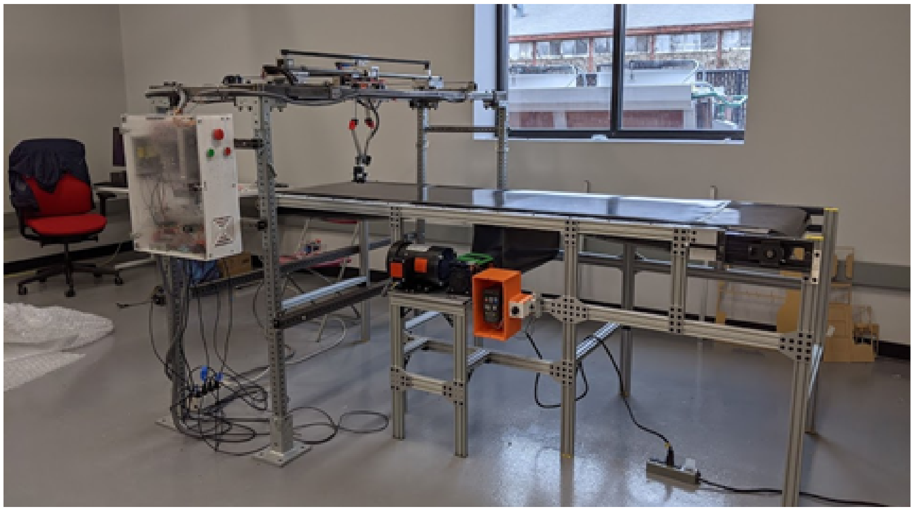
Worcester Polytechnic Institute

ROBOTIC WASTE SORTING



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A Major Qualifying Project

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ABSTRACT

The U.S. recycling industry depends on material recovery facilities to process materials collected through single stream recycling. A growing global population and recently imposed higher material purity standards require more efficient waste-sorting methods. This project contributes to research on automated solutions to this problem. A modular cartesian robot with a closed-loop linkage arm and 3-pronged gripper was designed and built to assist in sorting cardboard. Additionally, a conveyor belt for testing was designed and built, and a preliminary machine vision program to detect cardboard was developed. This work provides a basis for further research and development of waste sorting technologies.

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Chapter 1

Introduction

According to the U.S. Environmental Protection Agency (EPA), the public companies, private companies, and municipal governments which comprise the U.S. waste management industry manage over 267.8 million tons of municipal solid waste per year. Waste management includes reducing production (source reduction), and reusing, landfilling, incinerating, composting, and recycling materials.[1] Of the 267.8 million tons of municipal solid waste produced in the U.S. each year, 67 million tons (25.1%) are processed by recycling facilities.[2] However, U.S. recycling facilities currently cannot sort the volume of recyclable materials they receive fast enough, and to the degree of material separation that manufacturers require, to recycle all of the materials produced. When the materials cannot be processed by the recycling facilities, it is instead landfilled or incinerated.[3] Improving the waste sorting process in recycling facilities will allow them to process more material and send less to landfills and incinerators.

One reason U.S. recyclers currently cannot sort all recyclable materials effectively enough is that recyclable materials often arrive at recycling facilities mixed both with other recyclable materials and with contamination (non-recyclables such as food waste). Recyclable materials include glass, paper, cardboard, metals, plastics, and a few other materials.[4] These materials may be collected in multiple streams, such as separate bins for collection of glass and metals, or collected in a single stream.[5] Once recyclables are collected, they must be sorted into separate materials in order for manufacturers to reprocess them into new products, and

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[1] US EPA. "National Overview: Facts and Figures on Materials, Wastes and Recycling". In: (2020). URL: `https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials`.

[2] Ibid.

[3] Nicole Javorsky. *How China's Policy Shift Is Changing U.S. Recycling - Bloomberg.* 2019. URL: `https://www.bloomberg.com/news/articles/2019-04-01/how-china-s-policy-shift-is-changing-u-s-recycling` (visited on 04/01/2021).

[4] US EPA, "National Overview: Facts and Figures on Materials, Wastes and Recycling", see n. 1.

[5] Javorsky, see n. 3.

contamination must be removed. Contamination refers to non-recyclable materials unintentionally mixed into the recycling stream, such as food waste and garbage.[6] Contamination can damage recycling facility equipment by interfering with machinery, and in addition, costs recyclers money to sort and send to landfills. If the contamination in a load of recycled materials is not reduced to an amount accepted by the manufacturers, the entire load of material may be sent to landfill.[7] The U.S. uses mostly single stream recycling, which often has higher contamination than multi-stream recycling. High amounts of contamination make recyclables difficult to sort.

A second reason recycling facilities are still developing the ability to sort materials to manufacturers' standards is the recent change in policies regarding exporting recyclable materials. Prior to 2018, U.S. companies had sent approximately 40 percent of recyclables to China to be sorted and processed there, rather than processing this material in the U.S..[8] However, in 2018 China enacted its National Sword policy. This policy banned the import of some materials and set stricter contamination rates, in some cases as low as 0.5%, for other accepted materials.[9] As a result, U.S. recyclers could no longer send a large portion of their recyclables overseas for processing. U.S. recyclers accustomed to sending materials abroad became responsible for removing contamination from waste streams to a higher degree than before and were ill-equipped to process the volume of recyclable materials themselves.[10]

Automation of recycling processes can increase efficiency and throughput rates. Waste-sorting facilities in the U.S. currently rely on human workers to remove items that can damage recycling equipment and to conduct quality assurance. Yet workers in waste-sorting facilities face loud, stressful, and possibly dangerous environments due to the possibility of toxic, sharp, or heavy items in the waste stream.[11]

The conditions these workers face, and the need for improved efficiency, have led to increasing efforts to automate the waste-sorting process. Various waste sorting robots are currently in development or on the market, each with unique capabilities. This project contributes to the goal of developing waste-sorting robots to efficiently sort recyclables in waste-sorting facilities.

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[6] Cody Marshall and Karen Bandhauer. *The heavy toll of contamination - Recycling Today.* 2017. URL: `https://www.recyclingtoday.com/article/the-heavy-toll-of-contamination/` (visited on 04/01/2021).

[7] Javorsky, see n. 3.

[8] Ibid.

[9] Ibid.

[10] Ibid.

[11] Mikayla Fischler, Kyle Heavey, and Arianna Kan. *Robotic Waste Sorting Major Qualifying Project.* Tech. rep. 2019.

The project was started by an MQP team in 2019-20. The first MQP team began development of a robotic arm to detect and pick up cardboard from a conveyor belt filled with other recyclable materials. Wet cardboard was chosen as a target because it often degrades or breaks into small pieces before being sorted at recycling facilities. This makes wet cardboard hard to sort using existing sorting systems, which are designed to sort dry, fully intact pieces of cardboard. This year's team modified and expanded on the initial design to build, assemble, and test the robotic system. Additionally, the robot control system was developed, focusing on general movement of the robot and a machine vision program to detect cardboard. This paper outlines the background research, methodology, design and implementation, testing procedures and results, ethical implications, and recommended next steps for the waste-sorting robot.

Chapter 2

Background

This chapter first outlines the aims, process, and problems of the current recycling system in the United States. It then describes existing technologies that aim to address the problems with waste sorting and how this project fits in.

2.1 Process and Problems: Recycling and Waste Sorting in the U.S.

This section outlines the process of the U.S. recycling system. In particular, it describes the process and current problems in the waste-sorting aspect of recycling.

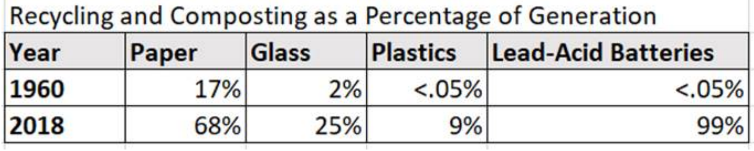
2.1.1 U.S. Recycling System: Current Numbers

In 2017, the Environmental Protection Agency (EPA) measured U.S. waste production at 267.8 million tons of municipal solid waste (MSW) per year, or 4.51 pounds of waste per person per day. Of those 267.8 million tons, 139 million tons (52.1%) of U.S. waste were added to landfills, 34 million tons (12.7%) were incinerated with energy recovery, 27 million tons (10.1%) were composted, and 67 million tons (25.1%) were recycled. Figure 2.1 shows total U.S. waste numbers from 1960-2018 from the EPA.

Figure 2.1: EPA USA Waste Numbers

As shown Figure 2.1, U.S. total waste production by weight has nearly tripled in the last 60 years. As a percentage of total material waste generated, the U.S. recycling rate has increased from less than 15% through the 1990s to 32.1% in 2018.[12] This positive trend in overall recycling rate is also visible in recycling rates for individual materials. Table 2.1, with data from the EPA website, shows the percentages of recyclable materials produced in the U.S. that were successfully recycled in 1960 and 2018. The table illustrates that although recycling rates have increased over time, improvement can still be made for recycling rates of all materials. The U.S. recycling system can continue to improve both by increasing the percentage of total waste recycled and by increasing the recycling of individual materials.

Table 2.1: Percent Recycled of Waste Generated Annually for Given Materials



Recycling and Composting as a Percentage of Generation

Year	**Paper**	**Glass**	**Plastics**	**Lead-Acid Batteries**
1960	17%	2%	<.05%	<.05%
2018	68%	25%	9%	99%

Improvement to recycling rates can occur at multiple stages of the recycling process. Once people and organizations finish using items, they may place the items into recycling bins. At this stage, recycling may be increased with efforts to improve public education and recycling behavior, and to better organize recycling and garbage collection sites. The materials in recycling bins are next collected and sorted, then sold to manufacturers to create new products. At the waste-sorting step, improvements may be made by enhancing the efficiency of sorting and the degree of separation of sorted materials.

Among the many opportunities for improving the U.S. recycling system, this MQP is part of the effort to address issues in the waste-sorting aspect of the recycling system (post-collection and prior to sale to manufacturers). The following sections describe U.S. waste-sorting from collection through current separation processes.

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[12] US EPA, "National Overview: Facts and Figures on Materials, Wastes and Recycling", see n. 1.

2.1.2 Single Stream Recycling, Sorting, and Contamination

Since 2014, the majority (80%) of towns in the U.S. have collected recyclable materials with a system called single stream recycling (SSR).[13] In single stream recycling, consumers place all materials into a single bin for collection, and which must later be sorted for manufacturing. Other systems include dual or multi-stream recycling. In multi-stream recycling, consumers place materials into different bins for collection by the recycler. Single stream recycling reduces the effort for consumers to recycle. In many cases, the introduction of single stream recycling increases the volume of material collected by recyclers. However, the increase in tonnage collected with SSR does not necessarily correlate with an increase in material recycled. Recyclers must separate materials and remove contamination, which requires more effort with single stream recycling because recyclables are mixed together and contamination rates may increase.[14]

Currently, U.S. manufacturers recycle paper, cardboard, glass, metal, and some plastics.[15] Once recyclers collect waste material, they need to sort it into separate materials in order to sell it to manufacturers. Materials that can be recycled vary by location depending on what each recycling company can sort and sell to manufacturers.[16] For manufacturers to convert waste materials into new products, they need pure, or mostly pure, materials. For example, a paper manufacturer using recycled paper in production prefers to use pure paper, not paper mixed with plastic or glass. Therefore, recycling companies aim to divide waste into separate materials to sell to manufacturers.[17] They also must remove contamination from the waste stream.

Contamination refers to garbage (non-recyclable materials), food, items placed in the wrong bin, and anything else that cannot be recycled or that cannot go through the waste-sorting system. Contamination is often caused by the public's confusion about what can and cannot be recycled. Rules about recycling differ widely from place to place, even within the same country or state. This results in people placing materials that cannot be recycled into recycling bins. Contamination is exacerbated by "wishful recycling," when people place non-recyclable items in recycling bins because they feel as though these items should be

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[13] Maggie Koerth. *The Era Of Easy Recycling May Be Coming To An End — FiveThirtyEight*. 2019. URL: `https://fivethirtyeight.com/features/the-era-of-easy-recycling-may-be-coming-to-an-end/` (visited on 04/01/2021).

[14] *Single-Stream Recycling - Scientific American*. 2013. URL: `https://www.scientificamerican.com/article/single-stream-recycling/` (visited on 04/02/2021).

[15] US EPA, "National Overview: Facts and Figures on Materials, Wastes and Recycling", see n. 1.

[16] Drew Desilver. *Recycling perceptions, realities vary widely in U.S. — Pew Research Center*. 2016. URL: `https://www.pewresearch.org/fact-tank/2016/10/07/perceptions-and-realities-of-recycling-vary-widely-from-place-to-place/` (visited on 04/01/2021).

[17] David Biddle. *Recycling for Profit: The New Green Business Frontier*. 1993. URL: `https://hbr.org/1993/11/recycling-for-profit-the-new-green-business-frontier` (visited on 04/01/2021).

recyclable and feel bad about throwing them in the trash. The increase in total recycling resulting from higher rates of participation in SSR programs is therefore often counteracted by the much lower quality (more highly contaminated) waste streams that result from it.[18]

High contamination of the recycling stream is one of the drawbacks of single stream recycling and is detrimental to the recycling industry. Separating recyclable materials becomes more complicated when contamination is added. The contamination can soil other, clean materials or interfere with machinery in the waste-processing facility. If the contamination goes unnoticed and gets mixed in with another material, manufacturers are more likely to reject the recycled material and the material may be sent to a landfill. Higher contamination can thus increase sorting costs and may decrease profit from selling materials to manufacturers. In fact, the cost of managing high rates of contamination has forced many municipalities to restrict or even completely shut down their recycling programs.[19] An alternative to the high cost of sorting waste in U.S. facilities is exporting waste to be processed elsewhere

2.1.3 Alternatives to U.S. Sorting and China's National Sword Policy

Rather than reprocessing materials themselves, U.S. recycling companies can export waste to China or other countries for materials to be sorted and processed there. U.S. companies thus avoid or decrease the cost of sorting the materials themselves. For the past several decades, sending material to China was easy and inexpensive due to favorable prices for the material. In addition, shipping was practically free for recyclers because ships that arrived from China carrying consumables took the materials with them on their way back.[20]

In 2018, this exporting of recyclables was brought to a halt when China enacted its National Sword policy. The National Sword Policy severely restricted the materials that could be imported and what level of contamination they could have. This policy aimed to protect the people of China from deteriorating environmental conditions. It was a continuation of the country's similar but less strict Green Fence policy of 2013. Among other restrictions, the National Sword policy set a maximum 0.5% contamination allowance on imported recyclables. In 2018, the recycling industries in many wealthier countries did not have the capability to meet this contamination standard. As a result, recycling imports to China

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[18] US EPA. *The U.S. Recycling System.* URL: `https://www.epa.gov/americarecycles/us-recycling-system#CurrentChallenges` (visited on 04/01/2021).

[19] Koerth, see n. 13.

