ECE 480 Design Team 16 Final Report

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Maximizing Use and Efficiency of Robotic Sorting Technology

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Executive summary

Design Team 16 was selected to complete a project for the MSU Surplus Store and Recycling Center (SSRC) and AMP Robotics. The project was composed of three separate objectives, the first being to improve the SSRC operations to improve productivity. The second objective was to design and implement a prototype to reduce chute misses. The third objective was to design and produce a burden depth prototype for the AMP Robotics sorting arm. Objective one, to improve operations, was met by investigating changes in the priority of objects and in methodically sorting the conveyor line. Results showed that setting the priority of the robotic picking system to select for the objects that most commonly run down the line increases the picks per minute rate the most. To meet the requirements of objective two, a chute shield was designed to divert recyclables into the chute openings and prevent spillover when the robot is off. The final design reduced chute misses and a permanent version is scheduled to be made of steel and plexiglass in the coming months. The third objective resulted in two separate methods to gather burden depth, the first being a Laser Ladder and the second being an implementation of a LiDAR sensor. The results of the Laser Ladder showed that it was a simple and low cost solution to achieve an approximate burden depth estimation of material of the plant's conveyor belt down to the distance between lasers (in the prototype, this was 2”). The LiDAR system that was implemented produced more accurate data and was concluded to be the more practical of the two systems, but struggled with clear materials. Overall the depth sensing would allow for obstacle avoidance and alter the priority of materials to be grabbed.

Acknowledgements

Design Team 16 for ECE 480 Spring 2022 would like to thank their facilitator, Dr. Daniel Morris for his role in answering questions and offering feedback throughout the semester. Team 16 would like to thank Mr. Dave Smith and Mr. Sean Barton at the MSU Surplus Store and Recycling Center for their flexibility in down times of the robotic system, their regular communication with the team, and their financial support in this project. This team would like to thank Ms. Amanda Marrs, Mr. Alex Laydon, and Mr. Matthew Stanton at AMP Robotics for their roles in helping the team identify the functionalities and capabilities of the robotic arm and their financial support in this project.

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Chapter 1 - Introduction and Background

Introduction

As consumption of plastic packaged products grows, so does the importance of finding sustainable and effective ways to dispose of them. In 2006, Michigan State University (MSU) launched the "Be Spartan Green Environmental Stewardship Initiative" to help reduce the impact of Spartans on the environment [1]. Now, MSU is home to the Surplus Store and Recycling Center (SSRC) that processes between 20 to 25 million pounds of material annually. Of that material, 8 and 9 million pounds comes from recycling material from MSU's campus in their material recovery facility (MRF) [2].

MRFs rely on the speed and accuracy of sorters to effectively bale recyclables for sale. Traditionally, these sorters were humans who would load and hand sort the line. More recently, in the rise of artificial intelligence cyber-physical systems, robotic sorters have been developed to surpass the speed in picks per minute of human sorters. Robotic sorting systems can nearly double the speeds achieved by human sorters [3]. In the context of MRFs, this increased speed directly correlates to increased profits for the facility. An additional benefit provided by the robotic sorting systems is a decrease in risk to employees. The position of sorter includes the risk of encountering sharp and toxic materials such as broken glass, needles, and medications. Robotic sorting arms can take on and mitigate this risk.

MSU SSRC began investigating the implementation of one such sorting robot [4]. With a $250,000 grant from the Michigan Department of Environmental Quality's Environment, Great Lakes, and Energy, MSU bought AMP Robotics Cortex delta armed robotic sorter [5] to add to their MRF. The main goal of the addition of this AI powered sorter is to reduce human interaction with the recyclables to mitigate future risk of exposures to dangerous materials by increasing the efficiency of the robotic sorting arm.

Problem Statement

In regards to both workers and the AMP Cortex, the safety and efficiency of MSU's recycling process are suboptimal. First, the recycling line is not loaded in a way that fully utilizes the efficiency of the AMP Cortex. In addition, the AMP Cortex often misses the correct recycling chute, or causes materials to go down an incorrect chute by dragging non-targeted items across the belt. Also, since the AMP Cortex obtains no depth information, it may try to compress an object that is non-compressible, which can cause expensive damage to the robot.

Thus, the aims of this project can be broken down into three main objectives, each rooted in the prospect of reducing the number of employees interacting with the recyclable materials and increasing their effectiveness. Firstly, ECE 480 Team 16 works to identify processes to optimize the use of the AMP robotic sorting system at MSU SSRC through increasing the number of picks per minute performed by the robot. Secondly, the work constructs additions to the chutes in which recyclable materials are sorted to reduce instances of spillover. Thirdly, this project investigates the addition of a sensor to the Cortex system to identify the burden depth, height, of the recyclables on the conveyor belt.

Prior Work and Shortcomings

The AMP Cortex is an intelligent robotics system that is used for identifying and sorting recyclable materials to increase the overall efficiency of recycling centers. For picking and sorting recyclable materials, a worker will have an average of about 40 picks per minute (ppm), whereas the Cortex can operate up to 80 ppm. The identification system that the Cortex system uses to sort materials is AMP Robotic's Neuron system. The Neuron is an artificial intelligence and computer vision system that is regularly being re-trained from the images it captures in recycling centers. After identification of the material, the Neuron then guides robots to pick and place the material to be recycled [6]. From the combination of the Neuron and the Cortex the overall system is able to identify materials such as municipal waste, electronic waste, and also construction and demolition, double the sorting output of a recycling center, and also provide safety as it prevents workers from being in close contact with sharp objects or dangerous substances.

Evergreen, a bottle recycling plant located in Clyde, Ohio, was an early adopter of AMP Robotic's Cortex robot. This facility has six Cortex robots on its quality control and residue lines that pick and sort a numerous amount of plastic bottles. The implementation of the robots led to a 200% increase in picks per minute [5].

In 2021, the MSU SSRC purchased and integrated an AMP Cortex robot into its plastic and metal lines in order to increase the overall efficiency and safety for its workers [4]. The workflow of the Recycling Center starts with manually pre-sorting out high density polyethylene (HDPE) colored recyclables, HDPE natural recyclables, and any materials over the 11" clearance of the robotic arm from the conveyor belt. After this, the remaining polypropylene 5 (PP5), polyethylene terephthalate (PET), and non-recyclables under 11" are sent down the line where the Neuron system identifies and categorizes the items and determines which chute it should be dropped into or if it should continue as a non-recyclable item. Finally, the Cortex system picks and places the PP5 recyclable or PET recyclable into the chute it identifies in the Neuron classification system.

