. The SP3-37 panels are cheap per unit. We considered these cells because the spec sheet on the listing showed promising specs. However, the datasheet of these cells do not contain much useful information, and we believe that it would be best to stay away from the cells. The solar cells made by SUNYIMA are a possible candidate, because they come in a large quantity for a fair price. The only problem is that they can only supply up to 60mA at maximum output. This can be solved by adding more cells in parallel, but that may conflict with how much room we have on Trash-E to add cells. The solar cells made by ALLPOWERS are a good candidate because they can supply up to half an amp at maximum output.

Out of the above options, we believe that it is a good idea to get the SM500K12TF and the panels made by ALLPOWERS. These panels seem to have the best output for our case, and we can compare the two panels once we physically have them.

6.2.9.1 Solar Panel Test Plan

The test plan for the solar panels is to test the solar panels when they are receiving the maximum amount of sun they can receive, and when the panels are getting partial coverage.

1. Create a text fixture so the solar panel can get maximum coverage from the sun on a sunny day.
2. Connect solar panels to a DC electronic load, and have a voltage recording device such as a 34970A Data Acquisition / Data Logger Switch Unit.
3. When the sun is at its peak, and when there are no clouds, record the voltage and current from the solar panels over an hour, as that is how long we aim to have Trash-E running.
4. When the sun is not at its peak, or when there are partial clouds or obstructions between the sun and the panels, repeat step 3.
5. Take the readings from the Data Acquisition Unit and plot a current and voltage curve. With this, we can determine which panels are the best fit for us, and if they follow the datasheet that are provided.

6.2.10 PCB Design

Due to the package of our microcontroller (LQFP), we must make a printed circuit board (PCB) to use it. The plan for the PCB is to make a breakout-style board that has headers connected to the desired pins we want to use. An issue we ran into while selecting the pins was that a pin can have multiple functionalities, and the specified use is configured in software. This means that while the microcontroller can have a specified maximum amount of capabilities, that's not always the case depending on the amount of a specific feature the design requires. While optimizing the PCB for space and shortest traces, we tried to use pins 13 and 14 which are not only PWM signal generators, but are also UART pins as shown below in Table 17 and were the ones we are already using to communicate with the Jetson Nano.

Table 17: Conflicting Pin Functionalities

Pin Number	Pin Name	Description
13	PC7 U3Tx WT1CCP1	GPIO port C bit 7. UART module 3 transmit. 32/64-BIt Wide Timer 1 Capture/Compare/PWM1.

14	PC6 U3Rx WT1CCP0	GPIO port C bit 6. UART module 3 receive. 32/64-BIt Wide Timer 1 Capture/Compare/PW0.

Before designing the PCB we made a schematic with all the necessary parts and connections using Autodesk Fusion 360 as seen below in Figure 51. The selected components are shown in Table 18. We decided on the 1206 package for the slightly larger size and availability of components. Having the 1206 will make it a bit easier for us to solder the components by hand due to the larger pad sizes when compared to other packages like the 0805. Many basic components such as the capacitors and resistors are relatively cheap across different packages so price did not play a large role in this selection process.

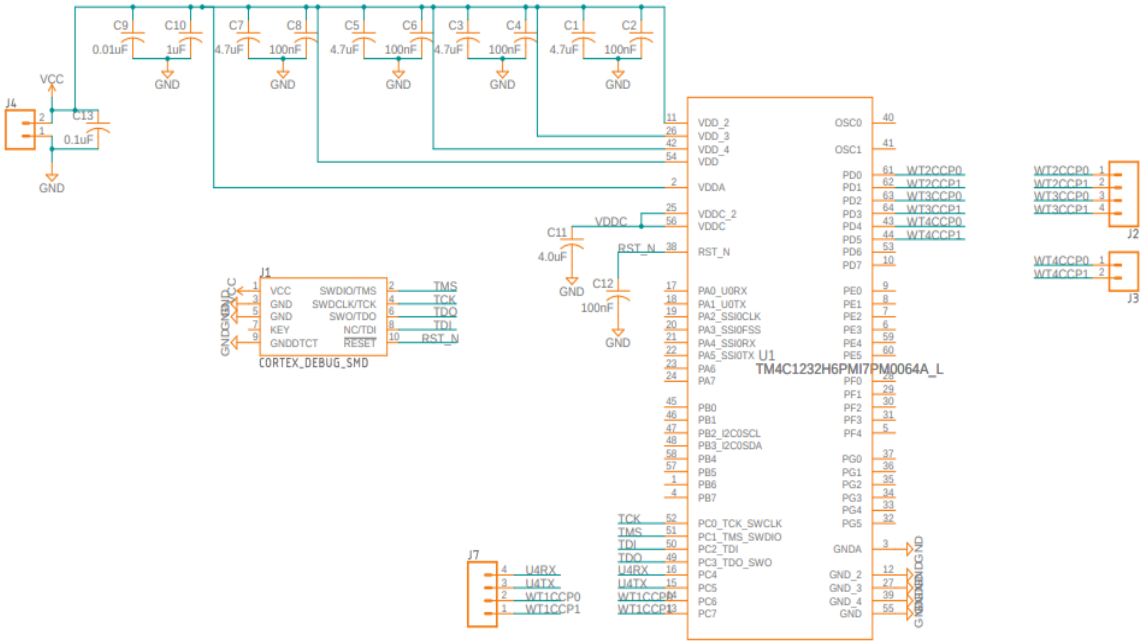


Figure 51: Microcontroller PCB Schematic

Table 18: Microcontroller Schematic Components

Schematic Part	Value	Part Number	Type
C1,C3,C5,C7	4.7uF	UMJ316BC7475KLHTE	Multilayer Ceramic
C2,C4,C6,C8,C12,C13	100nF	C1206C104K5RAC7867	Multilayer Ceramic

C9	0.01uF	C1206C103J3GECTU	Multilayer Ceramic
C10	1uF	C1206F105M5RACAUTO7210	Multilayer Ceramic
C11	4.0uF	C1206C395K3PACTU	Multilayer Ceramic
U1	-	TM4C1232H6PMI7	Microcontroller
J1	-	-	JTAG connector
J2	-	-	Header 4x2-pin Female
J3	-	-	Header 4-pin Female
J4	-	-	Header 2-pin Female
J5	-	-	Header 2-pin Female
J6	-	-	Header 4-pin Female

The datasheet indicated that decoupling capacitors are required to filter out high frequencies as well as stabilizing the supply voltage to the microcontroller when voltage dips occur due to changing load requirements. We opted for a design that minimizes space and maximizes routability. To do this we chose the pins we knew we would need to implement the basic peripherals as well as a few extra so we can further expand upon our design in the future with stretch goals. We have two pins dedicated to UART transmission between the microcontroller and Jetson Nano, as well as eight pins that can be used for GPIO or PWM purposes to allow for motor control or ultrasonic sensor trigger and feedback signals. Ground pins are available for each PWM pin for the connections to motors.