[20] Cheryl Katz. *Piling Up: How China's Ban on Importing Waste Has Stalled Global Recycling - Yale E360.* 2019. URL: `https://e360.yale.edu/features/piling-up-how-chinas-ban-on-importing-waste-has-stalled-global-recycling` (visited on 04/01/2021).

plummeted. In the first year of the program, plastic imports decreased by 99%, and paper imports went down by a third.[21]

This policy had an enormous impact worldwide. In the 25 years leading up to the new policy, China had handled nearly half of the world's recyclable waste. 95% of the E.U.'s and 70% of the U.S.'s plastics were being exported to China.[22] Countries that had been exporting large amounts of waste suddenly faced the problem of where to send their waste or how to deal with it themselves. Many began exporting scrap to other countries in southeast Asia, once again relying on cheap, international labor to manage the material.[23] Exporting materials to other countries is often not an environmentally friendly option. Most facilities in the United States do not track what happens to their waste once it leaves the country. Many of the waste sorting facilities abroad are illegal factories in which workers are placed in unsafe conditions.[24] Several countries have followed China in enacting policies similar to National Sword and shutting down illegal facilities, but these facilities and the problem of highly contaminated waste imports persist. In many cases, much of the waste imported to these countries goes straight to landfills or is burned without energy or pollutant recovery, further contributing to global warming and pollution.[25] Other countries increased development of their recycling and sorting infrastructures to manage the waste, but continue to send material that cannot yet be managed to landfills or incinerators.

These changes mean that whether they process materials themselves or meet the new requirements of sending them abroad, U.S. companies need to improve their waste-sorting facilities in order to recycle materials rather than sending them to landfills. Improving facilities can mean sorting faster, more cheaply, or with a higher degree of separation. The next section describes the current waste-sorting process in the U.S.

2.1.4 Current U.S. Waste Sorting Process

The current sorting process varies by recycling facility. The following is a description of the Casella recycling facility in Auburn, MA, based on a tour video taken by last year's MQP team. (Casella is the waste management company for the Worcester area). First, recyclable materials are collected and brought to the waste-sorting facility. There, the materials are received in a loading bay and loaded onto conveyor belts. Non-recyclable items and items that cannot go through the sorting system are identified and manually removed by workers

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[21] Katz, see n. 20.

[22] Ibid.

[23] Dominique Mosbergen. *Here's Why America Is Dumping Its Trash in Poorer Countries – Mother Jones.* 2019. URL: `https://www.motherjones.com/environment/2019/03/heres-why-america-is-dumping-its-trash-in-poorer-countries/` (visited on 04/01/2021).

[24] Ibid.

[25] Ibid.

in a pre-sort area. The materials then move through a series of mechanical and automated "screens", devices which help separate the various materials. The first screen is a triple-deck screen that separates cardboard, containers, and paper (items too heavy or too light for the next level of processing). Heavier containers drop to the bottom level while lighter items continue to the second level; cardboard is drawn up over the top. This screen also breaks the glass containers for the safety and convenience of workers and removes most of the glass from the single-stream load so that it can be sent to cullet suppliers. The remaining materials pass under a powerful magnet, which separates tin and steel cans. Next, a reverse magnet (eddy current) causes aluminum cans to lift off the conveyor into a bin. In some facilities, optical sorters are then used to separate the different types of plastics. Throughout this process, workers act as quality control and remove materials that have made it down the wrong line (for example, plastics in the paper stream). At the end of the line, the staff separate cardboard, newsprint, and office paper into separate areas. Once separated, the material is baled and shipped to manufacturers for processing into new material.[26]

However, the volume of materials collected is often higher than the facility can process or sort quickly enough. Sorting facilities may be unable to separate materials to the purity standards required by manufacturers and other countries. Additionally, human sorters are necessary for quality control at the end of the process. They also monitor the waste stream before it reaches the automated equipment to remove items that could damage the machinery such as hoses, plastic bags, and hazardous material. Unfortunately, these workers are exposed to intense stress, dangerous machinery, and hazardous materials. They routinely encounter used syringes, glass shards, and biochemical waste, sometimes suffering injury, illness, or musculoskeletal disorders from maintaining constant strenuous positions along the conveyor belt.[27] The waste management industry has twice the injury rates compared to the average of other industries. For these reasons, the waste sorting process needs to be improved.

2.1.5 Need for Development in Waste Sorting

In recent years, it has only become more apparent that the problem of waste management is a global one. Within the recycling system, continuing to export waste or failing to recycle it at current rates may damage the environment and threaten human life.[28] Recycling industries in many developed countries, especially the U.S., are far from where they need to be to deal with the waste their countries produce. Within the U.S., more waste is being sent to landfills as other countries impose stricter regulations on imported recyclables. In order to improve recycling, major changes must be made to the recycling industry.

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[26] Fischler, Heavey, and Kan, see n. 11.

[27] Ibid.

[28] US EPA, "National Overview: Facts and Figures on Materials, Wastes and Recycling", see n. 1.

One of those changes is creating a better means of dealing with contamination so that more material gets recycled, rather than sent to landfills.[29] In the waste sorting process, one way to do this is through automation, which can speed up the process and remove workers from the labor-intensive and often hazardous conditions (large, heavy, sharp, or otherwise dangerous objects) involved with the waste sorting process. Robotic solutions can increase safety for human workers and allow for these workers to dedicate their efforts to other areas of the facility. This MQP project is part of the effort to improve automation in waste-sorting systems. Some work has already been done to develop automation solutions, as outlined in the next section.

2.2 Existing Solutions and Emerging Technologies

Robots specializing in waste sorting started emerging in recent years. The first sorting robot to be installed in a U.S. recycling facility was only installed in 2016. As of September 2019, there were at least 88 systems either in-use or purchased for use across 39 recycling facilities in the U.S. and Canada.[30] As of late 2018, there were 633 materials recycling facilities in the US alone.[31] Since less than 14% of these facilities use robotic systems, there is much room for increased use of robotics and development of better systems. Additionally, many robots feature similar systems: for example, a delta robot using a vacuum EOAT (end of arm tooling) partnered with some sort of visual sorting system. This section builds on the previous team's research of existing robots by focusing more on machine vision and modular non-delta robot systems including the AMP Robotics Cortex, ZenRobotics Fast Picker, and TOMRA AUTOSORT.[32]

2.2.1 AMP Robotics Cortex

AMP Robotics is one of the leaders in robotic recycling. Their Cortex system also uses a delta robot with a suction cup EOAT. Much like its competitors, their vision system uses AI and deep learning to properly identify items. The machine vision system can identify objects through different methods including looking at the brand of packaging and SKU (stock-keeping-unit) barcodes, in addition to analyzing the shape, color, size, and texture of the item. As a result, the Cortex system can sort through several types of paper and plastic

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[29] US EPA, "National Overview: Facts and Figures on Materials, Wastes and Recycling", see n. 1.

[30] Jared Paben. *Rapid adoption - Resource Recycling.* 2019. URL: `https://resource-recycling.com/recycling/2019/09/09/rapid-adoption/` (visited on 02/07/2021).

[31] Kate O'Neill. *The plastic waste crisis is an opportunity for the U.S. to get serious about recycling at home.* 2018. URL: `https://phys.org/news/2018-08-plastic-crisis-opportunity-recycling-home.html` (visited on 02/07/2021).

[32] Fischler, Heavey, and Kan, see n. 11.

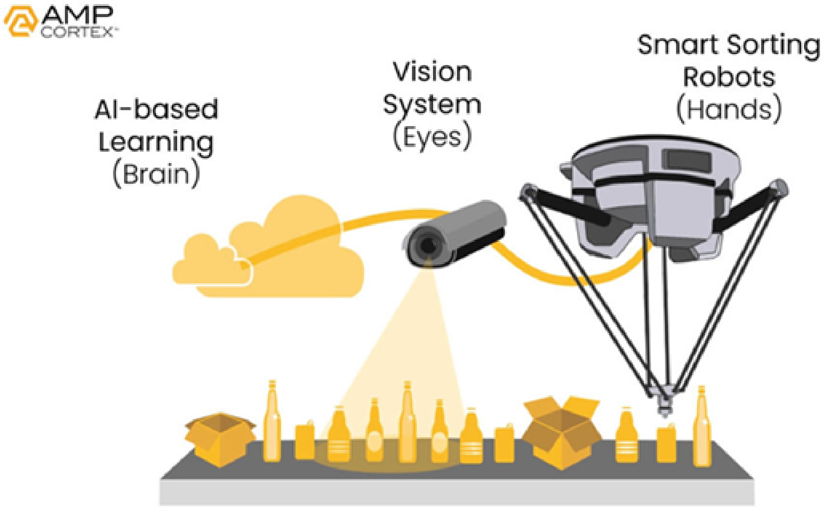

Figure 2.2: AMP Cortex

products.[33] A summary of this system can be found in Figure 2.2.

2.2.2 ZenRobotics Fast-Picker

The ZenRobotics Fast-Picker is a Cartesian-style robot (seen in Figure 2.3), produced by the same company as the Heavy Picker but for smaller items. Like many waste-sorting systems, it uses a vacuum gripper EOAT. A sensor bar 250mm wide in front of the robot is equipped with LED lamps, RGB cameras, and other sensors to scan the waste. While vacuum grippers are great for dry and rigid recyclables, they are not capable of picking up wet or flexible items like plastic bags.[34]

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[33] *AMP Cortex — AMP Robotics.* URL: `https://www.amprobotics.com/amp-cortex` (visited on 08/07/2020).

[34] *Fast Picker — ZenRobotics.* URL: `https://zenrobotics.com/solutions/fast-picker/` (visited on 08/07/2020).

Figure 2.3: ZenRobotics Fast-Picker

2.2.3 TOMRA AUTOSORT

TOMRA offers a variety of waste sorting systems specific to certain materials through its AUTOSORT line but they all have the same functionality. The machine is placed at the end of a conveyor belt and a vision or sensor system detects which objects to reject. Objects that are rejected are shot with a blast of air at the end of the conveyor belt, sending them over a barrier separate from the accepted pieces. This type of separation technology has already been implemented at Casella facilities. What differentiates Tomra is their vision and sensing system. Their FLYING BEAM technology is a type near-infrared vision scanner that does not require an external light source. It uses a rotating polygon mirror to see the entire length of the belt. Material absorbs the infrared light and reflects partial light back. Using this technology, it can determine the color and type of plastic for a given item.[35] Two of their other technologies can accomplish even more. For example, SHARP EYE uses a larger lens of higher light intensity, allowing it look at chemical composition and distinguish between single-layer PET trays and PET bottles. Their DEEP LAISER technology can detect almost everything else, from black plastic to glass. The TOMRA AUTOSORT is shown in Figure 2.4.[36]

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[35] *FLYING BEAM® : TOMRA.* URL: `https://www.tomra.com/en/sorting/recycling/tomra-technology/flying-beam` (visited on 08/07/2020).

[36] Ibid.

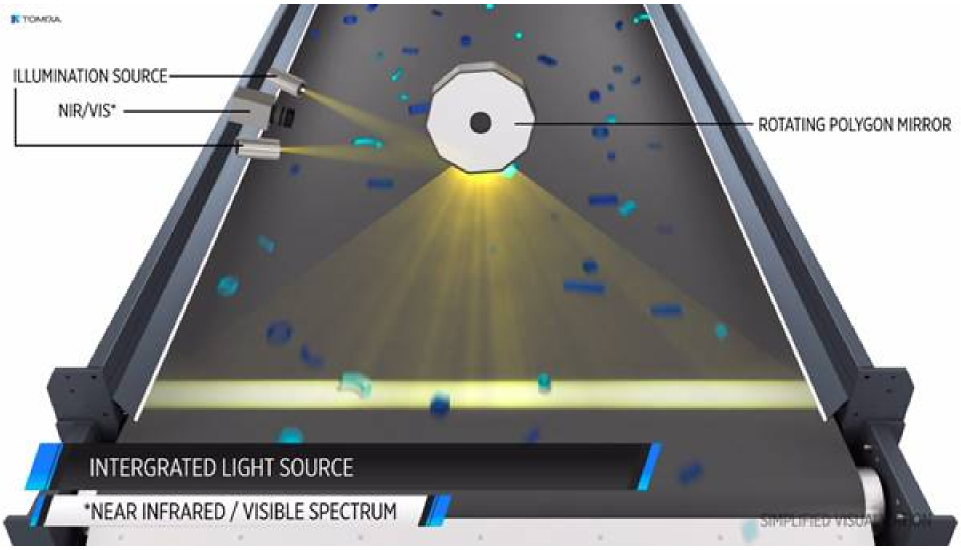

Figure 2.4: TOMRA AUTOSORT

2.3 Previous year's work

This project was started by an MQP team last academic year (2019-2020). The previous team fully designed the robot frame arm, and gripper, and began programming for the robot. This section describes the key aspects of the design; for specifics and the development of the design see the methodology (Chapter 3) and Design and Implementation (Chapter 4). The final robot from last year is show in Figure 2.5, and the gripper system from last year is shown in Figure 2.6.[37] The final design for the frame used a Cartesian system in which the robot moves in the X and Y directions on linear rails. The robot's arm moves in the vertical (Z) direction by use of a closed-loop, five-link arm mechanism. The naturally modular Cartesian system allows future teams to easily make changes or additions as needed. Lastly, the team created an end of arm gripper designed to grab wet cardboard. Wet cardboard was targeted it is difficult to sort with existing systems. The gripper has three carts that move in a linear motion towards the center of the gripper to create a claw mechanism. Small piercers were added to the bottom of each cart to puncture and grab the wet cardboard. A preliminary arm and gripper design was completed and all individual parts were made and ordered, but the prototype system was not fully assembled.

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[37] Fischler, Heavey, and Kan, see n. 11.

Figure 2.5: Last Year's Robot

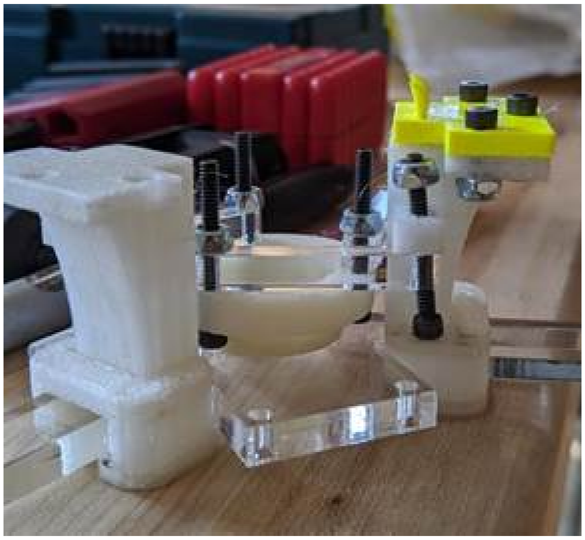

Figure 2.6: Last Year's Gripper

2.3.1 The Purpose of this Project

This year's project builds on the work completed last year. As outlined previously, several waste-sorting robots are already on the market. However, the problems facing the waste-sorting industry (Section 2.1) exceed the capabilities of any single existing robot. To tackle the problems facing the recycling industry is a massive undertaking. Due to the broad scope of the problem and the industry, more research and development needs to be undertaken before any solutions will be widely implemented. This project aims to contribute to these research efforts by developing a robotic waste sorting test environment. The test environment includes a conveyor belt testbed and focuses primarily on recognizing and gripping cardboard material while maintaining a modular robot design which can be expanded upon in the future.