Since implementing the AMP Robotic's Cortex system, MSU's Recycling Center has seen a relative increase in efficiency; however, the Cortex system is not reaching its ideal pick rate of 80ppm. The Cortex system is capable of replacing up to four workers, but at its current rate is only replacing two [4]. Assuming the ability to increase the picks per minute rate of the robot, problems still remain impacting the accuracy and efficiency of the Cortex robot at MSU's SSRC. It is not uncommon for the Cortex system to miss the item that was identified from the Neuron system due potentially to poor suction or movement of recyclables between the vision system and the grabber cage. Another shortcoming of the system is that when the robot goes to pick and place an item into a chute, it does not take into consideration the other recyclable materials around the target item which then may be dragged with it. This can cause materials to be placed in incorrect bins leading to bale contamination. Assuming the Cortex arm guides the recyclable, for example water bottles and milk jugs, to the correct chute, sometimes they will bounce out and spill into the incorrect chute as well or become lodged between the chutes requiring downtime to unclog the system.

Objectives

The AMP Robotic's Cortex system is a powerful robot that is being used in many well-known recycling centers. The larger recycling centers use a series of robots to sort various materials off the line with limited human interaction. On the other hand, MSU uses manual pre-sorting methods prior to sorting with the robot, which has many downsides. As mentioned earlier, not only is this method less efficient than multiple high-speed robotic sorters, but it also introduces potential health hazards for the employees working on the line. This project aims to improve the sorting mechanism, ultimately decreasing the potential hazards that the workers might face through three major objectives.

The first major objective is to increase the efficiency of the uses of the Cortex system at MSU's SSRC. The team investigated changing the priorities of each recyclable on the line and the organization of the load of the line as variables in improving the picks per minute rate of the Cortex arm. Prior to the team's work in the SSRC, the robot was programmed to prioritize PP5 and PET plastics without relation to the height of the objects or relative frequency of the object. This work aims to reduce problems such as collision on the conveyor belt and failed pick attempts by altering the standard operations in the pre-sort line and the sorting priority.

One of the main problems with the Cortex sorting arm is that it often misses the chute openings through dragging materials along the line or materials bouncing out of the chute leading to downtime for unclogging the chute side of the robotic cage. An additional problem is that when non-targeted materials, such as paper, are run down the line, spillover causes contamination of the bunkers. In order to reduce instances of missed drops and contamination spillover, this project altered the chutes directing the recycled material to the designated sortation bunkers and allowing for closing the chute to non-targeted items. This chute redesign represents the second major objective of this project.

The third major object of this project involves proving the feasibility of the implementation of additional sensors and cameras that could improve the AI sensing of the robot. The additional sensors make it possible to determine a volumetric estimate of the objects before selecting to pick it up. Such improvement in the robot's filtering mechanism can eliminate potential dense and hard objects that will damage the carbon fiber arm and may allow for object avoidance algorithms to be enabled.

Chapter 2 - Technical Description

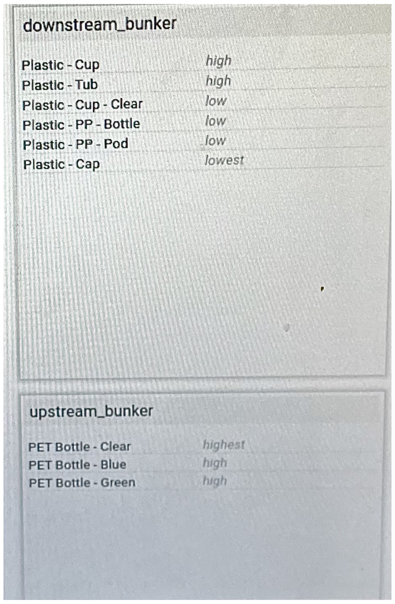
Operations Objective

The first objective is to develop recommendations on how to maximize the use of the robotic sorting technology by increasing the number of picks per minute (ppm) performed by the robot. As aforementioned, the robot located in the SSRC is only operating around an average pick per minute rate of 40ppm, much lower than AMP's claim that each robot will operate at 80ppm. There are two variables that affect how efficient the robot is able to sort items, human presorting, and pick priority. Currently, at the SSRC up to four workers presort the recyclable items before they are sent to be sorted by the robot. Presorting items manually ensures safety to the workers and the robot. Figure 1 and Figure 2 display how the workers presort the materials that are then sent to be sorted by the robot.

Figure 1: Presorting recyclable materials

Figure 2: Items entering the robots vision system to then be sorted

It is not uncommon for dangerous items such as 16oz propane tanks or larger items that will damage the robot's arm to be found on the recycling belt. Sharp objects such as syringes or needles may also be seen on the line, and these will need to be presorted to protect the robot. The second variable that affects the efficiency of the robot is the pick priority. Using a 5-point likert scale, the robot also assigns a priority to each of the plastics from lowest to highest. Both the PP5 and PET plastic types are subcategorized and assigned a priority manually set by the SSRC. Figure 3 shows a picture of the SSRC's priority settings prior to the work in this project.



downstream_bunker

Plastic - Cup	*high*
Plastic - Tub	*high*
Plastic - Cup - Clear	*low*
Plastic - PP - Bottle	*low*
Plastic - PP - Pod	*low*
Plastic - Cap	*lowest*

upstream_bunker

PET Bottle - Clear	*highest*
PET Bottle - Blue	*high*
PET Bottle - Green	*high*

Figure 3: Screenshot of AMP's pick priority system

In order to develop recommendations that will increase the pick per minute rate of the robot experiments were designed that alter the presorting process and pick priority of the plastics to identify methods to increase the pick per minute rate. For presorting, experiments were run to determine if presorting items based on the size of the item, and the predetermined priority of the item would increase or decrease the pick per minute. For the pick priority, tests were run to identify how changing the priority of PP5 and PET plastics affected the pick per minute rate of the robot. AMP stores data of what types of plastics the robot encounters through its Clarity system. The priority that was assigned to certain plastics for the pick priority experiments were based on the data the AMP Clarity system stores.

Chute Shield Objective

The second objective is to design and construct shielding to add to the existing recycling chutes to prevent misses. A miss can be defined as any material not entering the intended chute, examples include bouncing back to the belt, falling between the chutes, and/or falling into the wrong chute. The goal of this design focuses on mitigating misses from each of those categories.

Figure 4: Photograph of recyclables lodged between the chute and cage.

The design proposed (Figure 5), prototyped (Figure 6), and iterated in this project tackles the richochetting and clogging problems by suggesting the use of steel diverters to fill in the gaps between the cage and the chute openings. These are to be welded onto the edges of the chutes and conveyor line. For this project, the diverters were constructed out of cardboard and attached with duct tape to the chute openings, as seen in Figure 6.