There are two PCB designs that can be sent to a manufacturing house. Design 1 as shown in Figure 36 is the initial design that is focused on minimizing the amount of layers as well as cost. Design 2 as shown in Figure 53 is focused on minimizing space and traces to keep the board compact. The major difference between these designs is that Design 2 has two copper ground pours, and the capacitors placed on the bottom. The copper pour increases the cost of the overall board since there are now two layers of copper, but it also reduces the amount of traces needed and

the routing is much simpler. As seen in Figure 52, the amount and length of traces is drastically longer, as well as the number of vias drilled into the board. Design 2, however, is much simpler and keeps the traces, especially between the capacitors and microcontroller, nice and concise. It is also worthy to note that Design 2 has the capacitors placed on the back to reduce the amount of vias needed for routing, as well as ground vias placed throughout the board to ensure every component is properly grounded to the copper pours. The microcontroller is placed in the middle of both designs since it has the most connections. This reduces the complexity of the board by keeping traces direct and not having to go roundabout ways to connect to their destination. Finally, four mounting holes are added to the corners to allow for easy attachment to the Trash-E's chassis. With there only being one voltage supplied to the board, this makes it easier to design as there's no worries about noise between nets. We considered adding the voltage regulators to this board as well but decided against it. It would be more beneficial to have the voltage regulators on their own boards so we can test their functionality easier by probing the inputs and outputs of the regulators themselves. This also provides easier placement of the voltage regulators on the chassis since different components need to be powered by the different voltages and they won't be near the microcontroller PCB.

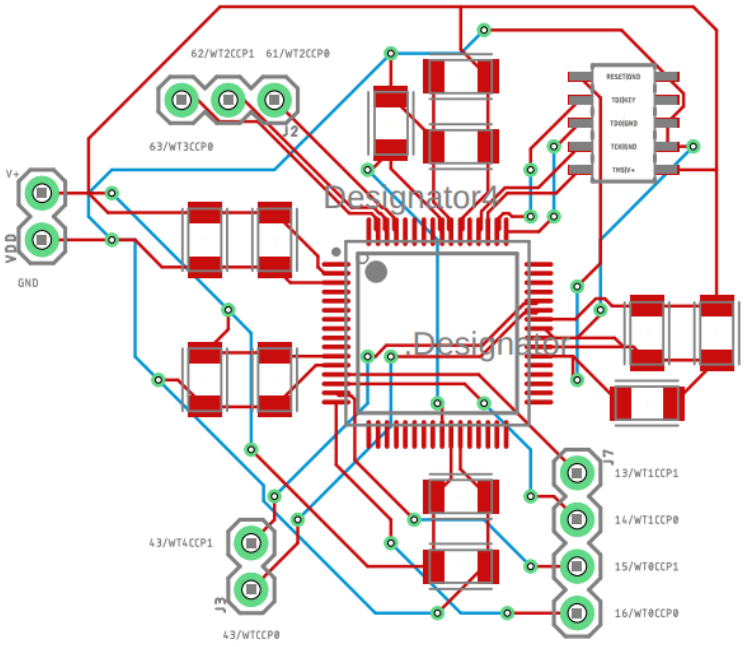


Figure 52: Design 1 PCB Layout

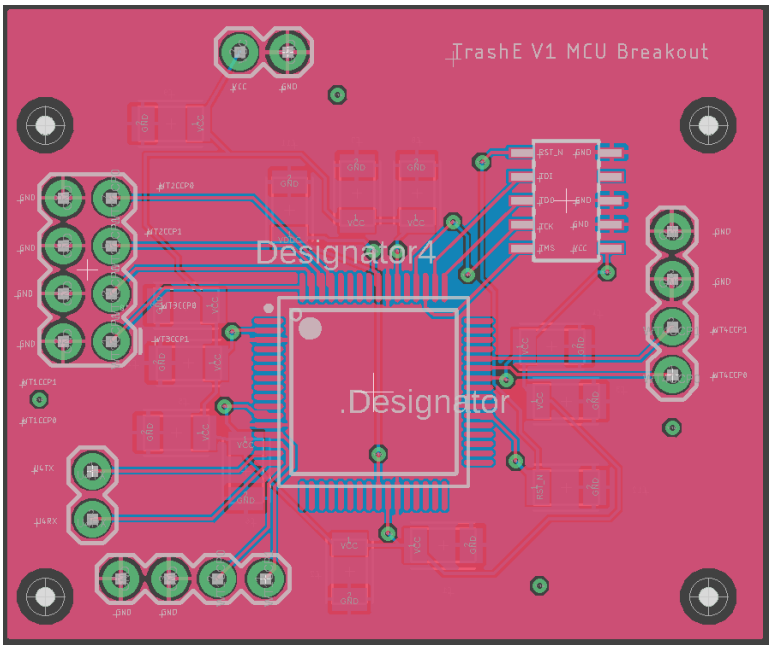


Figure 53: Design 2 PCB Layout

Table 19: PCB Manufacturing Costs

Manufacturing House	Design	Number of Boards	Price
JLCPCB	Breakout 2	5	$9.37
OSH Park	Breakout 2	3	$11.50
PCB Way	Breakout 2	5	$14.93

We uploaded the Gerber files for our PCB design to different PCB manufacturers' websites to get quotes on how much it would cost for our PCB to be made. After an online search to find a few reputable manufacturing houses, we decided on these three as candidates: JLCPCB, OSHPark, and PCBWay. JLCPCB and PCBWay are based in China, whereas OSHPark is based in the United States. Being based in the US is nice for us because it can help save on shipping since the boards don't need to be shipped across the sea. For the base material of our board we will be choosing FR-4. Aluminum has better heat dissipation and thermal transfer than FR-4, but it is also more expensive and won't be necessary for our PCB with the few components we are putting on the board. Choosing aluminum also restricts other decisions for our board, like the minimum thickness of the board or the amount of layers to be one layer maximum. We know our board needs two layers so aluminum is not an option based on that requirement. The delivery format will be a single PCB where they only manufacture the design how it is and don't add components onto it. We want this option since we will be soldering the components on ourselves. Doing the soldering ourselves will decrease the cost

and also increase our skills with dealing with electrical components and PCBs. The outer copper weight will remain at 1oz since it will be sufficient for our ground planes, as well as the 2oz option being much more expensive to have manufactured. The default, also the cheapest, options will be chosen for color, silkscreen, thickness, gold fingers, probe testing, and castellated holes.

Manufacturing houses have different requirements for the minimum amount of boards that can be printed in a single order. Since we are not mass producing these and don't want to spend all of our budget on just the boards, being able to order small batches is necessary. We want multiple boards to prototype, and also to ensure we have extras in case one gets damaged while we are soldering. JLCPCB allows a minimum of five boards to be printed. PCBWay also has the same minimum requirement. OSHPark, however, has a minimum requirement of three boards. Being able to have three boards is enticing to help keep costs down since more materials won't be used to manufacture more boards, specifically the copper.