Chapter 3

Methodology

This section describes the starting point for this year's team and outlines the design goals developed for new components as well as for improvements to existing parts. The mechanical subsystems include the arm and gripper, robot frame, electrical enclosure, and conveyor belt. The software components for the robot include the computer hardware (consisting of a desktop, Raspberry Pi, and Teensy 3.6), the code (utilizing python, C/C++, and ROS), and a machine vision system.

3.1 Mechanical

3.1.1 Arm

The preliminary design by the previous team consists of a closed-loop, five-link mechanism, driven by two Dynamixel motors. The linkage mechanism produces linear motion of the end effector along the Z-axis, allowing the robot to lift objects. A preliminary prototype of this design was built by the previous year's team, consisting of aluminum hex standoffs connected with 3-D printed brackets as seen in Figure 3.1.

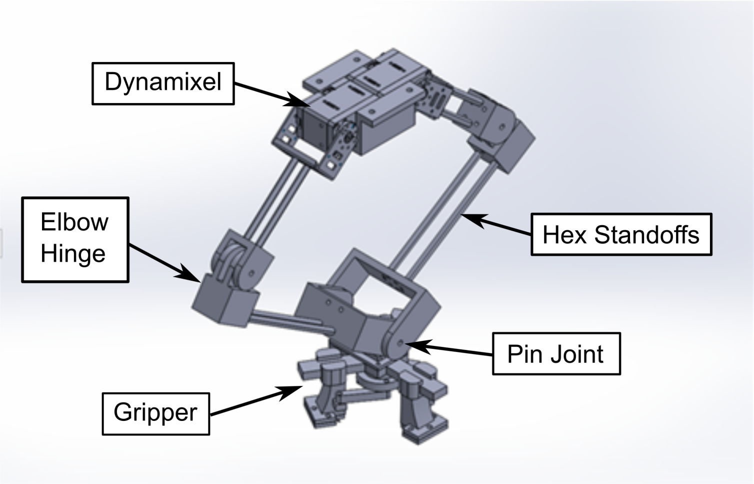

Figure 3.1: CAD of Original Arm

In the preliminary prototype, the lower arm links, comprised of two hex standoffs each, allowed for unintended rotation between the elbow and the pin joint connection between the arm and gripper. Once the previous prototype was fully assembled, it was also discovered that the arm, if it was able to reach a raised position, was able to sustain that raised position for only for a few seconds before causing the motors to stall. The goal this year was to modify the initial design to produce a fully functional arm with the strength and stability necessary to pick up pieces of cardboard off a conveyor belt. The following design goals were identified and used to guide changes made to the assembly:

1. Ease of Assembly: Components should be easy to take apart and put together should any changes need to be implemented
2. Minimize cost and time to manufacture
3. Minimize friction in the joints of the hinges in the arm assembly
4. Minimize weight of the assembly
5. Lifting capabilities of the arm should be sufficient for the weight of the arm, the gripper assembly, and recyclable materials being lifted

3.1.2 Gripper

The gripper designed by the previous year's team consisted of three two-pronged arms, guided by an acrylic Y-rail and driven by a Dynamixel motor attached to the end of the robot arm. The gripper was designed to pick up material with a pinching action combined with the piercing action of the prongs. All individual components were manufactured by the previous team, and many of the hardware components had been assembled.

The gripper prototype (diagrammed in Fig. 3.2) could be manipulated to open and close by hand. The motorized version of the gripper had not been tested prior to the beginning of the 2020-2021 academic year. During the previous year's testing, the Y-rail and the links connecting the moving carts to the center disk had fractured. Stress concentrations on the existing cardboard piercers caused the piercers to snap off during use. The existing moving carts were not designed to come together fully when in use.

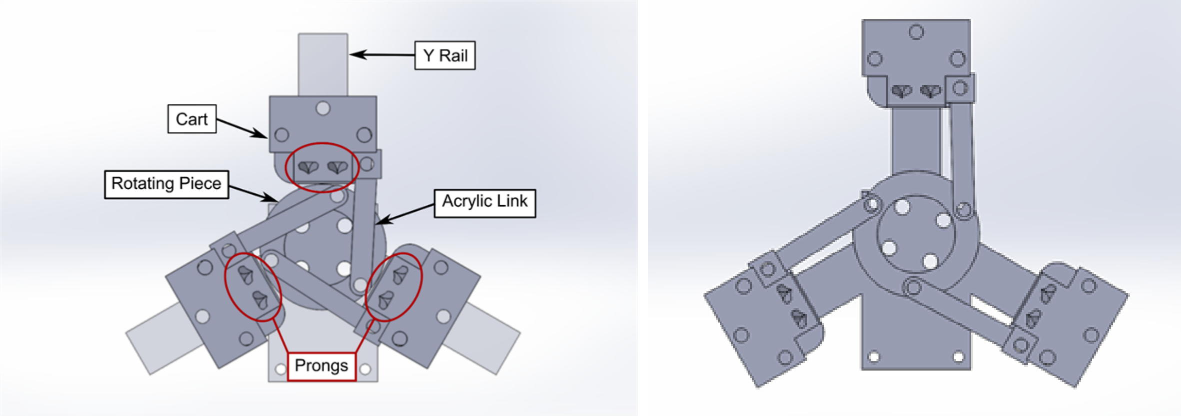

Figure 3.2: (a) Original Gripper (Closed Position) Bottom View; (b) Original Gripper (Open Position)

Assembling and disassembling the gripper was time consuming and difficult due to the sizes of fasteners selected and the geometry of connecting components, making it hard to change out and test new gripper components. In particular, the connection between the rotating piece connecting the Dynamixel to the links (shown in Fig. 3.3) was difficult to access due to the tight tolerance of the lock nut mounting slots and the precision required to hold the nuts in place during assembly. Additionally, the original design required that the M2 screws connecting the rotating piece to the Dynamixel be at least 10mm long, due to an offset between the rotating piece and the motor rather than the faces of these parts mounting directly together. This created a greater bending moment experienced by the screws than necessary, increasing the risk of failure of this component.

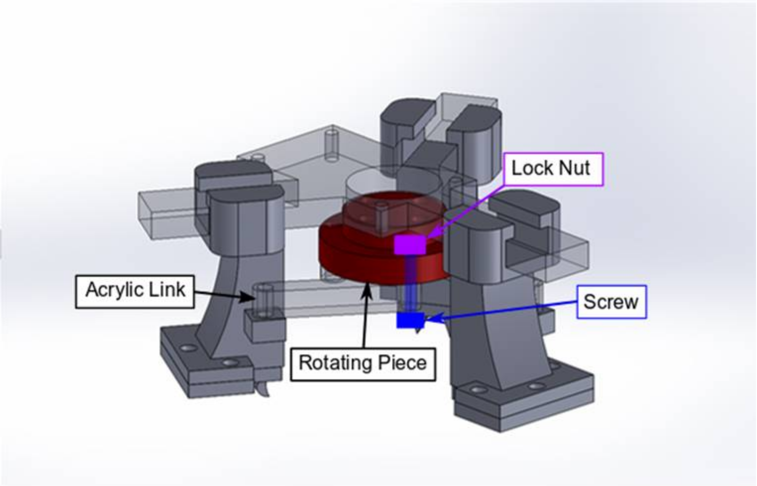

Figure 3.3: Original Gripper with Original Rotating Piece

The following design goals and constraints were identified for modifications the gripper assembly:

1. Ease of assembly
2. Minimize cost and time to manufacture
3. Reduce stress on breakable pieces
4. Minimize weight of the assembly
5. The gripper should be able to grip pieces of cardboard, both wet and dry

3.1.3 Robot

The robot was initially designed, manufactured, and assembled by the previous year's team. The robot consists of a lower, supporting frame constructed from steel bolt-together rails, with a welded steel rectangle on top to which the X- and Y-axis rails and all moving parts of the mechanism are connected. The original assembled robot is shown below in Fig. 3.4.

Figure 3.4: Original Assembled Robot

While moving between lab facilities, the robot was disassembled. During reassembly, it was discovered that the dimensions of the welded frame were inconsistent with the dimensions of the bolt-together framing. Additionally, the side rails of the bolt-together framing were connected only with a single bolt at each end, creating a pinned joint rather than a clamped or fixed joint. A pinned connection keeps two points attached while allowing rotation between the two components, while a fixed connection prevents rotation of the two components relative to each other. In context, this meant that the supporting rails for the robot were unstable and could easily pivot from side to side. This pivoting had allowed for the rails to be oriented at an angle to support the welded frame. Without the angled rails, the welded frame could not be mounted due to the dimensional inconsistency.

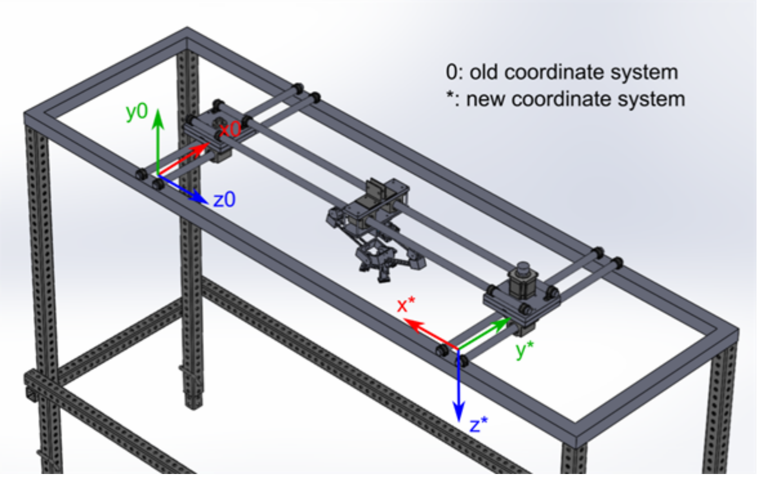

Figure 3.5: Axis Change

An important change was made in how this year's team defined the coordinate system, outlined in Fig. 3.5, and described in this section for consistency throughout the paper. The coordinate system was adjusted to align the X and Y axes with the motion of the stepper motors and the Z axis with the motion from the Dynamixels. Throughout the rest of this paper, the X axis will refer to the long length of the robot (across the conveyor belt), the Y-axis will refer to the short length (in line with the conveyor belt movement), and the Z axis will refer to the vertical axis.

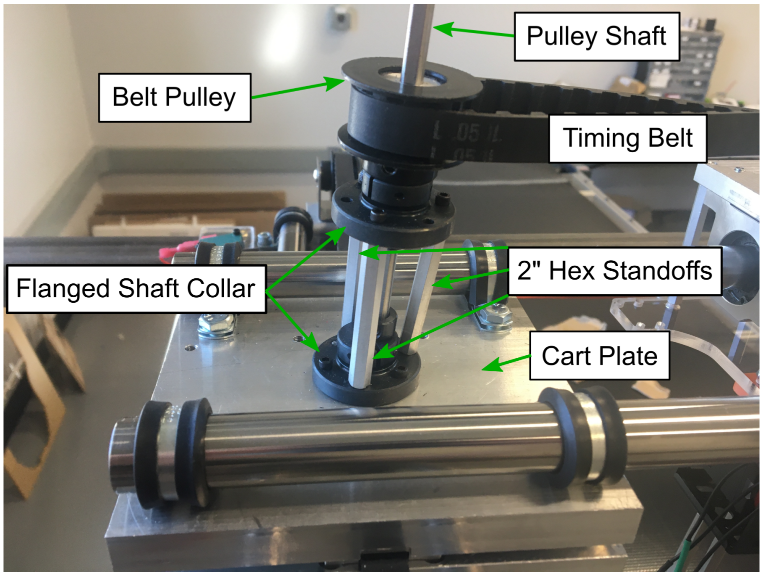

Figure 3.6: Original X Axis Pulley Support

The X-axis is composed of two carts which sit on top of the two carts on the Y-axis attached by two linear rails, shown in Fig. 3.6. One cart holds the stepper motor controlling the timing belt of the X-axis. The other side holds an assembly supporting the pulley where the belt wraps around. This assembly was attached to the cart base via three hex standoffs with a pair of flanged shaft collars which were offset by three 2-inch hex standoffs. These standoffs had 4-40 threaded ends, one male and one female. The male ends screwed into the bottom shaft collar. Two out of the three of these threaded pieces broke within the shaft collar, meaning another method of securing the belt pulley to the base was required. Additionally, because the top frame was welded together and already had several components fastened to the framing, it was difficult to make any modifications to this part. Holes created to fasten the limit switches for the Y-axis were inconsistently placed on the framing (for example, the distance between the two holes on the rails where screws would secure the mount to the framing were not all the same). There also were no locations to fasten the drag chains without drilling new holes.

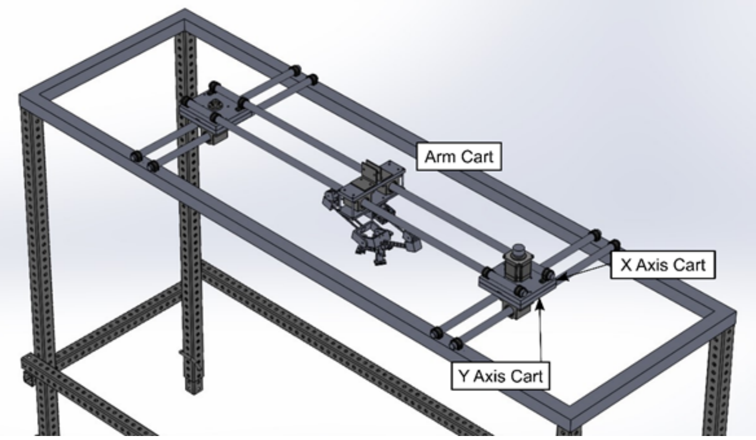

Figure 3.7: Original Robot Frame Overview

Based on these findings, two main goals for the frame were identified: improving the stability of the steel rails and finding a way to mount the welded frame effectively and safely. The existing part supporting the X-axis pulley broke close to the end of the project, so it was important that the new part be quickly manufactured but sturdy. With these goals in mind, the following design constraints were identified as a guide for potential solutions:

1. The existing major components (welded frame and steel rails) should not be replaced if possible
2. Minimize cost and time

3.1.4 Conveyor Belt

Based on the previous team's recommendations, it was determined that a conveyor belt would be necessary for testing the robot in a simulated MRF environment. Functional

requirements for the size and operating capabilities of the conveyor belt (to replicate those found in MRFs) were outlined by the previous team. These functional requirements are as follows:
The conveyor belt must

1. Be between 8-10ft long
2. Be between 2-3ft wide
3. Be reversible
4. Operate at variable speeds
5. Travel up to 60ft/min

3.1.5 Electrical Enclosure

The electrical components of the robot were not yet mounted to any surface at the start of the project this year. An enclosure was chosen as a method of storage for these components. The following design goals were identified for the enclosure:

1. Ease of assembly and organization
2. Minimize cost and time to manufacture
3. Contain all electronics without causing overheating of components

3.2 Software

Last year's MQP team proposed preliminary design decisions for the software and hardware that control the robot. The system is discussed below, and was intended to be expanded upon by future teams. Changes to these decisions are discussed in the next chapter.