Additionally, the design tries to reduce misses in the category of falling into the wrong chute. For this, the back panels of the diverters are attached on hinges. These hinges allow the panels to close and cover the chute opening and can be operated by a cord attached to a tie-down-ring through the back side of the cage. Oftentimes, the conveyor line is run with other materials such as paper or trash when the robot is off. This allows the SSRC to close the openings and prevent spillover into the tops of the chute bunkers when non-targeted material passes through the cage to the end of the conveyor line. These hinged diverters are to be created in reused plexiglass for the final implementation by the SSRC. This will retain visibility through the cage system and continue to allow the SSRC to show guests the functionality of the robot from either side of the cage.

Dimensions of each component can be found in Figure 29 of Appendix 3 of this document.

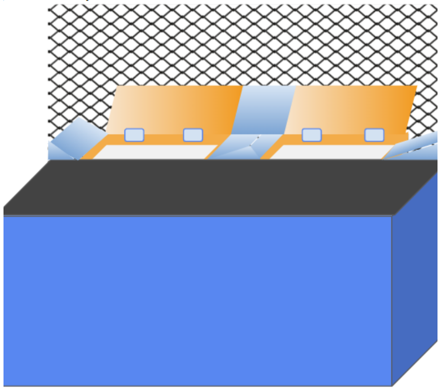


Figure 5: Proposed model of the chute diverters and lids.

Figure 6: Prototyped cardboard chute diverters and lids.

Iterations to this design for the steel and plexiglass chute shields include creating a variable sloped upstream diverter. The working region of the robotic arm spans 72” in diameter from the center of the cage where it is mounted. From this, the intersection point of the working region and the front corner of the upstream chute opening is 9.155” from the upstream edge of the cage. Anything within that working region, within the circle of Figure 7, is recommended by AMP Robotics to be under 1.5” tall. The base of the upstream bunker exceeds the 9.155” maximum and is 12.728”. To ensure the maximum of 1.5” tall at 9.155” into the cage, the front diverter slope is varied to create the front component seen in Figure 8.

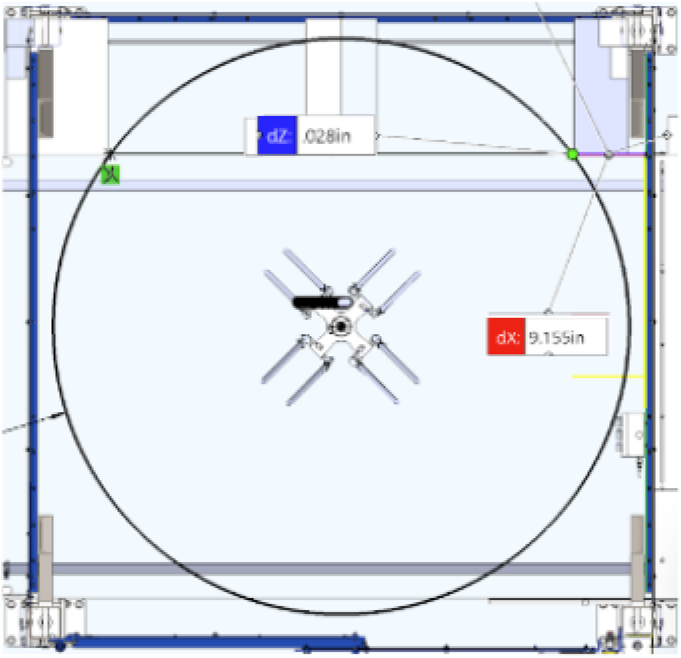


Figure 7: Working region of the robotic arm.

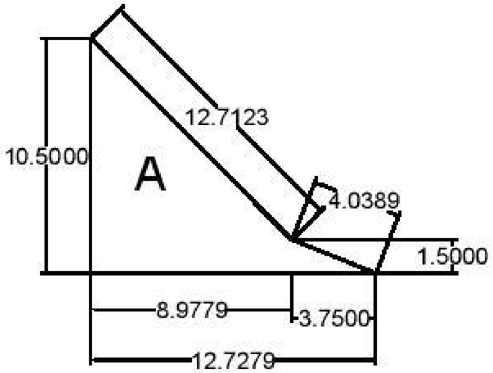


Figure 8: Front component of the upstream bunker.

The final CAD design of each of the components to create the steel and plexiglass chute shields can be seen in Figures 28 and 29 of Appendix 3.

Depth Sensing Objective

The third objective of this project was to determine the optimal placement of additional sensors in order to obtain a volumetric estimate of the objects on the recycling line. This objective aims to identify a burden depth of each recyclable on the line to prevent unintended collisions with the Cortex arm and with other recyclables on the line. Within the context of this project, two unique approaches to potentially solve this problem were explored.

Figure 9: Screenshot of AMP Robotics Identification Interface

i) Laser Ladder

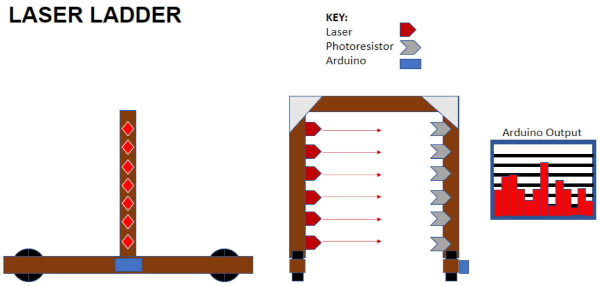


Figure 10: Illustration of the mechanisms and functionality of the laser ladder system.

The "Laser Ladder" is a relatively low-cost potential solution to obtaining the height of material on the belt. The system works by aligning equidistant lasers with photoresistors on two posts on either side of the conveyor belt. The photoresistors are light-sensitive devices whose resistance will change based on the light intensity that it is in contact with. The alignment of lasers and photoresistors is shown on Figure 10. The lasers are powered by a Raspberry PI. The transmitter circuit can be seen in Figure 11. Note that the 18 Ω resistor is a limiting resistor that ensures that the max current in each laser is below the rated max current to prevent the resistors from burning out. When an object passes through the system, depending on the height of the object, the laser will be blocked, resulting in a change of resistance in the corresponding photoresistors. Each photoresistor is in series with a 6.8 kΩ resistor. The positive voltage of these resistors are connected to consecutive GPIO pins of a Raspberry Pi and a common ground is shared. For this system, when the laser light shines directly on the laser, the photoresistor has a low resistance and, from simple voltage division, the majority of the voltage drop is on the 6.8 kΩ resistor. When no light shines on the photoresistor and it has a high resistance, there is a smaller voltage drop across the 6.8 kΩ resistor. The GPIO pins on the PI read a low when the input voltage is less than 1 V and a high when the input voltage is greater than 2.5 V. The 6.8 kΩ resistor was chosen because the voltage drop across the resistor is above this 2.5 V limit when the laser light shines directly on the photoresistor, and when blocked, the voltage drop is well below 1 V threshold. This circuit schematic for this receiver can be seen in Figure 12. Using this circuit, with code on the Raspberry PI, visualizations are created to show the highest blocked sensor and indicate that there is an object of that size on that belt. This data will be shared with the recycling center's sorting system; depending on the height set by the recycling center, the robot will then identify if the object's height could cause potential damages to the arm. This system is therefore a conservative depth sensing system that can alert a MRF when it shouldn’t pick an object since it is too big and is not worth the risk of damaging the MRF arm.