Speed of the manufacturing and delivery of our PCBs is also crucial for Trash-E. Houses from China will obviously introduce longer shipping times and cost more for the same time period shipping than a US based house. JLCPCB offers 12-20 business day shipping as their cheapest and slowest option and PCBWay offers 6-16 business day shipping for theirs. OSHPark has free, five business day shipping since the company is in the US. We will be utilizing OSHPark for our PCB manufacturing needs. We might be receiving less boards and the price per board is higher than JLCPCB, but the turnaround time of the manufacturing and shipping as well as the higher quality, lead-free boards make it worth the extra money for the detail-oriented craftsmanship.

6.2.11 Manufactured PCBs

Figures 54 and 55 show the PCBs of the Trash-E Breakout Board. They were ordered from OSHPark and took a turnaround time of two weeks from the initial placement of the order to the boards being shipped to the final address. Overall, the boards are good quality and do not bend. There is complete separation between pads and the contacts are properly grounded.

Figure 54: Top Side of Trash-E MCU Breakout

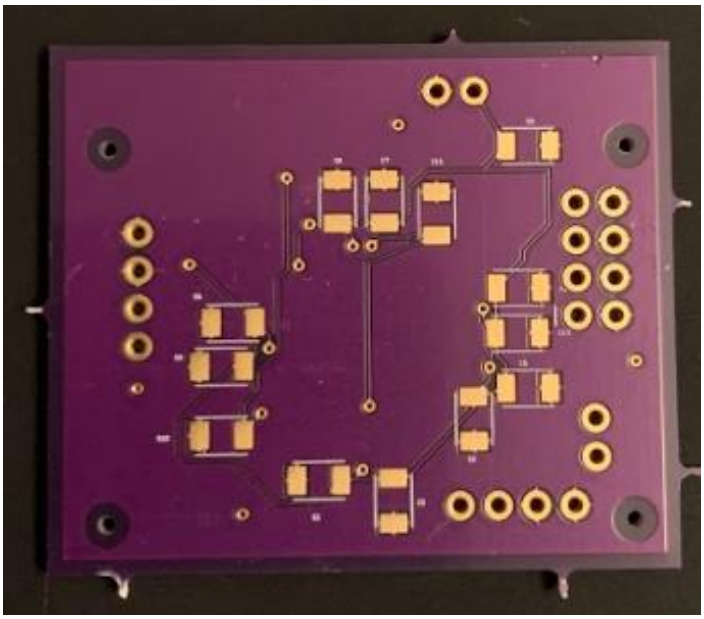


Figure 55: Bottom Side of Trash-E MCU Breakout

6.2.12 Determining When the Bin is Full

Trash-E will continuously run until its power shuts off or its trash bin is full. Therefore, we need a way of determining that the trash bin on Trash-E is full and we can end the execution of the program.

We will use an ultrasonic sensor to determine whether the bin is full or not. This sensor will be placed near the top the of the inside of the trash bin on one of its sides. The sensor will be constantly reading the value of the distance from itself to the other side of the bin. Every time that Trash-E picks up trash to throw into its bin, the sensor will wait a few seconds so that it does not falsely detect a full bin when the object passes it as it falls into the bin. Once those few seconds have passed, the sensor will sample the reading and determine whether its distance is within the threshold of the other side. In other words, if the distance from the sensor and the other side of the bin has not changed significantly, then that means that the bin is not full. Once the bin has been filled to a certain capacity, the reading that the sensor samples will no longer be within the threshold set for the distance between the sensor and the other side of the bin. It will be less and that means that there is an object in between and that the bin has reached a capacity that we determine as full. Once the sensor has determined that the bin is full, then Trash-E should stop searching for trash and adding trash to its bin. This essentially will stop Trash-E's program execution until it is started up again with a bin that is no longer full.

6.3 Bill of Materials (BOM)

Table 20: Bill of Materials

Type	Part Name	Description	QTY	Unit Cost	Total Cost*
Wheels	Pololu Wheel for Standard Servo	Wheel for robot to move.	2.00	$4.75	$9.50
Motor Driver	A4988 Stepper Motor Driver Carrier	Drive stepper motors.	5.00	$5.47	$27.35
Stepper Motor	Twotrees Nema 17	Move the arm (Design 1)	1.00	$9.99	$9.99
Servos	154	Move the wheels	2.00	$11.95	$23.90
Micro Servo	SER0006	Servo to open and close gripper on arm.	1.00	$3.62	$3.62
Ultrasonic Sensor	SainSmart HC-SR04	Sensor to detect cup distance from gripper.	1.00	$4.45	$4.45
MCU	TM4C1232H6PMI7	Microcontroller for peripherals	1.00	$7.14	$7.14
Jetson Nano	2GB Mini-Computer	For Computer Vision	1.00	$59.00	$59.00
Camera	Logitech C270	For CV	1.00	$25.00	$25.00
Lidar Rangefinder	MakerFocus YDLIDAR X2L	For SLAM	1.00	$69.99	69.99

Chassis/ Bucket	3D Printed	Robot Chassis	1.00	3D Printed	3D Printed
Arm	3D Printed	Arm to pick up cups	1.00	3D Printed	3D Printed
Gripper	3D Printed	To grip cups	1.00	3D Printed	3D Printed

7.0 Prototyping, Build, Test, Evaluation Plans

7.1 Prototyping

7.1.1 Block Diagram Explanation

The hardware composition of Trash-E is visualized on the block diagram below in Figure 56. The block diagram contains the overall grasp of the project. This gives a development path as well as a visual representation of how each part connects to each other.