Last year's team proposed a hardware setup consisting of a desktop computer, Raspberry Pi, and Teensy 3.6 microcontroller. The desktop computer would coordinate parts of the robot, complete any necessary calculations such as kinematics and vision processing, and control the arm and gripper through the Dynamixel motors. The Raspberry Pi was intended for use if libraries or devices compatible with a Raspberry Pi were needed. The Pi would be connected to the desktop via ethernet. The Teensy 3.6 microcontroller would be used to monitor the limit switches and start and stop buttons, as well as control the stepper motors. The Teensy would be connected to the desktop via USB. Last year's team also purchased an Intel RealSense Depth Camera D435 to be used for machine vision.

Last year's team proposed coding in the python programming language, with which they were familiar, and the desktop files were written in python. The code for the Teensy, however, was written in C/C++ Arduino code to be compatible with the Teensy. Last year's team proposed to use ROS (Robot Operating System), a framework that is commonly used in robotics, on the desktop to coordinate components of the robot. ROS facilitates using existing robotics libraries and writing robot components in multiple languages by allowing each file or component to be defined as a 'ROS node.' A robot operator launches the ROS program (ROS master) prior to launching these component nodes. ROS master then provides the communication interface between nodes through defined message types and service calls (similar to having separate classes with callable public functions in Java). The previous team also used the AccelStepper library written by Mike McCauley to control the stepper motors. They wrote a DynamixelMotor wrapper class providing functions from the Dynamixel SDK to simplify control of the Dynamixels, and wrote preliminary code to control the Teensy and communicate from the Teensy to the desktop.

The design goals for the code this year were:

1. Identify items to pick up on the conveyor belt using the camera;
2. Communicate between the motors on the robot platform, arm, and gripper where and when to go to pick up and drop off the item; and
3. Respond to operator instructions to turn on and turn off.

Chapter 4

Design and Implementation

At the start of the 2020-2021 academic year, all parts of the robot (for last year's design) had been manufactured, the robot frame assembled, and individual motors tested for functionality. The robot arm based on the previous year's design was assembled. None of the major components - the frame, arm, and gripper - were attached to each other (details of the prototypes for each of these components are outlined in the previous chapter). Significant wiring and assembly of components needed to be completed. This year's team identified several areas for improvement and created design goals for each subsystem (detailed in the previous chapter) including stabilization of the robot frame, an improved gripper, and arm functionality. This chapter discusses the design changes made to this project based on those goals.

4.1 Mechanical

Functional Objectives

Once all changes and new additions are implemented, the robot should:

- Be able to pick up a piece of stationary dry cardboard
- Be able to pick up a piece of dry cardboard moving on the conveyor belt at 30ft/min
- Be able to pick up a piece of stationary wet cardboard
- Be able to pick up a piece of wet cardboard moving on the conveyor belt at 30ft/min
- Cease powered movement upon the activation of the e-stop button

For the system to accomplish all of these objectives, several improvements were made to existing hardware. Limit switch mounts and the robot frame were made more stable. Improvements were made to the gripper to increasing its chances of grabbing on to cardboard and allow the arm to lift it from the belt. An organized electrical system was created to bring everything together. Lastly, a conveyor belt was designed so that the speed was adjustable and users are able to determine the speed of the belt easily.

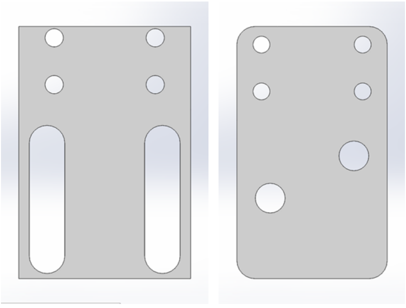

Figure 4.1: (Left) Previous Limit Switch; (Right) New Limit Switch

4.1.1 Robot

Limit Switch Mounts

Modifying the robot frame to fix the inconsistencies of the limit switch mounts was avoided as it was already functional, and (because it had been welded together, and due to its large size) was difficult to transport. No CAD was provided for the limit switch mounts, so new ones were laser cut based on physical measurements of the original mounts. These new pieces accommodated for the different drill hole positions and increased the thickness of the material between the hole and the edge of the mount, decreasing the chance that the acrylic mounts might break if the Y-axis cart were to run into the mount.

Electrical Enclosure

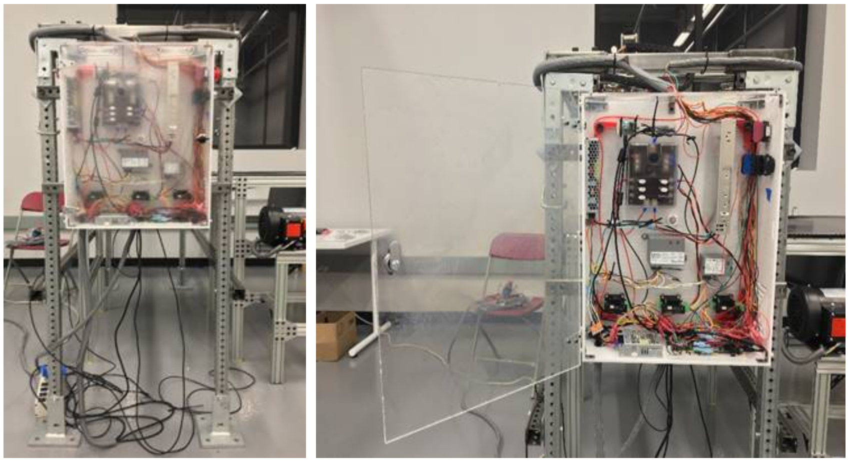

Figure 4.2: (Left) Electrical enclosure on robot; (Right) Electrical enclosure closeup with open door

A customizable pegboard layout in a laser cut acrylic enclosure was made to accommodate the variety of electrical components on the robot. The pegboard layout allows for future teams to change the layout or add additional components to the enclosure. The enclosure does not house the desktop or laptop connected to the Raspberry Pi and Teensy. The enclosure was sized larger than necessary and provided ventilation holes to prevent overheating, which would most likely be caused by the heat generated by the stepper drivers and power supplies. If the system were to overheat, components may fail to function properly or suffer damage. Calculations concerning the internal temperature of the enclosure can be found in Appendix A. Acrylic was chosen to create the enclosure due to its stability and manufacturing ease with the laser cutters at WPI. Because acrylic has a naturally static surface, anti-static spray was applied to the enclosure surface to prevent static from accumulating and damaging any electronic components.

Robot Frame

The first goal was to improve the stability of the lower portion of the frame. To create fixed rather than pinned connections at each of the joints, surface brackets were selected to prevent any rotation of the steel railing. Along the robot Y-axis, diamond shaped brackets were chosen (pictured in Fig. 4.3). Along the X-axis, tee brackets were chosen (pictured in Fig. 4.4.). In addition, new fasteners were selected at these joints to accommodate the added thickness of the brackets. The implementation of the brackets was effective in preventing any rotation at these joints and significantly improved the stability of the lower frame.

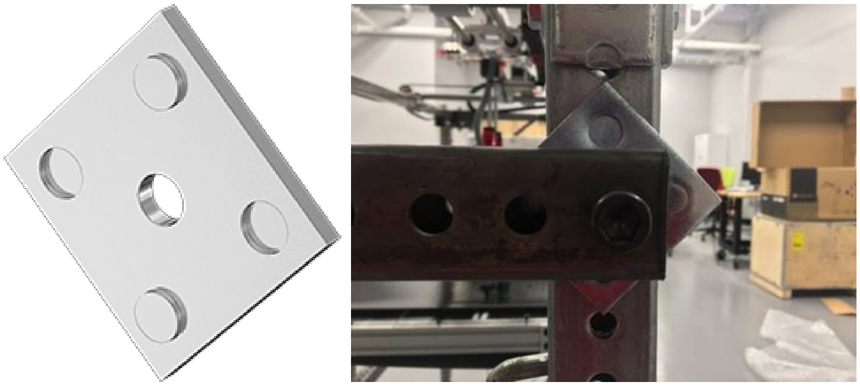

Figure 4.3: (Left) Diamond Bracket; (Right) Diamond Bracket on Robot Frame

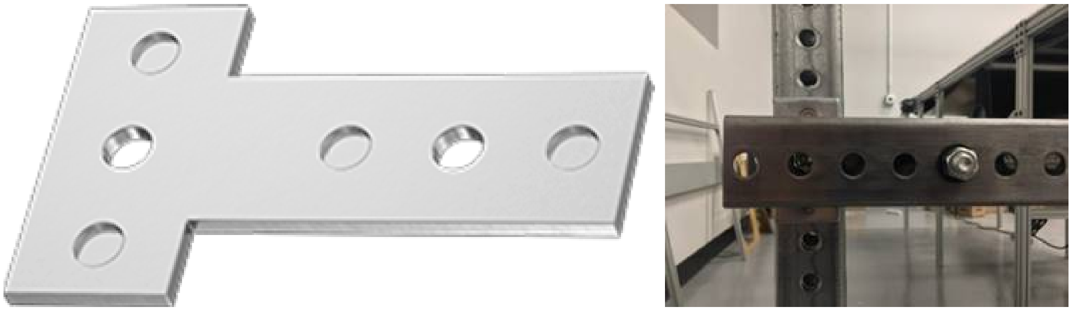

Figure 4.4: (Left) Tee Bracket; (Right) Tee Bracket on Robot

Next, a variety of solutions were considered to be able to mount the welded frame onto the lower steel rail frame despite the dimensional inconsistency between the two. The connection was initially designed to consist of an L-bracket connected to the steel railing along the Z-axis and to a 3-inch piece of this same railing along the Y- and X-axes of the robot. The 3-inch pieces were bolted onto the bottom of the welded frame. This setup is shown below in Figure 4.5.

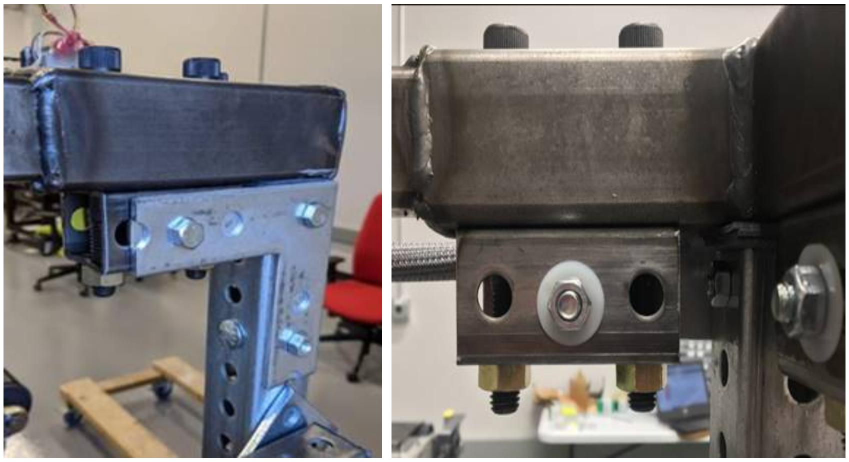

Figure 4.5: (Left) L Brackets; (Right) Unmodified Box Rail Attachments on Robot Frame (L brackets on opposite side)

As outlined in the design goals, the team wanted to avoid replacing any major components of the robot frame assembly. Because the top frame was welded together, and connection points on the steel railing were limited to the 1-inch spaced holes on the railing, dimensional changes to these components were restricted. Additionally, due to the weight of the system, repetitive assembly and disassembly was to be avoided if possible. Several ideas to fix this issue were considered, including changing the positioning of the 3-inch long box beam pieces, choosing new brackets, connecting the brackets to the welded frame directly, drilling new holes in the brackets, and drilling new holes in the box beam pieces. Based on cost, time, and ease of implementation, drilling new holes to create a slot in the box beam was selected.

This would allow the L-bracket to bolt on as intended with no further changes to the overall assembly. These slots were made in a Haas CNC MiniMill in WPI's Washburn Shops. Slotting the rail pieces was effective in aligning this component with the L brackets in the X- and Y-directions. The final slotted pieces are shown in Fig. 4.6.

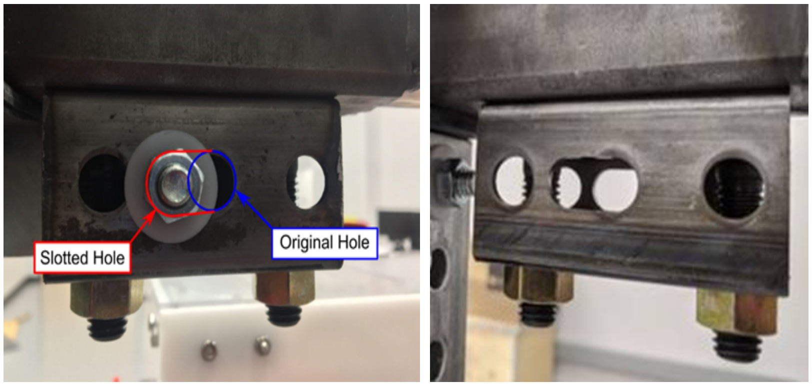

Figure 4.6: Slotted Box Rail Attachments on Robot Frame

To solve the issue of the welded frame not aligning in the Z-direction (the welded frame was too low when resting on top of the vertical steel rails), polyurethane rubber vibration damping pads were cut to size and attached in between the top of the steel rails and the bottom of the welded frame. These pads were also selected to minimize the transmission of vibrations from the top robot frame to the supporting steel rails. This solution was effective in raising the robot to the appropriate height and minimizing vibrations. This component is shown in Fig 4.7.

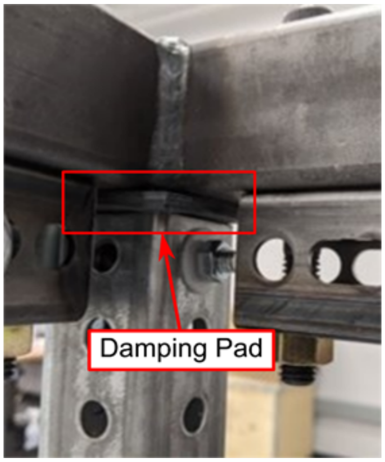

Figure 4.7: Vibration Damping Pad

Robot Cart

The component supporting the belt pulley on the X-axis needed to be replaced. Due to time constraints, a simple stand was milled out of aluminum to decrease the bending moment experienced by the screws holding the flanged shaft collar in place. This piece was secured to the plate below via M5 threaded holes already present on the cart. This component is shown in Fig. 4.8.