Here, for visualization purposes, the C++ program for LiDAR visualization is merged, to be discussed below, with the laser ladder visualizations. Using an open source GPIO for Raspberry PI library in C++ [9], the team collected the laser ladder data, and using that data, performed the necessary continuous time plotting.

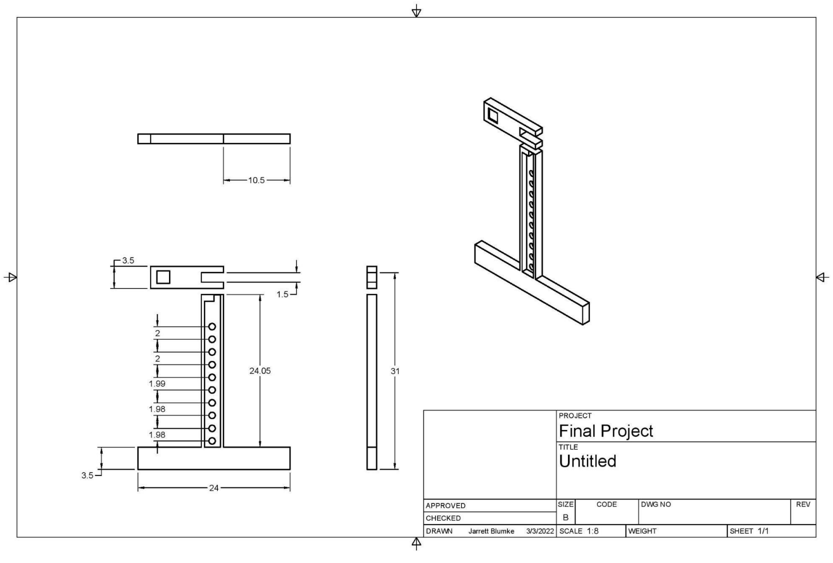


Figure 11:Design Blueprint of Laser Ladder

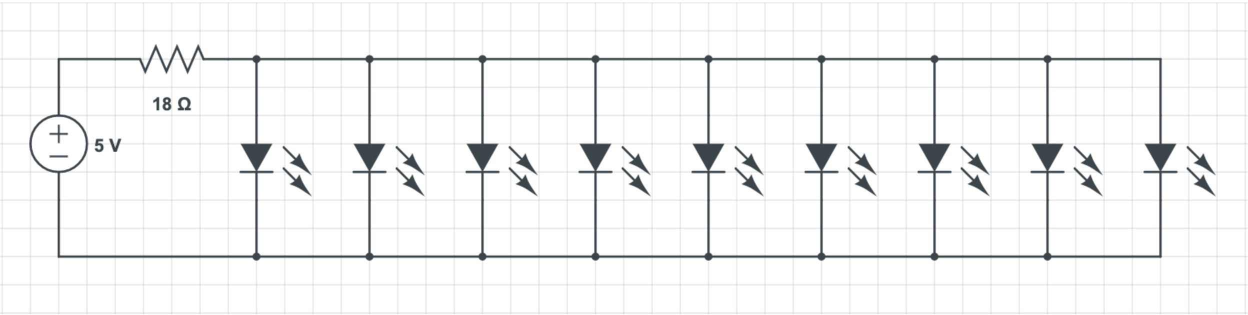


Figure 12: Laser Ladder Transmitter Circuit

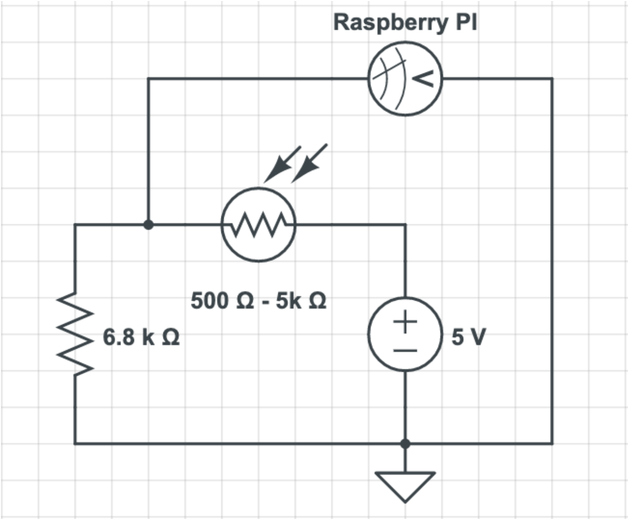


Figure 13: Laser Ladder Receiver Circuit

The limitations of the "Laser Ladder" design narrow down to the high identification accuracy. The height being identified is an estimate and will not be as accurate as the other designs, such as the implementation of a LiDAR Sensor.