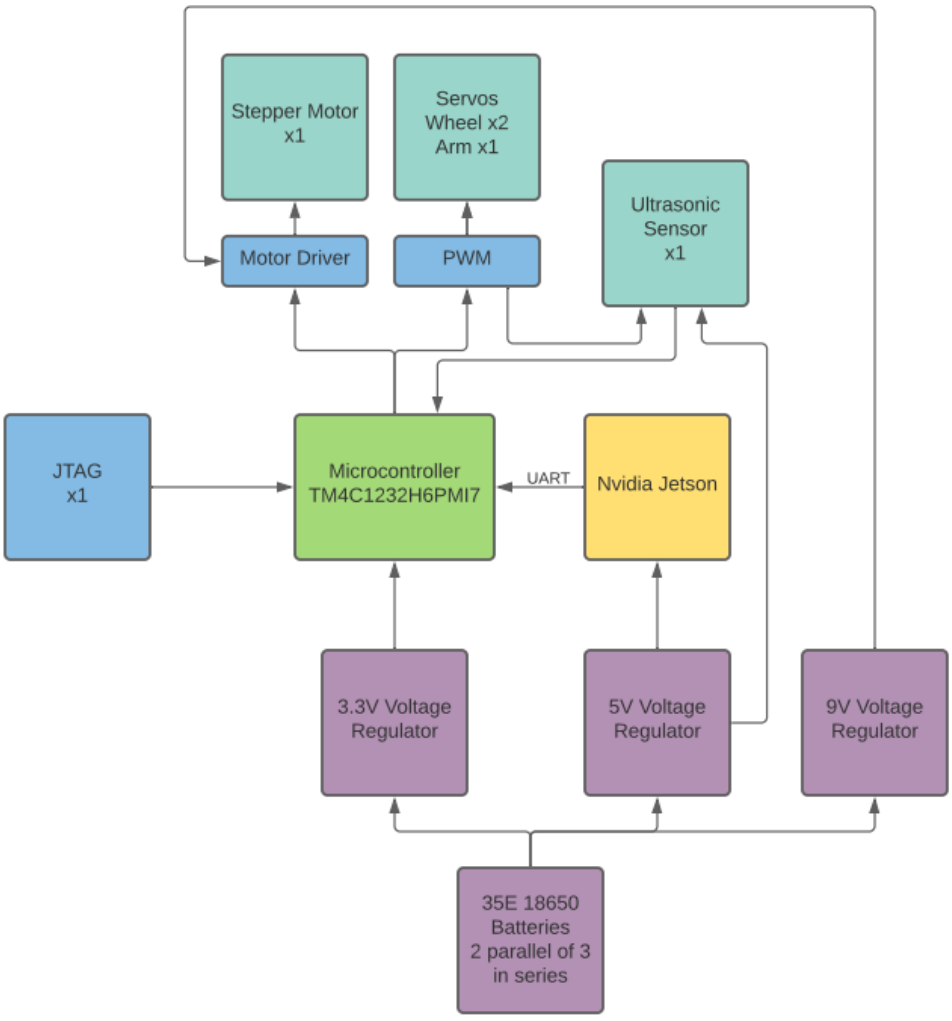


Figure 56: Trash-E Hardware Block Diagram

7.1.1.1 Electrical Components

Starting from the bottom of Figure 38, the power supply designed with constraints and standards in mind should be grounded and have no exposed circuitry. It should also be able to satisfy all power needs of one stepper, two continuous servos, one regular servo,a microcontroller, an Nvidia Jetson 2GB, as well as all the corrisponding peripheral components. To ensure everything receives the specified voltage and wattage to perform optimally a voltage regulator for two separate blocks of the project as they will have separate voltage requirements.

7.2 Computer Vision Testing

One of the most important aspects of Trash-E is the object detection component. Our robot would not do anything at all if our object detection software is not working or working optimally. For our computer vision object detection software we want to test a few aspects before even proceeding to the microcontroller software. Our object detection software should be able to accurately detect the trash objects that we train it to detect and should ignore any other object. It should be able to detect objects regardless of orientation and the surrounding environmental factors such as lighting and background noise. The software should be able to select the closest object of interest by the size of its bounding box. The software should be able to correctly track where the closest object is on the image and use the coordinates from its bounding box to calculate the correct result to send over to the microcontroller. The performance of the object detection should be fast enough that we can accurately detect objects while moving.

7.2.1 Testing Object Detection

The first step to successful object detection is being able to detect the object. For each class item of trash that we train our model to detect, we want to test for accurate detection meaning no false positives or negatives as well as accurate detection in different orientations, lighting, and backgrounds. The object should be detected from orientations horizontally and vertically. For example, we should detect a cup that is standing upright, sideways, flipped, or even rotated. We expect that we cannot detect objects in darkness but should function normally in natural and artificial light. Different color backgrounds and noisy backgrounds should not affect detection. We will be testing object detection before on the desktop instead of on the Jetson Nano. The reason is that it will be a lot more convenient and efficient to test on a desktop using a camera connected to it rather than the Jetson Nano and the model will perform exactly the same on the Jetson Nano. Successful detection of these objects means that we can move forward to sorting these detections and moving on in our object detection process.

Procedure:

1. Run the object detection model while using the camera feed as the image input.

2. Check that the video feed is live in the window.
3. Check that the frame rate performance of the model is more than 10 frames per second.
4. Check that no objects are being currently detected.
5. Place an unknown object in camera view and check that it is not detected.
6. For each trash object we have trained to detect, repeat steps 3 to 5.
7. In artificial light, place the object in view of the camera and do steps 7 to 10.
8. In natural light, place the object in view of the camera and do steps 7 to 10.
9. Check that the object is correctly identified and has been labeled correctly.
10. Check that the object is correctly identified in multiple orientations (rotations by 45 degrees, flipped, sideways).
11. Check that the object is correctly detected with a solid background as well as a noisy background.
12. Ensure there are no ghost objects or false positives being detected.

7.2.2 Testing Object Selection

Upon successful detection of trash, our algorithm should sort the detections and their respective bounding box coordinates. These detections should be sorted by decreasing area. This aspect is essential to Trash-E being able to decide which object it should head towards out of all objects in the camera view. During this testing we will use a plastic cup as our object.

Procedure:

1. Run the model and use the camera as the input.
2. Check that the program window is showing a live camera feed.
3. Check that the object detection is working by placing a plastic cup in the view.
4. Grab at least four plastic cups and place them in view at different distances away from the camera view.
5. Check that the program window has placed a circle outline on the closest object.
6. Repeat steps 4 - 6 as many times as needed.

7.2.3 Testing Object Tracking

Once the object detection model has successfully detected and selected the object that is closest, the algorithm should correctly calculate the position of this object relative to the image center and determine the direction that the robot should turn in order to make it face straight at the object. In this testing, we will only be checking for correct results prior to serial communication over UART. This test will only focus on the computer vision aspect of the software. During this testing we will use a plastic cup as our object.

Procedure:

1. Run the model and use the camera as the input.
2. Check that the program window is showing a live camera feed.
3. Check that the object detection is working by placing a plastic cup in the view.
4. With no objects in view of the camera, check that the displacement calculation is a null value and the value to be sent via UART is 0.
5. Use valid objects for the following steps.
6. Place one cup on the image center.
7. Check that the displacement calculation is zero and the value to be sent via UART is 1.
8. Place one cup to the left of the image center.
9. Check that the displacement calculation is negative and the value to be sent via UART is 2.
10. Place one cup to the right of the image center.
11. Check that the displacement calculation is positive and the value to be sent via UART is 3.

7.2.4 SLAM Test

The objective of this test is to ensure the SLAM algorithm can generate an accurate map of an unknown environment.

Procedure:

1. Connect the lidar sensor to the Jetson Nano GPIO pins.
2. Connect the 5V power supply to the lidar sensor.
3. Place various obstacles around the room. Ensure there are obstacles on every side of the lidar sensor to test the 360° rotation of the sensor.
4. Draw a map of the current environment, labeling walls and drawing the shapes of obstacles the algorithm will detect.
5. Transfer the SLAM algorithm onto the Jetson Nano, provide a power source and turn it on.
6. Wait for the algorithm to generate a map of the area.
7. Compare the generated map to the map that was drawn by the tester and ensure they are identical.

7.3 Hardware Testing Plans

Before we can build Trash-E, we need to test the individual aspects our design will achieve to ensure it will work overall. Testing will be done at the Senior Design lab in Engineering 1 on UCF campus or at a group member's residence. Location will be determined by each specific test and the equipment required by said test. Each test will have procedural steps so that the test can be replicated by anyone given they have the required equipment.