Figure 4.8: New X-Axis Pulley Support

4.1.2 Arm and Gripper

Arm

To improve on the strength and stability of the arm, two additional aluminum standoffs were added to the lower half of the arm. The standoffs were implemented in a diamond orientation relative to the hinge to (seen in Fig. 4.9.) prevent unwanted rotation of the arm outside of its plane of motion (original orientation shown in Chapter 3). This solution also kept weight of the arm, assembly time, and cost low.

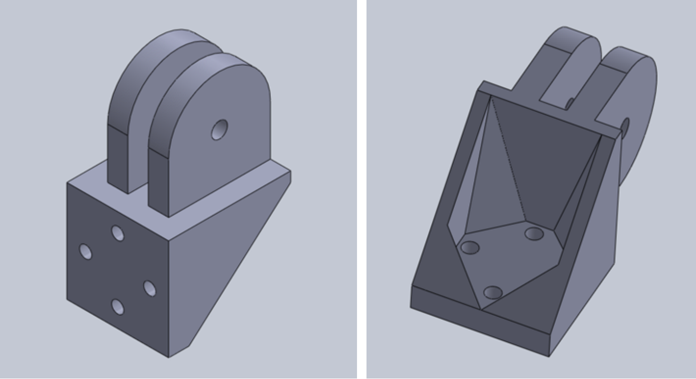

Figure 4.9: (Left) Isometric View of Elbow Hinge; (b) Rotated View of Elbow Hinge

New hinges for the connecting components of the arm were also implemented. The elbow hinges have an open design to allow for the screws connecting to the standoffs to be easily accessed. Additionally, the thickness of the interlocking components was reduced to minimize friction between moving parts. Reinforced interior corners and a triangular side profile were used to increase the strength of the part. This is shown in Fig. 4.9. The design of the hinges connecting the standoffs to the driving motors was modified for ease of assembly and strength of the component. The completed arm is shown in Fig. 4.10.

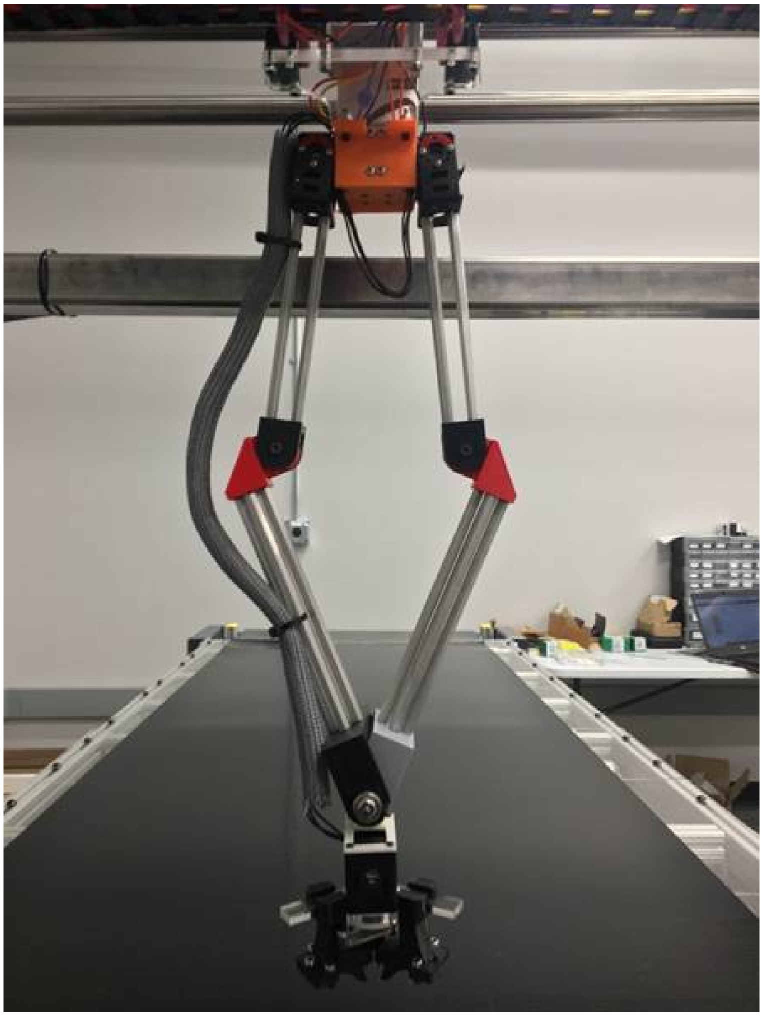

Figure 4.10: New Arm

New motors were selected to ensure sufficient lifting capabilities of the arm. The torque capabilities of the motors used for the starting prototype of the arm were found to be insufficient to lift the arm, gripper, and recyclables. The first step in understanding how to fix this torque issue was to check for a voltage drop in the existing system. Because the connectors used a gauge greater than 22AWG, using longer wires would make the system susceptible to voltage drops. Tests with a multimeter did not show any sign of a voltage drop. The gauge of the new connections was increased to 20AWG as a precautionary measure due to the increased wire lengths.

Calculations using the Jacobian of a kinematic model (expanded upon in the software section and found in Appendix C) of the arm were done based on the geometry and weight of the arm-gripper subsystem to determine the necessary torque to lift the arms. Based on these calculations, the findings from the performance graphs and Present Load tests, and geometric constraints of existing components, XC430-W240-T Dynamixels were selected to actuate the robot arm. The stall torque according to the performance graph was around 1.1N-m (compared to 0.75N-m). The new motors were also geometrically identical to the old ones, with the only difference between the models being the internal gear ratio (240 vs 150). Due to the larger gear ratios, the speed at which the new motors rotated was slightly slower; however, the new motors were successful in driving the arm mechanism.

Gripper

Several modifications were made to improve the function and durability of the gripper system. These components were redesigned to account for stress concentrations to prevent material failure from occurring again. The new Y-rail and links were made from laser cut acrylic. To prevent the cardboard piercers from snapping during use, the piercer geometry was updated to better account for stress concentrations, and the new piercers were printed with carbon fiber-reinforced filament to improve the strength of the component. The new piercer design features a larger contact area between the prongs and the base they sit on, as well as fillets with large radii of curvature between the prongs and the base, to lower the stress on the component experienced at this point (where the piercers were most likely to break). The piercers were also enlarged to more effectively puncture materials. The geometry of the carts was adjusted to allow for the prongs to come fully together when the gripper closes, creating a pinching action to work in combination with the piercers. These updated carts were 3-D printed from PLA as seen in Figure 4.11.

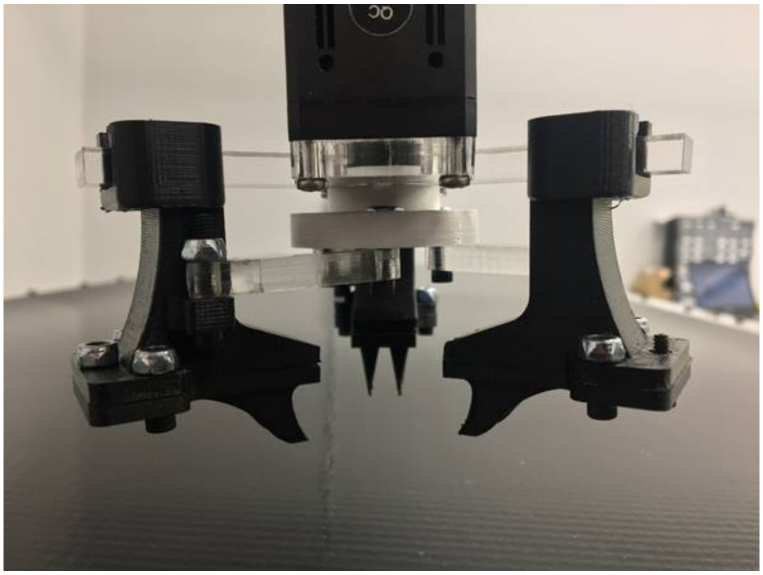

Figure 4.11: New Carts and Piercers (PLA carts and carbon fiber reinforced piercers)

The central rotating component was redesigned to make the surface of the rotating piece coincident with the Dynamixel. There was a space in between the two surfaces due a dimensional inaccuracy in the imported Dynamixel CAD model. Design changes were also made to improve ease of assembly of the gripper. The new rotating disk design allows nuts to press-fit into the disk rather than sit between the rotating piece and the acrylic Y-rail, allowing for easier access to the Dynamixel and links without disassembling the entire gripper. See Figure 4.12. for a comparison between the two designs.

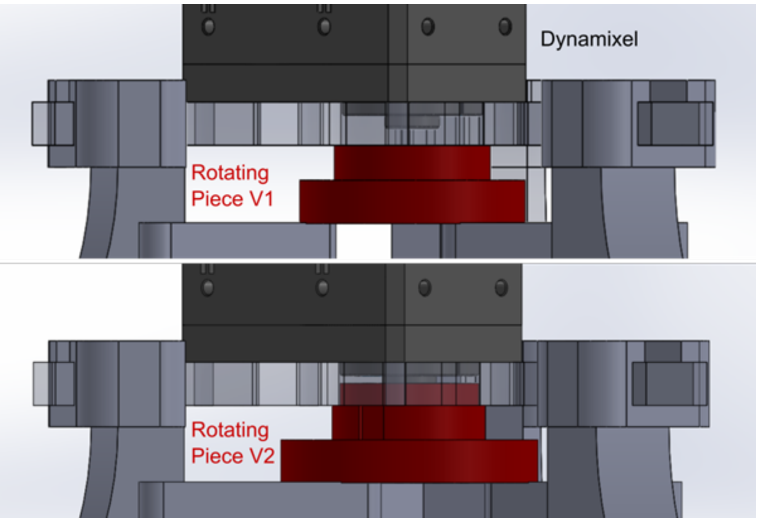

Figure 4.12: Rotating Piece Comparison

4.1.3 Conveyor Belt

Conveyor Belt Frame

Initially, research was done to find a commercially available conveyor belt to fit the functional requirements outlined in the Methodology chapter. Some options were found; however, none satisfied all the requirements and most of these models cost several thousands of dollars to purchase. For these reasons, the conveyor belt was designed and built from scratch. Although the cost analysis did not include the time and effort taken to build the conveyor belt, the decision to build from scratch was made to save monetary funds for other areas of the project.

The conveyor belt system was modeled in SolidWorks, consisting of an aluminum extrusion frame and the conveyor mechanism. A flat-bed conveyor belt design was chosen as the most appropriate for this application. Since the conveyor belt would only be carrying small, lightweight materials, aluminum was chosen for the frame, and acrylic sheet (rather than metal) was used for the flat-top conveyor bed to support the belt. Aluminum crossbeam supports act to reinforce the acrylic bed. The CAD model is shown below.

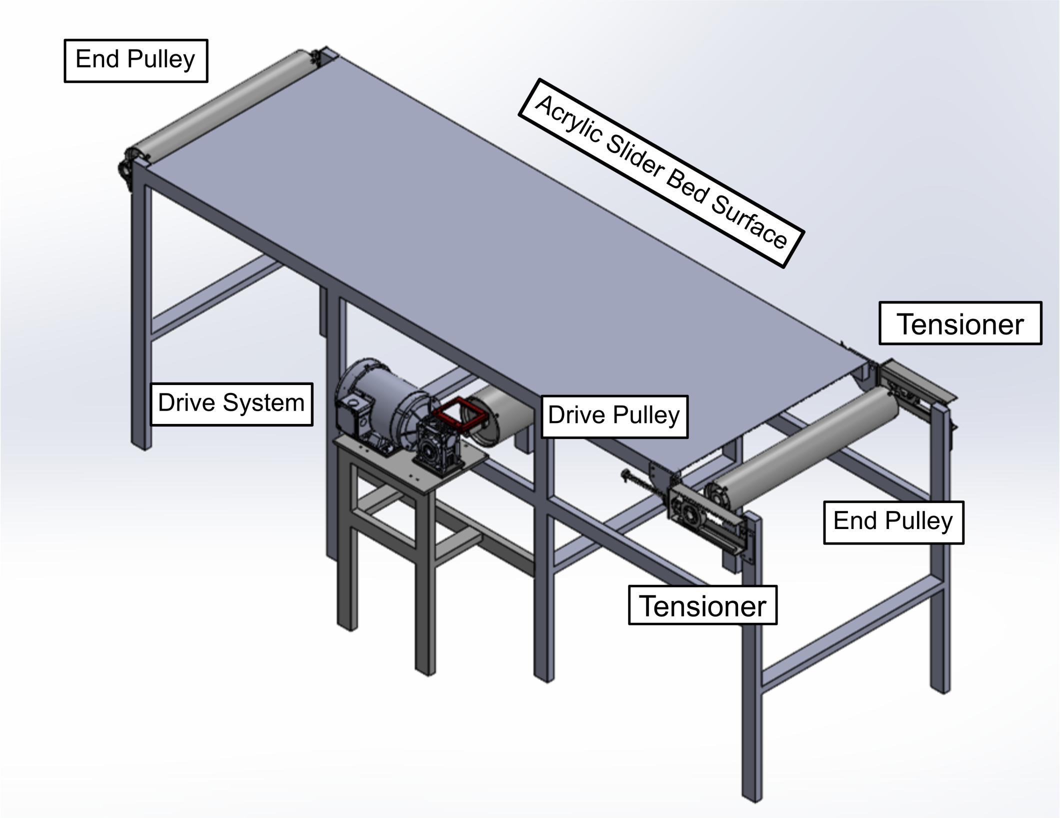

Figure 4.13: CAD for Conveyor Belt

The components were selected and ordered from McMaster-Carr and AutomationDirect. All manufacturing of the materials was completed in WPI's Washburn Shops. These manufacturing processes included cutting parts to size, performing finishing operations, laser cutting the acrylic for the flat bed, and CNC milling a custom mounting base for the conveyor drive system. The aluminum frame was then assembled, followed by the implementation of the drive system and various conveyor components (rollers, pulleys, bearings, flat bed, belting). Due to significant delays in receiving the drive system components, final assembly and testing of the conveyor belt were put off until later stages of the project.