ii) LiDAR Sensor

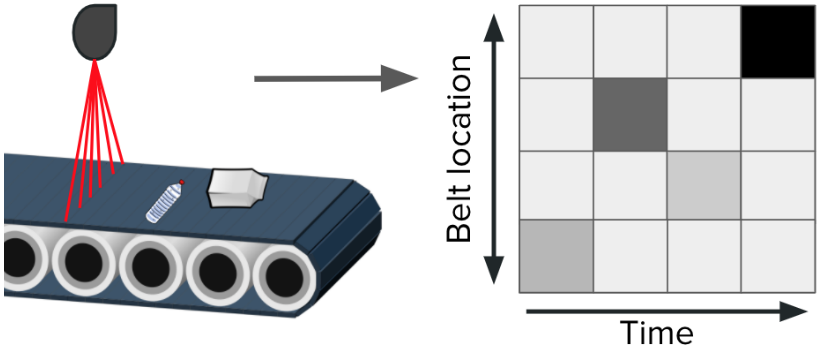


Figure 14: LiDAR design conceptualization

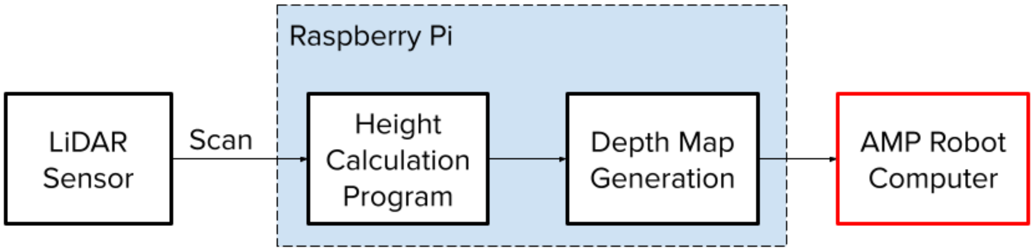


Figure 15: LiDAR schematic proposal

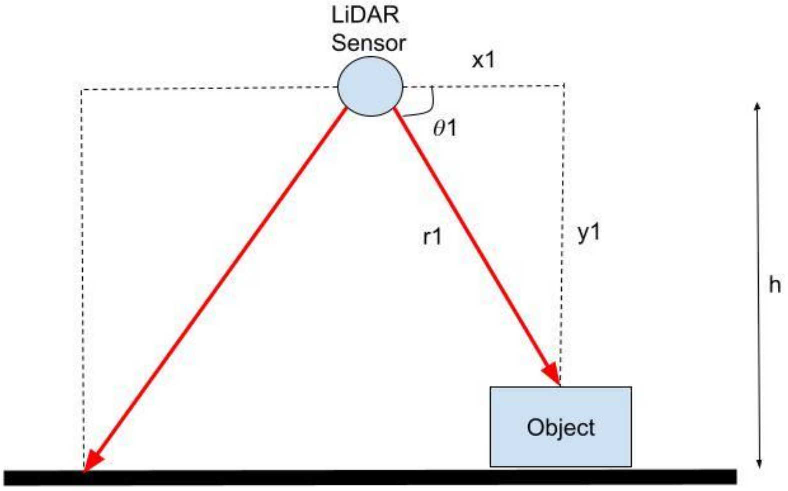


Figure 16: LiDAR schematic proposal

The LiDAR sensor was the second approach to the depth sensing objective. The original design concept can be seen in Figure 14. The system schematic can be seen in Figure 15. The Slamtec A1M8 RPLidar is the sensor that will be used, a 360 LiDAR sensor. Using this sensor, 360 depth scans were collected and then converted to a depth estimation on a flat surface. This conversion happened through some basic trigonometry, which can be deduced by Figure 16. This design was accomplished by interfacing with Slamtec's open source LiDAR sensor SDK [7] in C++ on a Raspberry PI to collect data, then, using Matplotlib for C++ [8], a C++ wrapper for Python’s matplotlib plotting library, the team was able to create real-time continuous visualizations. The idea was to append 1D scans to create a 2D depth map, and this idea was accomplished throughout the semester. An initial concept of the 2D depth map can be seen in Figure 14, and the final design was built on this in many ways, seen in Figures below.

Generating a 2D depth map required formatting the LiDAR scans to the area that it was mounted to on the laser ladder. Additionally, labels, graphs and more were added to the visualizations. The most difficult portion of this project was working with the Matplotlib for C++ to do continuous visualizations. The open source library only supported continuous updates for plots, not images. This meant that the team had to look into the library's source code, understand how it wrapped Python's matplotlib plotting library for plots, and then had to expand the library to do the same continuous updating with images as well. Another difficulty was creating the library to continuously update subplots in addition to plots. Using some provided examples and examining the source code, the team was able to do this without making any major changes to the library itself, but figuring out how to do this was difficult. Lastly, the laser ladder data was merged with the LiDAR data, and an intuitive and informative design for comparing the two methods was developed.

Chapter 3 - Test Data

Operations Objective

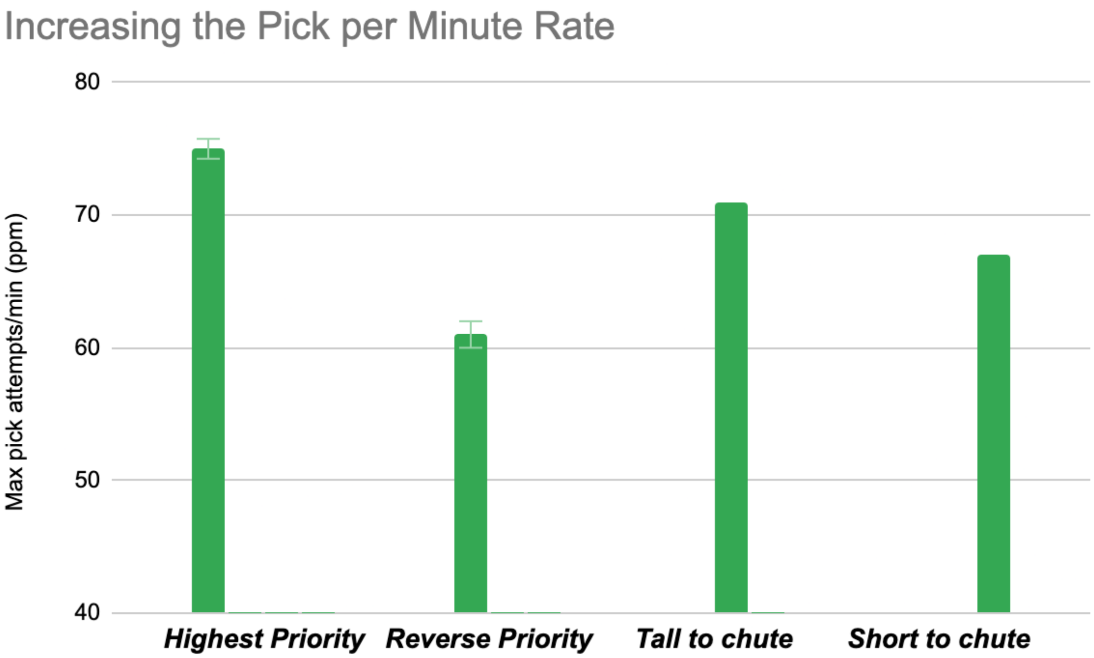


Figure 17: Results of objective one experiments

AMP's Clarity system provides information about the SSRC's robot, and what types of plastics the robot interacts with. It stores the amount of each type of plastic as well. Given this information, this "Highest Priority" trial the pick priority was altered to reflect this data. On average, the highest quantity plastic is the PP5 tub and the lowest quantity plastic is the PP5 plastic pod. On the 5-point likert priority scale these subcategories of plastics were assigned to the highest and lowest priority respectively. The other subcategories of plastics, pods, bottles, cups, caps, etc. were assigned priorities based on the average amount given from AMP's clarity data. This experiment resulted in a maximum pick per minute rate (ppm) of 80ppm. The "Reverse Priority" trial is similar to the "Highest Priority" trial, except that it reverses the pick priority settings (e.g., PP5 tub set to lowest priority, and PP5 plastic pod assigned highest priority). This trial resulted in the lowest pick per minute rate of the experiments, 61ppm. In the "Tall to chute" and "Short to chute" experiments the presorting process done by manual workers was altered. In addition to presorting large and dangerous materials, the workers also focused on putting taller materials closer to the chutes, or putting shorter materials towards the chutes. These two experiments resulted in pick per minute rates of 71ppm and 67ppm respectively. Looking at the results of the experiments run it is clear to see that the pick priority of the robot plays a large role is the efficiency of the robot. Assigning higher priorities to plastics that the robot is on average more likely to get yields a higher pick per minute rate. Also, moving taller recyclable materials closer to the side of the chutes also yields a higher pick per minute rate.