Equipment:
The following equipment will be required to complete all tests below:

- Multimeter
- DC Power Supply
- Oscilloscope or Discovery Kit
- 12V battery configuration
- Voltage Regulator PCB
- TM4C1232H6PMI7 Design 2 PCB
- Power Rail Breakout Board

7.3.1 Voltage Regulator Testing

The objective of this test is to ensure the batteries can power the components at the correct voltages using the voltage regulator PCB we had manufactured. This also checks to make sure the soldering is done correctly.

Procedure:

1. Check all solder connections through a microscope to ensure all components are secured and connected to the board, and that there is no solder bridging between pins.
2. Connect a jumper cable to the 5V output header “5V OUT” pin.
3. Connect a jumper cable to the 5V output header “GND” pin.
4. Attach the positive multimeter probe to the “5V OUT” jumper cable.
5. Attach the negative multimeter probe to the “GND” jumper cable.
6. Connect a jumper cable to the input header “VCC” pin.
7. Connect a jumper cable to the input header “GND” pin.
8. Attach the positive DC power supply alligator clip to the “VCC” jumper cable.
9. Attach the negative DC power supply alligator clip to the “GND” jumper cable.
10. Sample the voltages for ten seconds at each input voltage: 8V, 9V, 10V, 11V, 12V.
11. Ensure the multimeter is reading 5V +/- 0.2V at 10V and higher.
12. Turn off the power supply.
13. Connect a jumper cable to the 3V3 output header “3V3 OUT” pin.
14. Connect a jumper cable to the 3V3 output header “GND” pin.
15. Attach the positive multimeter probe to the “3V3 OUT” jumper cable.
16. Attach the negative multimeter probe to the “GND” jumper cable.
17. Sample the voltages for ten seconds at each input voltage: 8V, 9V, 10V, 11V, 12V.
18. Ensure the multimeter is reading 3.3V +/- 0.2V at 10V and higher.
19. Repeat steps 2-18 except change the DC power supply for the battery configuration that will be used with the robot.

7.3.2 Powering of the Microcontroller

The objective of this test is to verify that the microcontroller is receiving power and all soldering has been done correctly.

Procedure:

1. Check all solder connections through a microscope to ensure all components are secured and connected to the board, and that there is no solder bridging between pins.
2. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 35 in this document.
3. Flash the program “Hello.c” onto the microcontroller.
4. Connect a jumper cable to the input header “VCC” pin.
5. Connect a jumper cable to the input header “GND” pin.
6. Connect a jumper cable to the “WT4CCP1” pin.
7. Connect a jumper cable to a nearby “GND” pin.
8. Connect the probe of an oscilloscope to the “WT4CCP1” pin.
9. Connect the corresponding ground probe to the nearby “GND” pin.
10. Connect a DC power supply to the input header “VCC” and “GND” pin.
11. Turn on the DC power supply and set the voltage to 3.3V.
12. Verify the oscilloscope shows a square signal with a 50% duty cycle.

7.3.3 Powering a Servo Motor

The objective of this test is to ensure we can generate a PWM and power any servo motor that will be hooked up.

Procedure:

1. Check all solder connections through a microscope to ensure all components are secured and connected to the board, and that there is no solder bridging between pins.
2. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 35 in this document.
3. Flash the program “Hello.c” onto the microcontroller.
4. Connect jumper cables to both the 5V and 3.3V and their respective ground pins on the voltage regulator board.
5. Connect the 3.3V output of the voltage regulator to the input header “VCC” pin on the microcontroller PCB.
6. Connect the 3.3V ground cable of the voltage regulator to the input header “GND” pin on the microcontroller PCB.
7. Connect a jumper cable to the “WT4CCP1” pin.
8. Connect a jumper cable to a nearby “GND” pin.
9. Connect the 5V output of the voltage regulator to the positive power rail on the breakout board.
10. Connect the 5V ground pin of the voltage regulator to the negative power rail on the breakout board.

11. Connect the power connection of the servo motor to the 5V power rail.
12. Connect the signal connection of the servo motor to the “WT4CCP1” pin.
13. Connect the ground connection of the servo motor to the ground power rail.
14. Connect the DC power supply to the “VCC” and “GND” pins of the voltage regulator.
15. Turn on the DC power supply to 12V.
16. Observe that the servo motor is alternating between spinning one way 180° and the other way 180°.

7.3.4 Powering a Stepper Motor

The objective of this test is to ensure we can generate a PWM for the stepper motor and control it with the motor driver and microcontroller.

Procedure:

1. Check all solder connections through a microscope to ensure all components are secured and connected to the board, and that there is no solder bridging between pins.
2. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 35 in this document.
3. Flash the program “HelloStepper.c” onto the microcontroller.
4. Connect jumper cables to both the 5V and 3.3V output and their respective ground pins on the voltage regulator board.
5. Connect the 3.3V output of the voltage regulator to the 3.3V power rail on the power rail breakout board then to the input header “VCC” pin on the microcontroller PCB.
6. Connect the 3.3V ground cable of the voltage regulator to the ground power rail on the power rail breakout board then to the input header “GND” pin on the microcontroller PCB.
7. Connect a jumper cable to the “WT4CCP1” pin.
8. Connect a jumper cable to a nearby “GND” pin.
9. Connect a jumper cable to the “WT4CCP0” pin.
10. Connect a jumper cable to a nearby “GND” pin.
11. Connect the positive terminal of the DC power supply to one of the positive terminals of the power rail breakout board and the negative terminal to the ground rail.
12. From the positive terminal on the power rail breakout board, make one connection with a jumper cable to the “VCC” input on the voltage regulator and another to the “VMOT” pin on the motor driver as well as their corresponding ground connections to the power rail breakout board.
13. Connect the “WT4CCP0” and “WT4CCP1” pins to “STEP” and “DIR” on the motor driver, respectively.
14. Connect the 3.3V and ground pin from the power rail breakout board to “VDD” and the ground power rail to “GND” on the breakout board, respectively.
15. Turn on the power supply and set the voltage to 12V.

16. Observe that the stepper motor is alternating between spinning one way 180° and the other way 180°.

7.3.5 Ultrasonic Sensor Testing

The objective of this test is to ensure we can get a reading from the ultrasonic sensor with different distances.

Procedure:

1. Check all solder connections through a microscope to ensure all components are secured and connected to the board, and that there is no solder bridging between pins.
2. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 35 in this document.
3. Flash the program “HelloUltrasonic.c” onto the microcontroller.
4. Connect jumper cables to both the 5V and 3.3V output and their respective ground pins on the voltage regulator board.
5. Connect the 3.3V output of the voltage regulator to the 3.3V power rail on the power rail breakout board then to the input header “VCC” pin on the microcontroller PCB.
6. Connect the 3.3V ground cable of the voltage regulator to the ground power rail on the power rail breakout board then to the input header “GND” pin on the microcontroller PCB.
7. Connect the 5V output of the voltage regulator to the 5V power rail on the power rail breakout board then to the input header “VCC” pin on the ultrasonic sensor.
8. Connect the 5V ground cable of the voltage regulator to the ground power rail on the power rail breakout board then to the input header “GND” pin on the ultrasonic sensor.
9. Connect the “WT4CCP0” and “WT4CCP1” pins to “Trigger” and “Echo” on the motor driver, respectively.
10. Add an LED in series with the “Echo” pin.
11. Connect the DC power supply to the input header “VCC” and “GND” pin on the voltage regulator.
12. Turn on the power supply and set the voltage to 12V.
13. Move things closer and further away from the sensor and view the LED staying illuminated for longer intervals when the object is further away.