Conveyor Belt Drive System

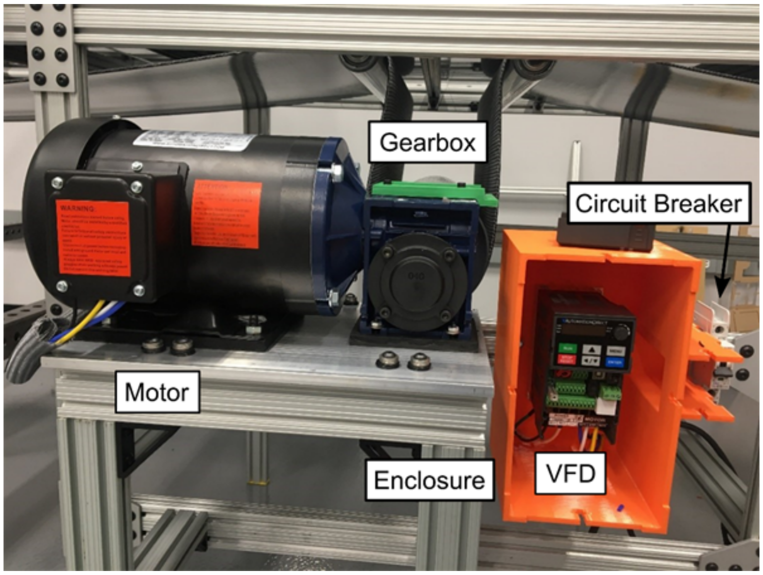

Figure 4.14: Conveyor Belt Drive

While the conveyor dimensions and need for reversibility were known, several other factors had to be determined to select the ideal drive components. Research suggested that industrial conveyor belts in recycling facilities travel up to 60ft/min.[38] A motor with a 1/3 horsepower was selected due to the minimal load on the belt based on calculations in Appendix B, and the part was ordered from AutomationDirect. The MTR2-P33-3BD18 is a standard 1/3 horsepower 3-phase AC induction motor with inverter duty, allowing for reversibility. A 40:1 gearbox reduces its top output speed from 1800rpm to 45rpm, resulting in a top conveyor belt speed of about 70 ft/min. This speed surpasses that of the industrial conveyor belts mentioned previously, allowing future teams the capability to test the robot at faster speeds. A VFD (variable frequency drive) was selected to control the motor. The selected VFD has a built-in PLC (programmable logic controller), allowing future teams to be able to control the conveyor belt without using the VFD control pad. Additional calculations for determining the drive parts can be found in Appendix B.

A shelf holding the motor and gearbox was secured to the conveyor belt frame and sturdily supported by legs extending to the floor. The gearbox output shaft was connected to the shaft holding the drive pulley drum using a flexible coupling. The flexible coupling dampened the effects of misalignment, reducing any backlash the gearbox may encounter. Misalignment was likely to occur as many of the frame components were cut using an often-imprecise

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[38] Automated Machine Systems Family of Companies. *Trash Belt Conveyor*. URL: `https://www.automatedmachinesystems.com/product/trash-conveyor/` (visited on 04/05/2021).

horizontal bandsaw, leading to small dimensional inaccuracies in assembly. Thick padding was also added between the motor and the plate attaching it to the conveyor belt frame to reduce vibration and comply with the recommended mounting configurations.

4.2 Software

The functional objectives for the software are outlined below, followed by implementation and results.

- A robot operator can turn the robot on and have it calibrate its location so that it can pick up objects at the right location.
- A robot operator can run a robot program on the Desktop, input a location, and have the robot move to that location, pick up an object, and drop it on the side.
- A robot operator can turn on the robot with the camera, and the machine vision program can recognize pieces of brown cardboard on the conveyor belt, draw a box around it, and give the center coordinates to the robot, which the robot can then move to and attempt to pick up in order to sort cardboard autonomously.

4.2.1 Control System Structure

Hardware Arrangement

Last year's team had written code and planned to place the Raspberry Pi between the Desktop and Teensy, as shown in the Figure 4.15.

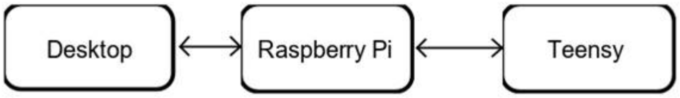

Figure 4.15: Old Hardware Setup

However, the Raspberry Pi was not put into use, and limit switch information and stepper instructions are transmitted directly between the Teensy and the desktop during execution. To minimize unnecessary code, the setup was changed to have both the Pi and Teensy communicate with the Desktop, as in Figure 4.16.

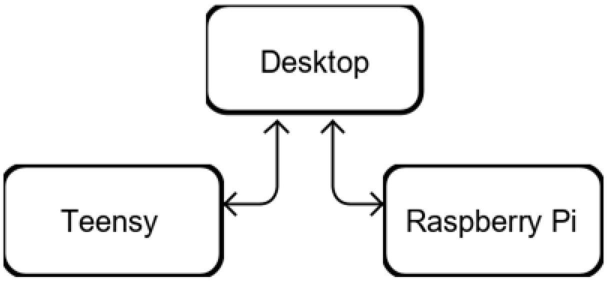

Figure 4.16: New Hardware Setup

Desktop Setup

The team had a desktop computer that was not yet set up. To keep the code up to date, the desktop was booted with Ubuntu 20.04 (the preferred platform for ROS Noetic) and the necessary software was downloaded, including ROS noetic and python 3 (see set-up instructions for details). The GitHub project was then cloned to the desktop. The GitHub repository for the project was created to make version control and collaboration easy. The desktop allows for easy editing of the code, particularly if one is not able to run some of the software, such as ROS, on a laptop.

ROS and Code Structure

Three changes were made this year with respect to ROS and code structure. First, the ROS version used in the project was updated to the thirteenth ROS release, ROS Noetic Ninjemys. Second, the python version was updated from 2.7 to python 3. These changes were made to keep the program up to date. Third, a new class diagram was also drafted to better understand how the code might work and to reflect the file structure.

As mentioned in the methodology, the previous team proposed using ROS to organize the desktop code. ROS Noetic was therefore downloaded to the desktop. Specifically, in this project, ROS would provide the following capabilities and functions:

- ROS would be the launch-point for the files that form the control system.
- Using ROS allows classes/files or “nodes” to be written a variety of languages (python, C, etc.), and allows for the use of the many existing code libraries written as ROS nodes (this collaboration in robotics software development is a big reason ROS was built).
- ROS would manage communication between nodes (which may be classes/threads/components of the program). Instead of having to implement communication between a python node and a node written in C, each class simply meets the ROS communication standards: each node provides publicly defined “services” (functions) and sends and receives

> “messages” (parameters and return values). ROS handles getting the information to the right place by providing a built-in observer/observable environment. ROS master is called to set up this environment. Then each node can publish channels to which that the node posts information, and can subscribe to channels other nodes publish.

Using ROS was new to this year’s team members. After many unsuccessful attempts at running the controls system with ROS, this year’s code was changed to running as a python program, with the recommendation that ROS be implemented by later teams.

Documentation

The code files received from the previous team had limited documentation. This caused confusion when attempting to start working on the project in understanding what the files were meant to do and how they were related. Documenting the code was one of the first steps this year. A README file was written for each folder. Headers for each function were created to describe the function’s purpose, parameters, and return values. This documentation was updated throughout the project with the goal of keep the code clear for next year’s team.

4.2.2 Robot Code

Homing Sequence

The first change to the robot code was developing a homing sequence for the motors. Both the X-Y steppers and the arm and gripper have a homing sequence. For the steppers, the homing sequence sends the motors towards the limit switches to synchronize them to a zero position. Positions for movement throughout the rest of the run can be given based on that zero location. For the arm and gripper homing sequence, the arm is moved to a set start position and the gripper is set to its open position. From here, the arm waits for the steppers to move before it moves.

Next, a state machine diagram was created for the steppers, with different states representing homing, moving, waiting for instructions, etc. The state machine was implemented using a switch statement. The state machine starts by waiting for the start button to be pressed before running. From there, it begins moving towards the minimum limit switches. Once they hit the limit switches, the steppers move away from them and stop, waiting until the other steppers also hit their limit switches. The system sets this position (just off the minimum limit switches) as its zero position. Then, the robot waits to receive instructions (for example, receiving a location to move to pick up an object).

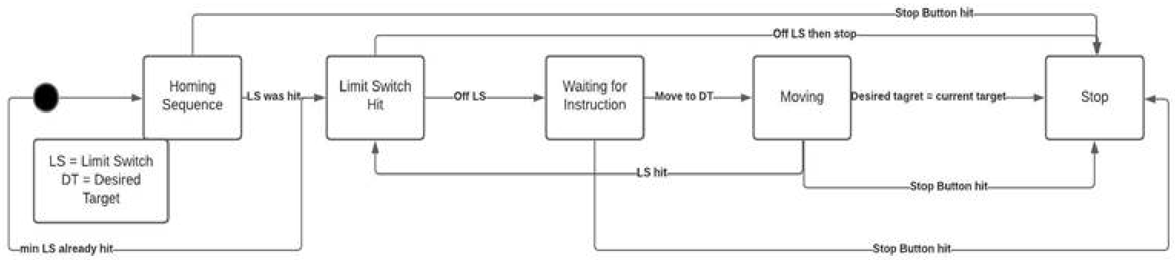

Figure 4.17: State Machine

Manual Control

Once the homing sequence is complete, the robot is ready for an X and Y position to move to. Having manual controls – allowing a person to manually enter a location – is useful for testing specific parts of the robot and while machine vision is not yet set up. When the robot is in the waiting part of the state machine, the Teensy uses serial output to ask the user to input these positions. After this is confirmed, the steppers move to that position and stop there. Once the steppers have reached their destination, the arm moves down towards the conveyor belt. When the arm is in its correct position, the gripper closes to pick up the item. From there, the robot can move back to its drop off position to be able to drop off the piece and be ready for the next item. This cycle continues until either the stop button is hit, or an error has occurred (such as something suddenly stopping or a stepper hitting its limit switch unexpectedly).

Kinematics

Using literature on five-bar parallel mechanisms, forward kinematics equations were derived to represent the movement of the arm if both Dynamixels rotate the same amount relative to the horizontal axis. From these equations, the team was able to write functions that could solve for the position of the EOAT given an arm angle. The equations these functions were based on can be found in Appendix C.

4.2.3 Machine Vision

The goal of the machine vision part of the controls system is to use images of the items on the conveyor belt to recognize target items to pick up. The machine vision node would detect the locations of target items in the image. It would then pass these locations to the node controlling the platform, arm, and gripper in order to pick up the items. The following sections describe the progress in this area.

Camera

An Intel RealSense Depth Camera D435 was chosen by last year's team to collect images. The camera has two RGB cameras and calculates the depth of the pixels in an image. This depth camera was used to be able to identify the position in X-Y-Z space of the item to be picked up. It was first tested using existing test files to see how it detected depth. The next step was for the camera to be connected to the robot frame. A camera mount was constructed to place the camera above and directly looking down at the conveyor belt in order to facilitate calculating positions for the steppers, arm, and gripper; the camera is not yet mounted.

There are various existing libraries which could be used with the RealSense camera. These include a python, C++, and ROS library. Ideally, the ROS node library would be chosen to stay consistent with using ROS throughout the project, and to maintain the ability to write other nodes that use the camera information as needed. The ROS camera node would publish the camera data on various channels to which other nodes could subscribe. However, because ROS was not yet functional for this project, the python library was used this year instead.

Images

A dataset was required to train the machine learning program to recognize cardboard. Ideally, the dataset would consist of pictures of cardboard among other items on a conveyor belt, in order to best match the real recognition task. The only cardboard existing dataset found was a set of approximately 400 images from TrashNet by (Thung, G., 2017). 85 of these pictures were used in this project. The rest of the TrashNet pictures contained cardboard as the whole picture, which is useful for image classification but not as useful for training a program to locate cardboard within an image. Another attempt at image collection was to use images from Google or Bing. However, very few of these images matched the types of images needed for this training (pieces of cardboard, among other items, close up or on a conveyor belt). A few dozen images were taken in the laboratory once the conveyor belt was set up.

The images can also be augmented in order to increase the number of images in the training set. For this year, the TrashNet images and lab images were augmented by being mirrored horizontally and vertically, and rotated 90, 180, and 270 degrees. Further augmentation could be done in the future if helpful.

The images were then marked with bounding boxes around each piece of cardboard. A program was written in Javascript/HTML to allow the user to click to mark boxes on images. However, there are existing tools for image marking such as Microsoft's Visual Object

Tagging Tool (VOTT). VOTT is easy to use for marking images. The CSV file of image annotations exported from VOTT can be reconfigured as needed to be input into a machine learning program.

Machine Learning Model

The machine learning program must be able to draw bounding boxes around pieces of cardboard in an image in real-time in order for the robot to pick them up as they move down the conveyor belt. Drawing boxes around items in a picture is known as object detection. An object detection program could have been created and trained from scratch, but there are existing pre-trained image recognition programs that are known to perform reliable object detection in real-time. One of the current best real-time object detection models is YOLO (You Only Look Once), a machine-learning neural network that can make detections at 45 frames per second.[39]

YOLO v3 was used to train various models on the images in the dataset. The first few attempts following a Yolo3 tutorial by Ang, H.N. resulted in detections that encompassed nearly the whole picture. The next few attempts following a tutorial by Muehlemann, A. resulted in much more accurate boxes, but failed to detect cardboard in many test images where cardboard was present. Results are discussed in the results section (Chapter 5), and recommendations for improvements are discussed in Next Steps (Chapter 7).

Machine learning programs can take a lot of computational power to train. The GPUs accessible through Kaggle, a machine-learning competition website, were used to train the program this year. However, other options such the WPI computing cluster, Amazon GPUs, or purchasing a GPU as part of the robot should be considered in the future.

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[39] Joseph Redmon et al. “You Only Look Once: Unified, Real-Time Object Detection”. In: *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition* 2016-December (2015), pp. 779–788. arXiv: `1506.02640`. URL: `http://arxiv.org/abs/1506.02640`.

Chapter 5

Results

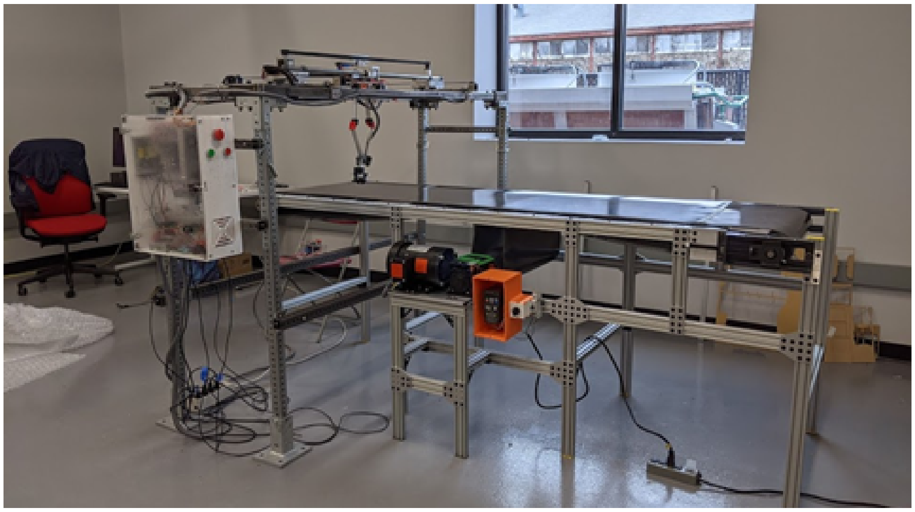

Figure 5.1: Completed Robot and Conveyor Belt

Figure 5.1 shows the completed and fully assembled robot over the conveyor belt. This chapter outlines results of this year's work.