Chute Shield Objective

Because the visual system of the AMP Robotic system resides outside of the picking cage, data to suggest that the chute shield design was working relied heavily on the customer satisfaction and visual reduction of clogged recyclables and overflow onto the bunker.

Figure 18: Photographs of clogged material before and after installing the chute shields.

Figure 18 shows the change in the amount of clogged material after running the line before and after installing the chute shield covers. This proves that the diverters and hinged back panels are sufficient for preventing clogging and further reducing associated downtime for unclogging the robot. Currently, the methods for unclogging include sweeping along the base or completing a lockdown tagout process for the robot and climbing onto the conveyor line. These chute shields reduce the frequency of the use of that procedure.

Depth Sensing Objective

As outlined in a previous section, one solution to the issues faced by the recycling center was implementing lasers and photoresistors to identify the estimated height of the objects passing through the robot. It's important to mention the laser ladder system was an alternative solution that provided a better cost to performance ratio. Although the lasers could not provide results as accurately as the other solution, LiDAR, it had the advantage of being much cheaper.

Due to the nature of the photoresistors, it's important to calibrate the resistivity of the device relative to the surrounding lighting. This created inaccurate results in different rooms that did not have the same lighting system as the ECE 480 Lab. To avoid inaccurate results, the team has placed the photoresistors deep inside the structure of the Lasser Ladder. This way of implementing photoresistors will provide shadow around the photoresistors, making them less sensitive to the surrounding light.

After implementing the design changes mentioned above, the Laser Ladder performed as expected to be outlined below. Since the recycling center sorting line was not available for the testing, different objects were placed on the ground and the laser ladder was manually pushed; simulating objects carried by the belt leading to the AMP Robotics Cortex system.

After completing both the LiDAR and laser ladder implementation, the biggest concern was the accuracy of the systems and how that accuracy varied by the transparency of the object being scanned. To test this accuracy, three different materials were used with varying transparency (Figure 19).

Figure 19: The tested recyclable materials were opaque (left), translucent (center), and transparent (right).

The opaque object (a recyclable dish detergent bottle), was chosen as the optimal kind of object for both the LiDAR and the laser ladder, as all light is reflected and none is transmitted. The object had a height of 30.2 cm and a width of 18.3 cm. Due to the positioning of the object (under the LiDAR and intersecting with the laser ladder), the recorded height by both systems was lower than the expected height (as seen in Figure 20). Nevertheless, the LiDAR retrieved several high quality readings along the object. Additionally, in all real-time plots of LiDAR data, there are points on the left and right side of the plot corresponding to the base of the laser ladder structure. These were included in the plots as reference points.

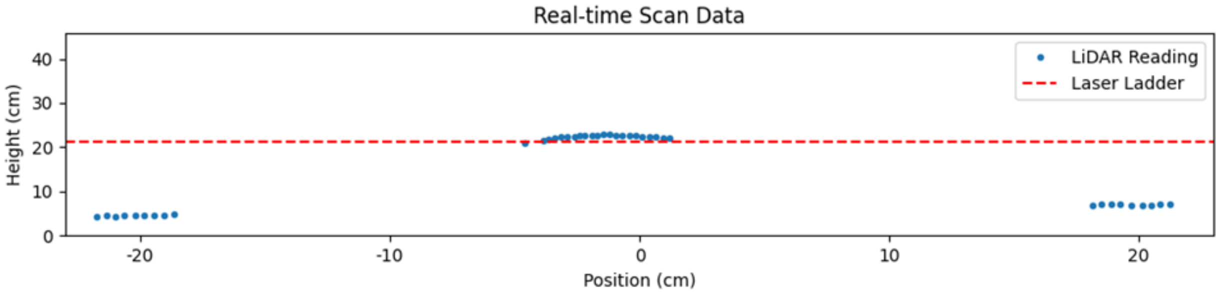


Figure 20: Scan of the opaque object.

Many of the objects that go down the recycling line are milk cartons and other translucent materials. The translucent milk carton that was chosen had a height of 14.9 cm and a width of 25.4 cm (given it was laying on the side, as seen above). Both the LiDAR and the laser ladder recorded a highly accurate height reading (as seen in Figure 21). This shows that both systems should be reliable on translucent materials.

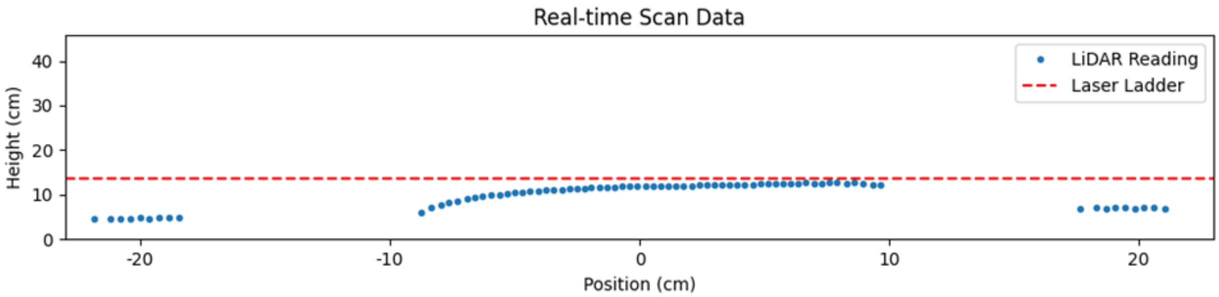


Figure 21: Scan of the translucent object

The largest concern was transparent materials. Since light passes almost completely through them, the data for the LiDAR and laser ladder would be much less reliable. This was seen in the test of the transparent object. The object was 27.1 cm tall and 11.1 cm wide. While both systems were able to output a nearly correct result (see Figure 22), good results were intermittent. As for the LiDAR, the amount of high quality readings were much more sparse than for the translucent and opaque materials.