7.4 Evaluation

After component testing, building, and software has been completed, the following tests will be run to evaluate Trash-E and confirm it works as intended.

7.4.1 Robot Movement Testing

The objective of this test is to ensure the robot can accomplish all types of required movement: forward, backward, turn left, turn right, and spin. Before starting, ensure the electrical components are hooked up correctly according to Figure 57.

Procedure:

1. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 56 in this document.
2. Flash the program “TestMovement.c” onto the microcontroller.
3. Connect the positive jumper cable of the battery to the “VCC” pin on the voltage regulator, and their corresponding ground pins.
4. Observe the robot perform the movements in this order:
    1. Move forward.
    2. Move backward.
    3. Turn left.
    4. Recenter.
    5. Turn right.
    6. Recenter.
    7. Spin 360°.

7.4.2 Collecting Trash Testing

The objective of this test is to ensure the robot can pick up trash in multiple different orientations. Five different trash orientations will be tested. Before starting, ensure the electrical components are hooked up correctly according to Figure 57.

Procedure:

1. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 56 in this document.
2. Flash the program “TestGrabbing.c” onto the microcontroller.
3. Connect the positive jumper cable of the battery to the “VCC” pin on the voltage regulator, and their corresponding ground pins.
4. Place a cup one inch away from the base of the gripper with the mouth of the cup facing up.
5. Observe the robot pick up the cup, raise it to the bucket on its back, drop it in, and move the arm back to starting position.
6. Repeat steps 4 and 5 with the following cup configurations:
    1. Mouth of the cup facing down.
    2. Cup on its side, mouth facing left.
    3. Cup on its side, mouth facing the robot.
    4. Cup on its side, mouth facing 45° (in between facing left and facing the robot).

7.4.3 Idle State Testing

The objective of this test is to ensure the robot will follow the path-planning algorithm until a cup is detected. Before starting, ensure the electrical components are hooked up correctly according to Figure 57.

Procedure:

1. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 56 in this document.
2. Flash the program “TestIdle.c” onto the microcontroller.
3. Connect the positive jumper cable of the battery to the “VCC” pin on the voltage regulator, and their corresponding ground pins.
4. Put a cup in an arbitrary place on the ground in any configuration.
5. Observe the robot detect the cup once it is in frame and collect it into the bin.

7.4.4 Multiple Cup Testing

The objective of this test is to ensure the robot can handle scenarios where there is more than one cup present. Before starting, ensure the electrical components are hooked up correctly according to Figure 57.

Procedure:

1. Connect the DAOKI ST-Link V2 to the JTAG connector on the board using the datasheet and Figure 56 in this document.
2. Flash the program “main.c” onto the microcontroller.
3. Place two cups in the frame of the camera that are both equally close to the robot.
4. Connect the positive jumper cable of the battery to the “VCC” pin on the voltage regulator, and their corresponding ground pins.
5. Observe the robot pick up one of the cups, then the other.
6. Repeat steps 3 through 5 with one cup closer than the other.
7. Repeat steps 3 through 5 with both cups out of the frame and equally close to the robot.
8. Repeat steps 3 through 5 with both cups out of the frame but with one cup closer than the other.