5.1 Mechanical

The functional requirements for the arm, gripper, and robot system were as follows. The system should:

- Be able to pick up a piece of stationary dry cardboard
- Be able to pick up a piece of dry cardboard moving on the conveyor belt at 30ft/min
- Be able to pick up a piece of stationary wet cardboard
- Be able to pick up a piece of wet cardboard moving on the conveyor belt at 30ft/min
- Cease powered movement upon the activation of the e-stop button

5.1.1 Arm and Gripper

Testing was performed with the arm to ensure sufficient lifting capabilities. The arm was successfully able to raise and lower the end effector along the Z-axis, supporting the weight of the entire lift assembly along with lightweight recyclables.

The gripper was tested with a variety of materials. The arm in its extended position rests slightly above the conveyor belt surface, so materials were held directly underneath the gripper for testing. Attempts were made to mimic the gripper grabbing from the test bed by holding them with an open hand. The gripper was successfully able to grab (upon closing) and release (upon opening) soft plastics, crumpled paper, and smaller, pre-ripped pieces of cardboard. It was also able to successfully grab flat pieces of cardboard from an angle. However, for flat pieces of cardboard which had not already been damaged, the gripper was not always able to effectively puncture the material due to the plane of motion of the gripper prongs. Successful lifts with a piece of thin cardboard and a piece of thick packaging paper are shown in Figures 5.2 and 5.3. Analysis of and potential solutions to this problem are further discussed in the Next Steps chapter.

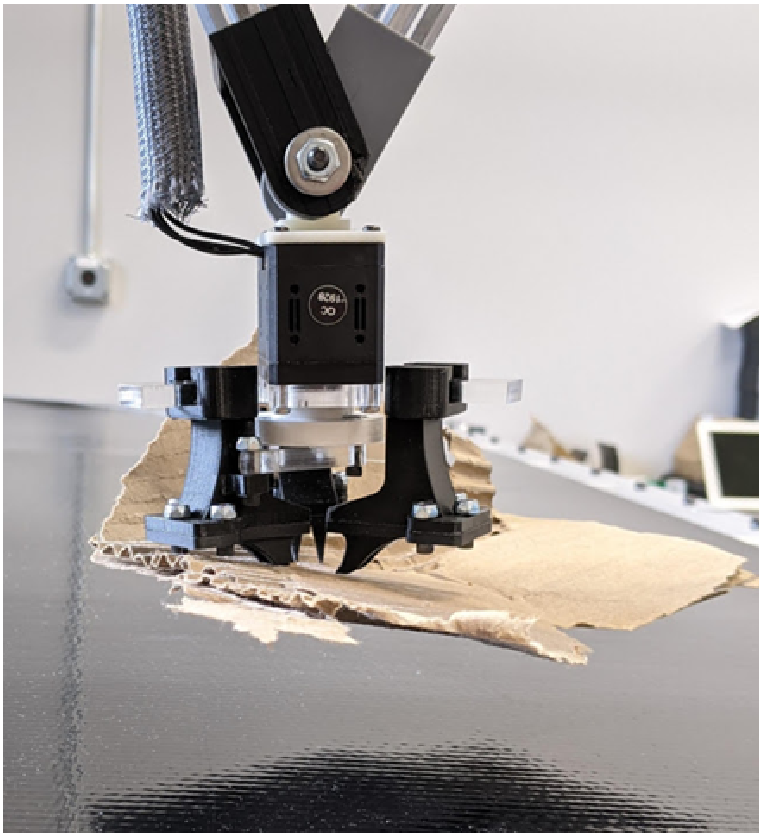

Figure 5.2: Gripper Holding Thin Cardboard

Figure 5.3: Arm and Gripper Holding Layered Packaging Paper

The arm and gripper were not tested with materials moving along the conveyor belt, because testing of the conveyor belt was postponed due to shipping delays for the conveyor drive components.

5.1.2 Robot

The robot was able to move along the X- and Y-axes with the software controls as intended. In addition, the stability of the assembly was greatly improved through the modifications described in the Design and Implementation chapter. The E-Stop button cuts power to all actuators found on the robot, arm, and gripper when pressed. The robot resumes motion when the E-Stop is released. The supporting structure of the robot is stable when the robot is in motion.

Slack in one of the Y-Axis belts sometimes causes the Y-Axis carts to begin movement at different times, resulting in the linear bearings catching on the rails. The steppers were run at 400steps/s (or the belts moving at 7.5in/s) as the frequency of the bearing getting caught increased as speed of the system increased. Running at this speed allows the robot to operate at approximately 570 picks/hour, as opposed to ZenRobotics' FastPicker system that can operate at a maximum of 4000 picks/hour.[40] To achieve a quarter of the FastPicker's speed, the stepper motor on the X-Axis must travel at 5500 steps/s.

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[40] See n. 34.

A similar problem occurred on the X-Axis, where the bearings would get caught on the rail when switching direction. When changing the direction of movement on the X-Axis, the force applied by the belt to the arm also changed direction, causing one bearing to get caught on its rail. This is likely because the belt clamp is not completely in line with the path of the belt coming off the pulleys as seen in Figure 5.4, creating forces on the clamp in directions other than the direction of travel. Continued use of the robot during testing is believed to have further damaged the linear bearings.

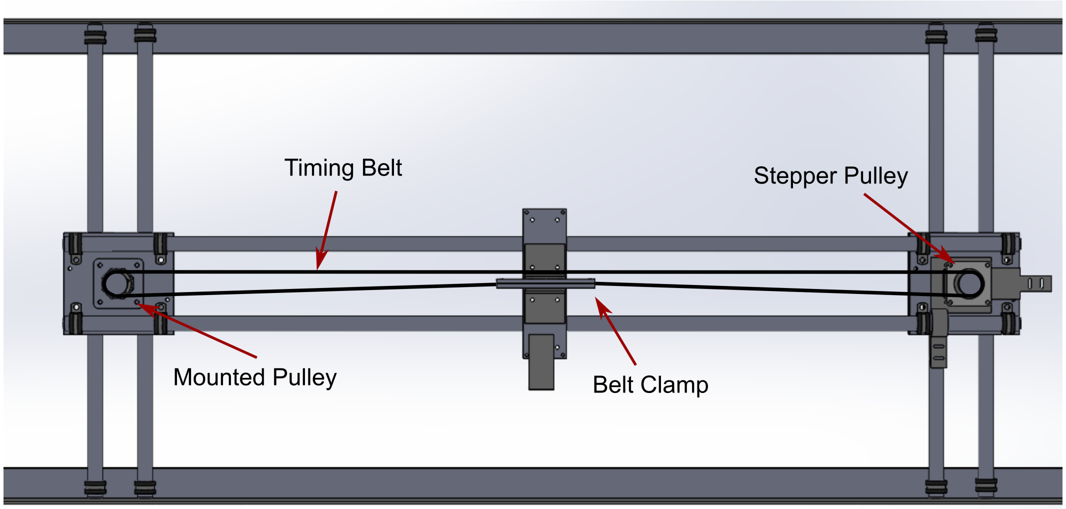

Figure 5.4: X-Axis Belt Path

Additionally, the X-Axis could not be properly mounted onto the Y-Axis carts. The intention of the previous team was for the X-axis cart to mount to the Y-axis by means of pockets milled on the bottom of the X-axis carts. These pockets were meant to connect directly to screw heads protruding from the top face of the belt clamp on the Y-axis cart. The tolerance between the slots and the screw heads was very small, so the two components could not be properly aligned. In its current state, the robot is not suitable for more rigorous testing, but was able to perform basic functions such as moving to a chosen location.

5.1.3 Conveyor Belt

The functional requirements for the conveyor belt were that the system must:

- Be between 8-10ft long
- Be between 2-3 ft wide
- Be reversible
- Operate at variable speeds
- Travel up to 60ft/min

All dimensional constraints were satisfied in the design of the conveyor belt. The system was run and found to move at the desired speed of 60ft/s. Additionally, the direction of the belt could be changed and the speed manually adjusted as necessary using the VFD. Therefore, all functional requirements for the conveyor belt were satisfied.

Preliminary work was done to implement a three-way switch to change the direction of the belt and stop it. This was not made functional due to time constraints, the minimal benefit adding using the switch would have, and recommendations that the belt should eventually interface with the desktop via the PLC. Power could be cut off from the system by using the circuit breaker fed to the VFD.

5.2 Software

The functional objectives conceived at the beginning of the year and their results are described below.

Homing Functional Objective: A robot operator can turn the robot on and have it calibrate its location so that it can pick up objects at the right location.

Results: The homing sequence is implemented with switch cases. When testing this, the robot was able to move towards the minimum limit switches and initialize that as its zero position. One error in the homing sequence was that if the X limit switch was hit first, then once the Y switch was hit, the X would home again. The arm and gripper's homing sequence was to move to a set position above the conveyor belt with the gripper open. This was successful when testing without any issues.

Manual Control Functional Objective: A robot operator can run a robot program on the Desktop, input a location, and have the robot move to that location, pick up an object, and drop it on the side.

Manual control was implemented and successful when tested. Starting with the steppers, the user is asked for a four digit number for the X stepper and a three digit number for the Y steppers. The Y-steppers move less than 1000 steps from the minimum to the maximum position, thus only three digits are used. The X steppers must move around 1500 steps in order to reach the maximum position when starting at the minimum position. Both steppers would move to the user's desired position and then wait for the next positions once finished. The arm and gripper also had their own set of manual controls. They would wait for the user to input home, pickup, or stop. Home and pickup indicate specific positions the robot would move the arm to, and would determine if the gripper was open or closed. This was also successful when tested.

Machine Vision Functional Objective: A robot operator can turn on the robot with the camera, and the machine vision program can recognize pieces of brown cardboard on the conveyor belt, draw a box around it, and give the center coordinates to the robot, which the robot can then move to and attempt to pick up in order to sort cardboard autonomously.

The final model program was run on 12 test images taken in the lab, containing multiple pieces of cardboard. The model detected cardboard in only 2 of 12 test images taken in the lab. Of the 2 images with detections, only one piece of cardboard was detected in each image. These two detections, however, were accurate to within a few pixels. This is shown in Figure 5.5.

Figure 5.5: Machine Learning Example Picture

The final model that was trained and tested on the test images could be connected to the robot, but would not reliably detect cardboard. Therefore, running the robot with machine vision identification of cardboard was not achieved this year. Recommendations for next steps are discussed in Chapter 7.

Chapter 6

Ethical Implications

6.1 Engineering Ethics

The Fundamental Principles, taken from the American Society of Mechanical Engineers (ASME) Code of Ethics of Engineers, is stated as follows:

Engineers uphold and advance the integrity, honor and dignity of the engineering profession by: i. using their knowledge and skill for the enhancement of human welfare; ii. being honest and impartial, and serving with fidelity their clients (including their employers) and the public; and iii. striving to increase the competence and prestige of the engineering profession

Our project upholds these standards by working toward an alternative to the labor-intensive and dangerous work in the waste sorting industry. In working to find an automated solution, we also hope to make the recycling industry more efficient, which is essential to reducing the amount of waste that ends up in landfills and pollutes the earth, thus enhancing human welfare. We also worked to be honest and impartial in our work, and to contribute positively to the competence and prestige of the engineering profession.

The ASME Code of Ethics of Engineers also provides ten fundamental canons for engineers to follow, which we have also worked to uphold where relevant in our work. The first fundamental canon states:

1. Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.

Our goal is to accomplish building a robot we hope will benefit the environment, laborers in the waste sorting industry, and society. In the development of this robot, we have taken measures to ensure our work is of a high level and will operate as intended (i.e. not failing in a way that could cause harm to humans). To act as a safeguard in case of unexpected issues during use, we have taken steps to implement safety features (for example, by use of guard rails and e-stop on our robot). The Societal Impact section of this chapter elaborates on how our project upholds this standard.

Another relevant canon is the eighth, which states:

8. Engineers shall consider environmental impact and sustainable development in the performance of their professional duties.

The overall environmental harm done in the manufacture of the robot (materials, shipping costs, etc.) is exceeded by the environmental benefit we hope for it to provide. This is elaborated upon in the Environmental Impact section of this chapter.

6.2 Societal Impact

The robot developed for this project is meant to aid research in automation of the waste sorting process in recycling facilities, allowing for lower contamination rates and higher recycling rates at MRFs. The ethical implications of automating the workplace is a controversial topic. In many cases, automation in the workforce is met with resistance due to concerns about human workers being replaced. The impact of automation on human workers is dependent on the company and the robot. In some scenarios, automation is used alongside humans, such as in the case of collaborative robots, changing the human worker's job responsibilities. For example, in assembling a product, a collaborative robot may be responsible for applying glue to a part, a task often requiring precision. A human may then take the part and assemble the remaining pieces. In other cases, automation may replace the human who once performed a task. For example, robot with a welding attachment may take the place of a human welder. When considering the impacts of automation in the workplace, it is important to note that there are varying degrees in which human workers are affected.

In MRFs, the effect might be somewhere in the middle. Waste sorting robots in MRFs decrease the need for human sorters but create a demand for more robot operators: people who can maintain and support the deployment of robots. This new role, as well existing jobs in other areas of the MRF, allow people whose jobs were taken by robots to find purpose elsewhere in the company. More research needs to be done on the impact of such automation to the workforce of the recycling industry. As part of automating the workplace, a company must be aware of their employees' wellbeing. Articles from Forbes, MIT, and Stanford concerning ethics and automation suggest that a responsible company should provide employees with training and support to transition to new roles within the company or find work elsewhere. Additionally, engineers behind the automation must be aware of the impact their work may have on the livelihood of these employees (Mayor, 2019). However, many of these articles are from technology-related businesses or institutions, which may impose potential bias.

Despite the controversy associated with automation in the workplace, our goal with this project is to provide current human waste sorters a better work environment. Implementing robots in MRFs will limit the number of people working in the harsh environment. The dangers of working at a waste sorting facility, where the rate of workplace injuries is high, will be greatly reduced. For example, human sorters will not be at risk for repetitive-motion injuries and employers can worry less about worker injuries from sharp or potentially toxic materials on the line. The hope with implementing automation is that dangerous jobs such as waste-sorting will no longer fully rely on humans, and that those that once worked these jobs will find better working conditions, whether this be within the current company or elsewhere.

6.3 Environmental Impact

The goal of this project is to design and build a robot that can help assist in advancing research on recycling and waste sorting. While there are material and shipping costs associated with robot, as well as costs to run the machines used to manufacture parts, these will not outweigh the positive environmental impact we hope this robot will have. Research based on our work will help to improve existing technology, increasing productivity and accuracy in recycling facilities. In MRFs, this will translate to less contamination and more throughput, allowing more materials to be recycled. Thus, less recyclable material will be sent to landfills, reducing further pollution of the environment.