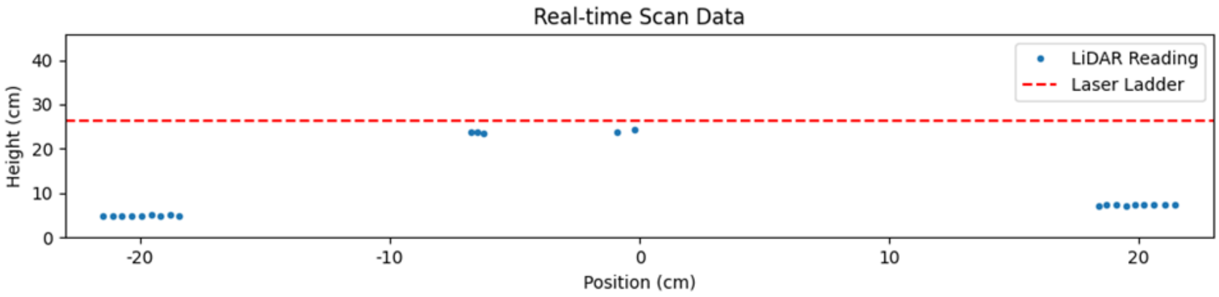


Figure 22: Scan of the transparent object

This shows that the LiDAR system worked very well for objects that reflected light, and it was able to detect correct heights at many locations each scan. For transparent objects, the results were much less accurate. The issues and consequences of low accuracy for clear plastics is discussed in greater detail in Chapter 4.

The team also implemented a display to the laser ladder structure to show the live data processed by both the lasers and LiDAR. With this feature, the users will be able to view the analysis being processed in detail, making it easier to identify objects above the height limit. The data represented on display is divided into three different sections shown in Figure 23. On the bottom left side of the display, a color-coded graph represents the data received by the laser ladder. As the object's height becomes closer to the height limit, the data shown will be represented with a darker blue color. The same implementation is done for LiDAR data in the bottom left corner. The main difference between these two graphs is accuracy. LiDAR technology makes it possible to analyze the shape of the objects and identify where each part of the object is placed. This feature makes it possible to identify what part of the object is exciting the height limit. On the other hand, the Laser ladder is activated once the laser beams are interrupted from intersecting the photoresistors. Although this will also notify the users regarding the height of the objects, the exact dimensions of the given objects can not be identified. The accuracy of the laser ladder also depends on the number of lasers implemented into the structure. As the number of lasers increases, the accuracy of the data will also increase. Lastly, the graph shown on top of the display represents both laser and LiDAR data. Representing such data in this format provides many benefits while highlighting the benefits of using LiDAR. For instance, the blue dots provide live feedback to the users regarding where each object is placed alongside the height related to the object. On the other hand, the red dotted line represents where the object's height is due to the interruption of the laser beams. By combining these three data, the users can identify the potentially hazardous objects that could damage the robot's arm.

The team believes that the Laser Ladder could be used as a secondary safety system if the recycling center simultaneously implements LiDAR and Laser Ladder. With the nature of LiDAR and the accuracy that comes with this system, it outperforms Laser Ladder’s data. That being said, in an event where LiDAR fails to perform as expected, Laser Ladder will also be able to identify potentially hazardous objects and notify the users.

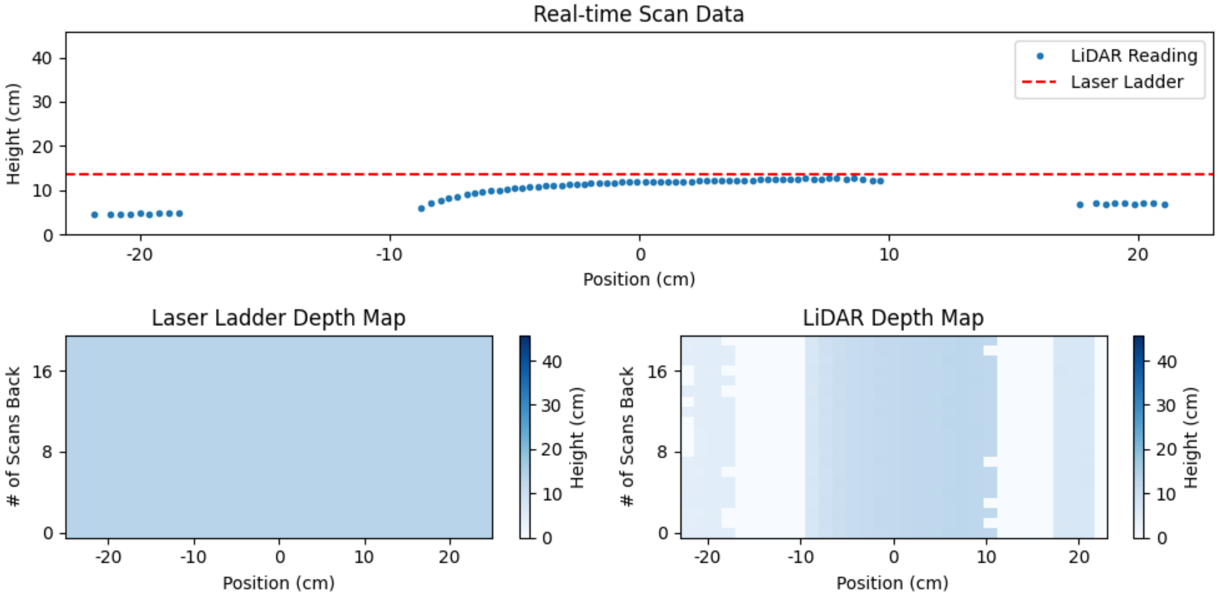


Figure 23: Laser ladder and LiDAR data during testing.

As an example of the LiDAR depth map working functionally, it was tested using the green dish detergent bottle laid flat (opaque object from Figure 19). The results can be seen in Figure 24. The color intensity correctly corresponds to the max depth of the object (11.1 cm). More interestingly, the outline of the handle is visible from the depth map. Information such as this could be useful for deciding where on the object the robot should press down.

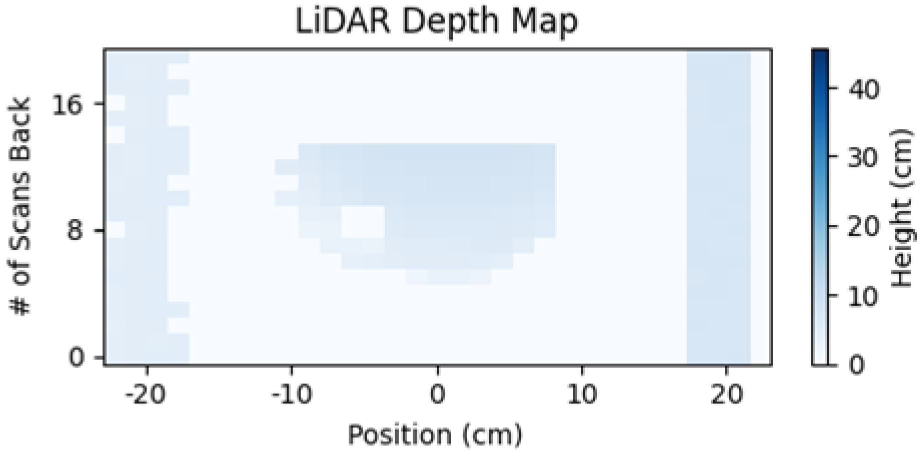


Figure 24: Depth scan of a bottle of dish detergent.