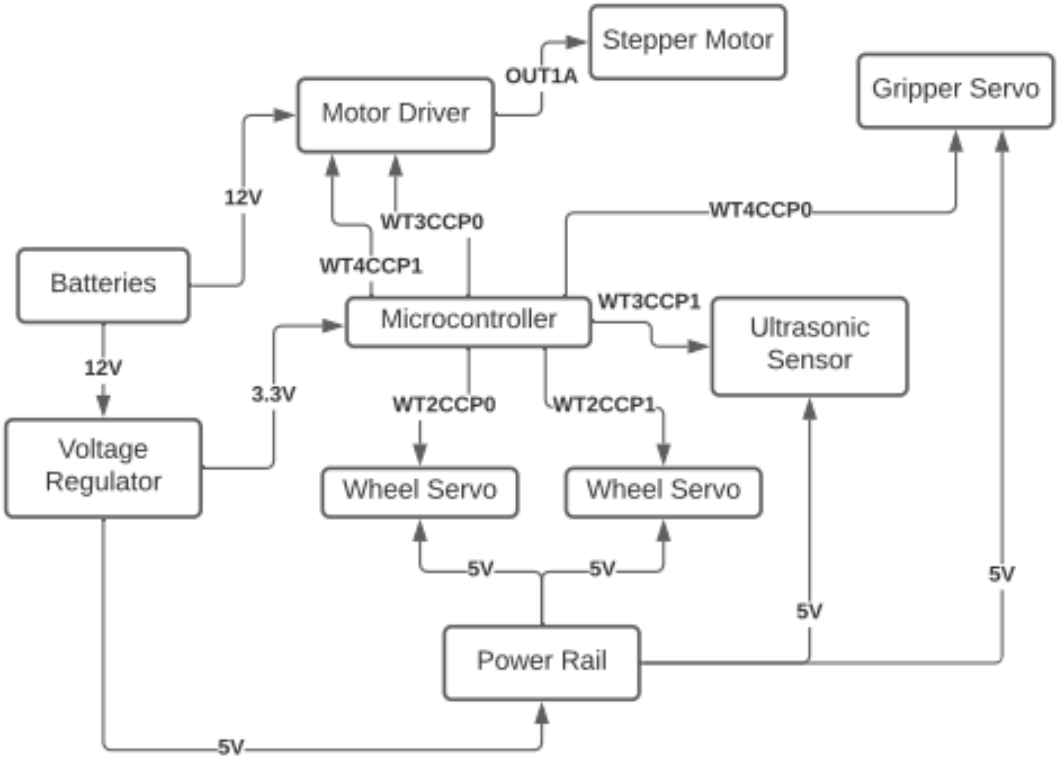


Figure 57: Electrical Connection Layout

7.5 Hardware Component Testing

7.5.1 Voltage Regulator Prototyping

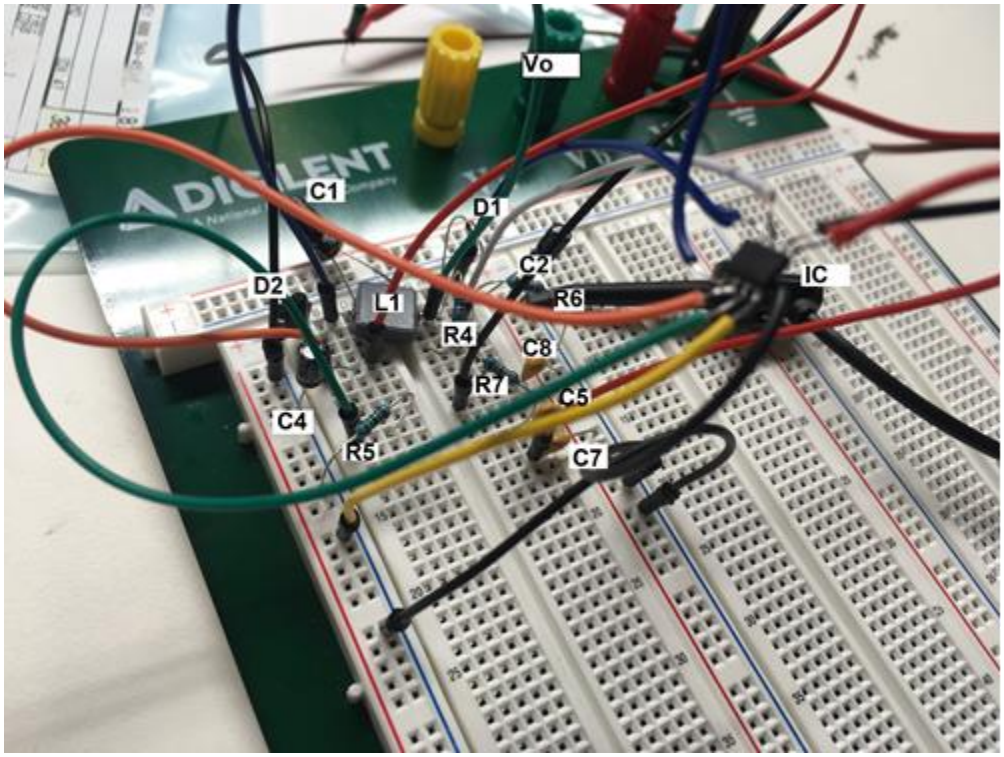


Figure 58: 12-5V Voltage Regulator Breadboard

Figure 59: 12-5V Voltage Regulator Breadboard

Figure 58 showcases the 12-5V voltage regulator that we have designed for the robot. Figure 59 shows the output of the voltage regulator at 4.699V. This is because while we were waiting for the specific resistor and capacitor values to come in, we used common resistor and capacitor values that are close to the values we want. Once we have the parts, we should be getting 5V output. If necessary, we will do tuning to the circuit to get the 5V output. The circuit above uses the SC4524F Integrated Circuit Voltage Regulator that we chose.
Table 21 shows the components that are to be used once the actual components have come in. In the meantime, the part numbers for the capacitors and resistors are omitted, as the current values are different. Once the new components arrive, the part numbers for each component will be updated.

Table 21: Components used in breadboard testing

Component Reference	Component Type	Component Value	Part Number
C1	Capacitor	0.33uF	-
C2		22uF	-
C4		2.2uF	-
C5		c5uF	-
C7		10nF	-
C8		10pF	-
R4	Resistor	102kΩ	56-MRS25000C1023FCT00CT-ND
R5			
R6			
R7		15.8kΩ	PPC15.8KYCT-ND
		25.5kΩ	RNF14FTD25K5CT-ND
		30.1kΩ	PPC30.1KZCT-ND
L1	Inductor	6.8uH	
D1	Diode	-	1N4148
D2		-	20BQ030
IC1	Integrated Circuit Voltage Regulator	-	SC4524FSETRT

The circuit must be able to hold a constant voltage of 5V when the input varies, from 10V to 14V, in case the battery pack has a fluctuation that may cause it to change. Voltages were varied from the input with the power supply from 10V to 20V. The results are in Table 22. From the table, we can see that the voltage difference between the input voltage at 20 V and 10 V are 0.2 V. Thus, the voltage regulator works for our use case. In Table 23 the output voltage differs by 0.3 V.

Table 22: Input and Output Voltage of 12 - 5 V Step Down Regulator

Input Voltage	Output Voltage
20 V	5.5 V
18 V	5.4 V
16 V	5.4 V
14 V	5.3 V
12 V	5.3 V
10 V	5.3 V

We are concerned that the current of the regulator may not be high enough for the autonomous robot, so we are considering using regulators with higher current capabilities. Further testing will be required once we have gathered all the components to the robot such as all the motors, sensors, and microcontrollers.

Table 23: Input and Output Voltage of 5 - 3.3 V Step Down Regulator

Input Voltage	Output Voltage
20 V	3.6 V
18 V	3.6 V
16 V	3.5 V
14 V	3.5 V
12 V	3.5 V
10 V	3.5 V
8 V	3.4 V
6 V	3.3 V
5 V	3.3 V

7.5.2 Ultrasonic Sensor Testing

This test utilizes the TI Evaluation Kit EK-TM4C123GXL since we were unable to complete the building of the PCB due to shipping delays from the PCB manufacturer. The microcontroller on the Evaluation Kit is the same microcontroller we will use on the PCB so it is an accurate representation of the environment the ultrasonic sensor will be powered by.

To determine the distance of the object from the sensor, the following equation is used

$$Distance = \frac{\left((High\ Level\ Duration) * 340\frac{m}{s}\right)}{2}$$

Based on this equation, the shorter the high pulse is from the ultrasonic sensor, the closer the object is to the sensor. Table X below compares the different values of the ultrasonic sensor output pulse width between the set distances we chose to test at. Since we want the ultrasonic sensor to be used to stop the robot when the trash is close to the arm and gripper, we chose a maximum of two feet (60 centimeters) and a minimum distance of two inches (5 centimeters). This will give us a realistic use case for the ultrasonic sensor when it is attached to the arm.

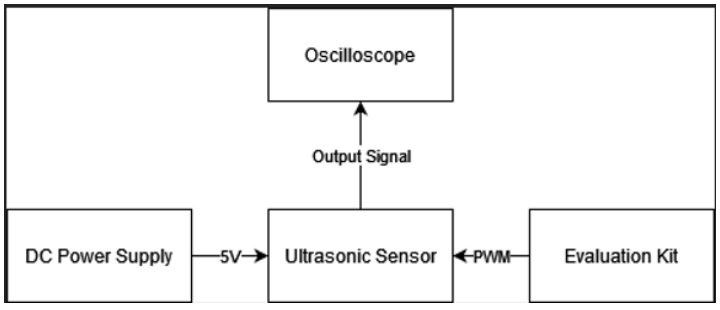


Figure 60: Test Setup for Ultrasonic Sensor

Figure 60 depicts the setup for this test. Code was written on the evaluation kit to continuously generate a PWM at 12kHz with a 50% duty cycle. This signal was sent to the trigger pin of the ultrasonic sensor which activates the ultrasonic waves to be emitted for distance detection. The ultrasonic sensor is also being powered by a DC power supply set to 5V. The output was viewed using an oscilloscope to check the length of the returning square wave.