6.4 Codes and Standards

Research was done to identify any technical codes or standards governing our work. ASME's database of codes and standards does not list anything related to robotics or recycling; however, an ASME standard governing the use of robotic arms is currently in the initial stages of development. OSHA currently does not have specific standards for the robotics industry; however, the website lists several relevant standards relating to use of robots in the workplace. Most notably, these include ISO (International Organization for Standardization) codes on safety requirements for robots for industrial environments (ISO 10218-1 and 10218-2) and safety design for end-effectors (ISO/TR 20218-1). These standards specify requirements and guidelines for safe design, integration, and use of robots in industrial environments. We have worked to design and build this robot with human safety at the forefront of our considerations.

Chapter 7

Next Steps

7.1 Mechanical/Electrical

7.1.1 Gripper

Based on testing results, the gripper is effective in picking up smaller, less dense, and angled or elevated pieces of cardboard. However, for flat pieces of cardboard which have not already been damaged, the gripper cannot always effectively puncture the material. This is because the gripper prongs move along one plane. This is effective for picking up many materials, and the current gripper is able to pick up most other small and lightweight items with ease. However, if cardboard remains the focus for this project, this problem should be addressed in the next iteration. Some potential solutions include:

- Adding an additional piercing component to the gripper which creates a downward piercing motion along with the inward motion of the carts (this could be added onto the current system, or be created as a new end effector that can be swapped out with the current one)
- Implementing a method of turning the gripper so that it can pivot about the Y-axis, allowing for it to grip pieces of cardboard from the side

Potential future work for the gripper can also include developing additional EOAT which can be interchanged with the current system to pick up waste pieces of different sizes and materials. One option that was researched during this year's project was vacuum EOAT. Vacuum grippers can pick up most lightweight materials with ease, regardless of shape, due to the flexible suction cups found in these systems. However, vacuum systems are expensive, and other mechanical systems can be designed to achieve similar results. Vacuum EOAT was not implemented due to the cost of this technology and the versatility of the existing system, but this could be a consideration for future teams.

7.1.2 Cable Drag Chains

Due to time constraints, the cable drag chains were not properly mounted to the robot. Currently, there is no part of the robot for designed for the drag chains to be mounted, so temporary components have been manufactured and fastened to the robot with zip ties. Movement of the robot is hindered by the placement of drag chains. Steps should be taken to improve the current system to avoid interference of robot movement and more secure methods of connecting the drag chains to the robot.

7.1.3 Belt Tensions

The current system requires that the belt be tensioned by moving the belt one tooth tighter within the belt clamps found on top of the arm cart and in between the plates of the Y-axis carts. This requires some disassembly and is often difficult and sometimes impossible to accomplish. The next team should introduce idlers or a tensioning mechanism to easily tension all the belts, making installation and tensioning of belts much easier.

7.1.4 X-Axis

The part manufactured to replace the structure supporting the pulley on the X-axis was made under time constraints, as the previous team's component broke during the last week of the project. Currently, this component simply acts as supporting piece for the pulley drum and shaft. Future teams can improve on this design if desired. For example, a bearing could be press-fit into the mount, creating less friction when the shaft is spinning and the X-axis is moving. As with the Y-axis, the X-axis should also include a mechanism to introduce belt tensioning.

7.1.5 Wiring

Wiring of the robot, specifically in the enclosure, should be better organized. The connections with the Teensy can be made cleaner, more secure, and more compact by designing and manufacturing a PCB where the Teensy can be attached. The connections that were once made from the breadboard to other components such as switches and drivers should then be made using screw terminals, allowing for a more secure connection and eliminates the need for crimping DuPont pins to make connections.

7.1.6 Safety

Additional safety features should be implemented to the system. The current relays should be replaced with relays marketed specifically as safety relays. Other methods of safety should be integrated into the system to prevent harm to people working in the nearby area. For example, laser fences could be implemented to stop the robot when they sense that someone has entered the robot area. Another solution could be installing a laser proximity system that senses how far someone is from the robot. Different distance ranges could be established, and the robot's speed vary with each area.

7.1.7 Conveyor Belt

The conveyor belt in its current state tracks to one side of the pulley on the end of the belt opposite from the tensioners. Running the conveyor belt over an extended period of time leads to the belt moving towards one side of the conveyor system, going over the side of the pulley drum. Future teams should address this problem before using the belt for long periods of time. Manually adjusting the belt tension by tightening the tensioners on one end may resolve this issue.

7.2 Software

7.2.1 Arm Control

The Dynamixels should be tested to tune PID settings of the internal controller. Kinematics for the arm were started, but not completed. These kinematic equations assumed that the two Dynamixels were driven to the same angle with the horizontal axis. The equations should be improved upon to account for different angles with the horizontal axis. This can also lead to more trajectory planning opportunities for future teams. Once the kinematics are improved, they should be implemented in the program controlling of the arm.

7.2.2 Connecting Conveyor Belt to the Robot Movement

The VFD installed to control the conveyor belt has a built-in PLC that allows the user to read and write to the VFD, controlling the speed of the belt during operation. This control should be implemented in the next iteration of the robot. If the proximity sensor suggestion from the mechanical safety section is implemented, this will allow the system to autonomously operate, slowing down the robot and conveyor belt when a human comes close to the system. Because the camera is positioned ahead of the robot on the conveyor belt, the robot could also be programmed to automatically adjust to changes in conveyor belt speed.

7.2.3 ROS Communications

ROS was not successfully implemented in the robot software this year due to issues with packages and file paths. Setting up ROS on the desktop could facilitate communication between software components, standardize the code, and allow ROS libraries to be used. Completing the ROS implementation could be a useful next step.

7.2.4 Machine Vision

In order to achieve machine vision, a few steps are recommended. The camera should be connected to the desktop. If ROS is implemented, the RealSense ROS library can be used, otherwise another library such as the python library can be used. Pixel locations and depths provided the camera need to be converted into locations for the steppers, arm, and gripper to move to. A machine learning model can then be used to predict bounding boxes in the images and send those bounding boxes for position calculation. In order to improve the machine learning model, more images should be collected and labeled. This could include taking pictures in the lab and marking them, which takes less time than one might expect. The images can be augmented. The model itself can be improved, either by tuning the parameters of the YOLO v3 model, exploring other models, or creating a model from scratch. Additionally, the team might consider adding a GPU to the robot setup if needed to process enough frames per second.

7.2.5 Testing

It was assumed test-driven development would work with the robot the same way it works in software development with Java Junit tests or python unittests. However, robot testing required in-person testing, which made implementing robot functionality difficult for remote team members. If any members of the team are remote next year, they might aim to develop a better testing and simulation system to facilitate remote robot work.

Chapter 8

Conclusion

This year's team completed in-depth background research to identify waste-sorting needs within the recycling industry, and based on these needs, expanded upon the development of a robot to address them. The robotic system from the previous year's team was improved upon with modifications to the robot frame, arm and gripper assembly, electrical system, and software. In addition, a conveyor belt setup for testing was designed and built to meet all testing requirements, and a machine learning algorithm was developed to advance the robot towards autonomy. This work resulted in a highly capable robotic system able to pick up a variety of recyclable materials, contributing to the overall goals of this research, with many potential areas of expansion for future teams. By the end of this year's project, the robot was fully assembled and able to manually execute actions, with all components tested and moving as directed.

Future work for this project may include expanded EOAT, additions and modifications to the electrical setup, implementation of ROS, and completed machine vision as detailed in the previous section. Teams may also explore adding to the conveyor belt system, requiring less human involvement in the testing process. Following these recommendations will help lead towards a more autonomous testing system. The accomplishments of this year's team, built on the previous year's work, have resulted in a preliminary robotic waste-sorting setup to be used for research and further development at WPI.

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Appendices

A Electrical Enclosure

Dimensions and other details:

- Width = 16in
- Height = 20in
- Depth = 6in
- $V = Volume = 1920in^3 = 0.03146m^3$
- $T_{max} = 104°F$[41]
- Q = Heat Produced
- Q_{ea} = Heat Produced
- Q_{aw} = Heat Produced
- Efficiency = 90%
- $c = 1.005\frac{kJ}{kg \cdot K}$
- $h = 10.45\frac{W}{m^2 \cdot K}$
- $\rho_{air} = 1.255\frac{kg}{m^3}$

Table 1: Summary of Power Lost

Power Supply Model	**Voltage [V]**	**Current [A]**	**Output Power [W]**	**Heat Produced [W]**
LRS-50-24	24	14.6	52.8	5.86
LRS-150-24	24	6.5	156	17.3
LRS-350-24	24	2.2	52.8	38.9
			Total Heat Produced (Q)	62.13

$$Q = \frac{OutputPower}{Efficiency} - OutputPower \tag{1}$$

$$m = \rho_{air} \cdot Volume \tag{2}$$

$$Q = Q_{ea} + Q_{aw} \tag{3}$$

$$Q = mc\Delta T + hA\Delta T$$

$$\Delta T = \frac{Q}{mc + hA}$$

$$\Delta T = 1.325K$$

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[41] Applied Motion Products. *STR3 Hardware Manual.* Tech. rep. 2018.

B Conveyor Belt Calculations

Constants used throughout calculations:

- S = 60ft/s = belt speed
- b_0 = 24in = belt width
- μ_R = 0.38 = coefficient of friction over rollers
- μ_T = 0.38 = coefficient of friction over slider bed
- m = load mass
- m_b = mass of all rollers and pulleys
- m_R = mass of all rollers and pulleys
- w = load weight
- w_b = belt weight = 37.77lb
- w_R = weight of all rollers and pulleys = 73.97lbf
- C_1 = 1.5 (Factor accounting for 180○ with smooth steel drum)
- $k_{1\%}$ = 86lbf/in = Relaxed belt pull at 1% elongation per unit of width
- K = 0.62 = coefficient for drive type

Horsepower Needed (HP)[42]

$$HP = \frac{\mu_T x S x (w_b + w_R)}{33,000} = 0.0399 \tag{4}$$

Maximum Effective Pull or Effective Tension (F_U)

$$F_U = \mu_T \cdot g \cdot (m + \frac{m_b}{2} + \mu_R \cdot g \cdot (m_R + \frac{m_b}{2}) \tag{5}$$

$$F_U = \mu_T \cdot (w + \frac{w_b}{2} + \mu_R \cdot (w_R + \frac{w_b}{2})$$

$$F_U = \mu_T \cdot (w + w_b + w_R) = 50.06lb$$

Maximum Belt Pull or Slack Side Tension (F_1)

$$F_1 = F_U \cdot C_1 = 75.09lbf \tag{6}$$

Elongation / Take-Up Length (ε)

$$\varepsilon = \frac{F_U \cdot (C_1 - K)}{k_{1\%} \cdot b_0} = 2.1\% = 4.87in \tag{7}$$

Steady-State Shaft Load (F_{WA})

$$F_2 = F_1 - F_U = 25.03lbf \tag{8}$$

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[42] Sparks. *Understanding Conveyor Belt Calculations — Sparks Belting.* URL: `http://www.sparksbelting.com/blog/understanding-conveyor-belt-calculations` (visited on 04/01/2021).

$$F_{WA} = F_1 + F_2 = 100.12lbf \tag{9}$$

Steady-State Shaft Load Snub Roller[43] (F_{WR})

$$F_{WR} = \sqrt{2 \cdot F_2 \cdot sin(\beta/2)} = 11.90lbf \tag{10}$$

Tight-Side Tension (E_2)

$$E_2 = F_U + F_1 = 125.15lbf \tag{11}$$

Operating Tension (T)

$$T = E_2/b_0 = 5.21lbf/in \tag{12}$$

Radial Load[44] (R)

$$R = F_U + 2 \cdot F_1 = 200.24lbf \tag{13}$$

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[43] Forbo Siegling. "CALCULATION METHODS - CONVEYOR BELTS". in: 305 (), pp. 1–16.

[44] Sparks, see n. 42.

C Forward Kinematics

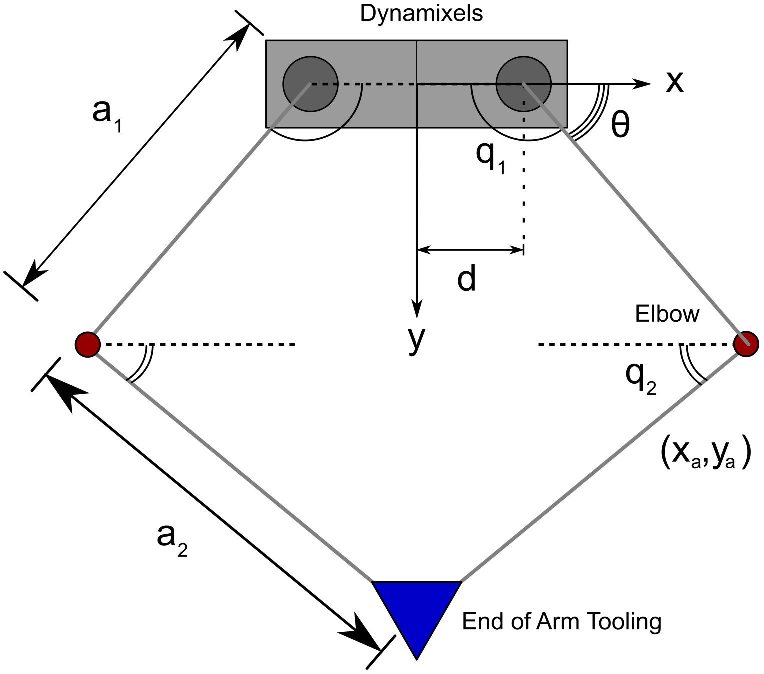

Figure 1: Forward Kinematics Diagram

These equations represent the movement of a five-bar linkage where the angle of the both arms with the horizontal are the same and are a simplified version of the ones created by Khalil and Seif.[45] x is assumed to always be 0 if the arms are sent to the same angle compared to the horizontal. As a result, only y needs to be solved for.
Dimensional Constants:

- $a_1 = 111.28$
- $a_2 = 146.605$

$$q_1 = \pi - \theta \tag{14}$$

$$x_a = a_1 cos(q_1) \tag{15}$$

$$y_a = a_1 sin(q_1) \tag{16}$$

$$q_2 = arccos(\frac{x_a + d}{a_2}) \tag{17}$$

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[45] Islam S M Khalil and Mohamed Abu Seif. *Modeling of a Pantograph Haptic Device Kinematics of the Pantograph Haptic Device*. Tech. rep.

$$y = a_1 sin(q_1) + a_2 sin(q_2) \tag{18}$$

$$J = \begin{bmatrix} -a_1 \cdot sin(q_1) & -a_2 \cdot sin(q_2) \\ -a_1 \cdot cos(q_1) & -a_2 \cdot cos(q_2) \end{bmatrix} \tag{19}$$