Table 24: Ultrasonic Sensor Testing Results

Distance From Sensor (cm)	Input Duty Cycle	Frequency (kHz)	Positive Sensor Output Duration (ms)	Measured Distance (cm)
60	50%	12	3.08	52.36
30	50%	12	1.6	27.2
15	50%	12	0.880	14.96
5	50%	12	0.360	6.12

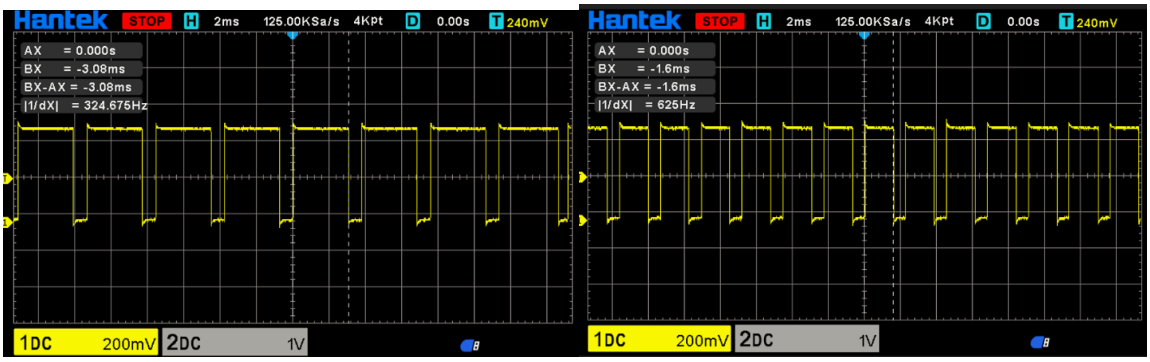


Figure 61: 60cm Output (Left) and 30cm Output (Right)

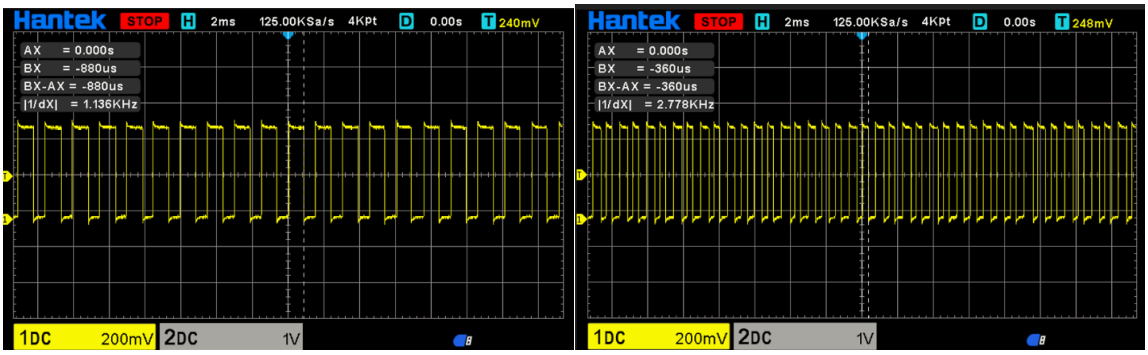


Figure 62: 15cm Output (Left) and 5cm Output (Right)

While an object is further away, it is not as accurate as can be seen with the distance of 60 centimeters. The measurements get more accurate as the object gets closer which is good for our use case. When we read that the ultrasonic sensor on the base of the arm is within two inches, we will want to stop the robot

to allow for picking up the trash. The inaccuracy of the further distances is negligible for our use case since the closer distance accuracies are good.

8.0 Administrative Content

8.1 Milestones

For the fall semester we have established milestones for the project. This semester will mainly be focused on research, documentation, and design as shown in table 20.

Fall 2021

Table 25: Fall Milestones

Week	Date	Milestone
1	8/23 - 8/29	• ~~Group Formation~~
2	8/30 - 9/5	• ~~Brainstorm Projects~~ • ~~Choose Project~~ • ~~Senior Design Bootcamp~~
3	9/6 - 9/12	• ~~Determine Project Requirements~~ • ~~Discuss Project Budget~~ • ~~Divide Project Block Diagram~~
4	9/13 - 9/19	• ~~Divide and Conquer 1.0~~
5	9/20 - 9/26	• ~~Decide Primary and Secondary Features~~ • ~~Revise Project~~
6	9/27 - 10/3	• ~~Divide and Conquer 2.0~~
7-12	10/4 - 11/14	• ~~60 Page Draft~~ • ~~Research and order Microcontrollers and other parts~~ • ~~Research Software~~ • ~~Begin PCB Design~~ • ~~Decide Pre-built or~~ • ~~Custom Chassis~~
13	11/15 - 11/21	• ~~100 Page Draft~~
14-16	11/22 - 12/12	• Final Submission

Spring 2022

As the spring semester approaches and more design specifics are fleshed out, the time frame will be determined. Table 21 below shows a general outline for milestones of the semester.

Table 26: Spring Milestones

Week	Date	Milestone
TBD		Understand component Implementation
		Construct Hardware
		Create Software
		Project Testing
		Project Website
		Final Presentation
		Final Report

8.2 Budget and Finance

For this project, we decided that a $450 budget is possible for the four of us to handle. Since there is no sponsor for this project, the funding is coming from all of us split at $112 per person. For robotic movement parts and sensors, we plan to have a maximum cost of $100. The mini-computer will be given a maximum cost of $80. Utilization of a group member's 3D printer, or the 3D printer that is on UCF's main campus, will be used to keep costs low for making the chassis. A budget of $70 will be dedicated to 3D printing. For electronic components, like the microcontroller and PCBS, a budget of $100 is allocated. Due to this project being prone to human error when assembling, we need to have overhead in case unforeseen issues arise and need to be fixed, or new parts need to be acquired. There will be $50 of overhead to cover these costs. The final $50 is allocated to implementing stretch goals and the possible new parts we will need to acquire.

9.0 Project Summary and Conclusion

During our research and prepared development of the trash picking up robot Trash-E, our group has learned about many topics that can be applied when making an autonomous robot. By researching topics from different projects such as autonomous drones, self-driving cars and other similar emerging technologies, we believe that we will be able to create Trash-E.

From our research, we were able to create an overall conceptual design that we believe will be able to properly do the objectives we want to do. With the robot being on four wheels, we will be able to maneuver terrain easily. The gripper will allow to pick up more than just small particles such as dust that previous robots which have been made before such as the Roomba, a robot vacuum. We hope to build upon these previous iterations by broadening the capabilities of a robot by picking up trash instead of just being a vacuum. Some self-driving cars and Roombas use LiDAR, which we believe is a fantastic way to help our robot navigate through its surroundings. The reason we chose our specific components were to keep costs down while also being efficient.

We chose to do this project because we are passionate about cleaning up the environment. With the popularity of social media trends such as cleaning up the beach, we hope to help motivate people to continuously keep the environment clean. We are also all interested in robotics, so we felt that this would be right up our alley. We felt that this robot would provide an adequate challenge to our abilities and allow us to learn a lot.

10.0 Appendices

This section is used to show the material that was referenced in the document.

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