Chapter 4 - Design Issues

Operations Objective

Although there is a metric to determine the efficiency of the robot, the pick per minute rate. This metric does not come without flaws. It is always possible that when the robot picks for a plastic it will miss the plastic entirely, or not have a strong enough suction to hold the item. Both of these failures result in an increased pick per minute rate, as the robot is going to pick for an item, but the failure or miss will not be monitored in AMP's Clarity system. Part of the experiments were also reliant on AMP's Clarity system. Although the SSRC currently has access to this data, their license for it will run out and were they to choose not to relicense for it they would not be able to quantitatively tell which types of plastics the robot sees the most.

Chute Shield Objective

There is an issue that comes with the planned design which has been expressed to the SSRC as considerations before implementation. The design extends the steel chute diverters all the way to the edge of the cage, but is not attached to the cage. This may result in rattling and scratching against the cage. To mitigate this problem, it is suggested to reduce the cage-side dimensions of the components by 1/4" and to pad them with a soft edge like a recycled carpet or foam. This would increase the length of the lifecycle of the chute shields and the cage.

Depth Sensing Objective

i) Laser Ladder

The design and construction of the Laser Ladder had several issues. Starting with the analysis of the construction of the prototype several issues arose in the materials used. The Laser Ladder frame was constructed out of wood because of its low cost and ease of construction. However because the frame housed the lasers and photoresistors it had to be aligned perfectly. That is where the issues started to appear, the wood had natural bends and twists in the boards. Which made the frame once fully constructed crooked. The way this was fixed was by adding a support board, turnbuckles, and several additional ninety degree brackets. Once those components were added the Laser Ladder frame straightened out considerably. But the lasers were still out of alignment so further manipulation was required to make it functional.

The laser ladder suffered from different flaws, such as cheaply made material. Prior to receiving a Raspberry Pi from MSU, the team had to be conscious of the budget spent on the different components. Due to the objective of Laser Ladder being the more price to performance conscious solution, alongside Raspberry Pi's potential cost, high-end lasers were not purchased. This introduced various issues such as a lack of proper documentation of laser properties. The lack of such documentation resulted in the destruction of the lasers due to exceeding the maximum rated current; this will be covered in more detail below. The team had to purchase new lasers in order to replace damaged parts. Since the original supplier was out of stock, another supplier had to be identified. A supplier named "HiLetgo" that provided the same aspect lasers with the same properties. Similar issues with the quality of the original photoresistors occurred, where many had voltage drops that did not correspond with the necessary change in voltage for the Raspberry Pi. After testing each photoresistor individually, the resistor in series of each was selected to create voltage drops in the needed range.

As mentioned above, burning the lasers became a big issue. During the early stage of testing, the team noticed that the original laser diodes were being affected due to an unknown reason. As different theories were tested, supplying the lasers with the higher-rated current was identified as the issue. The lasers required a five-volt power supply to function correctly; this is the same voltage as the Raspberry Pi output. That being said, after measuring the current being supplied to the laser circuit, the current being supplied was much higher than 20mA, the maximum rated operational current, to the lasers. With the use of different resistors, a new circuit was designed to keep the current throughout the circuit below 20mA to avoid burning the lasers. Different circuit design elements, such as color-coded wires alongside soldering connections, were implemented to create a better-performing circuit.

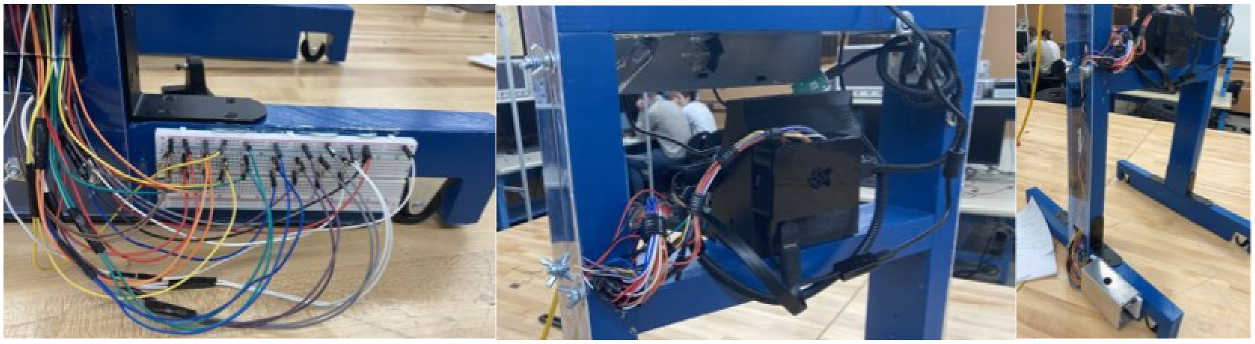


Figure 25: Wiring of Laser Ladder

ii) LiDAR Sensor

The issues pertaining to the design of the LiDAR sensing were not major and were outlined as merely challenges in the Technical Description section of this report. This section will discuss potential limitations of the LiDAR sensor rather than issues in the design, as no major issues exist in the design itself, rather the technology itself.

The largest concern with using a LiDAR sensor in the recycling center is its accuracy on clear plastics. Because most of the laser light transmits through clear plastic, the LiDAR readings are much less reliable the more transparent the object is. This is an issue, as many of the recyclables at the recycling center are clear plastics. Further testing would have to be done to know if the LiDAR can detect the height of these plastics with sufficient accuracy. Also, since the motivation behind height detection is avoiding damage to the robot, there needs to be a study conducted to determine how frequently clear plastics could potentially cause damage.

Since automated height measurement would lead to less workers on the recycling line, further testing of the system is currently needed (e.g, risk of LiDAR motor dying). In its current state, AMP would be taking too much responsibility as the limits of the system are not yet known. This example of product liability could cause great costs to both AMP and the recycling centers if not thoroughly researched and tested.

Chapter 5 - Final Cost, Schedule, and Summary

Cost

Table 1: Budget broken down by each part for this project.

Quantity	Part Description	Cost
1	LiDAR	$99.99
1	Pack of Wheels	$12.99
1	Pack of Wood Screws	$9.99
1	Pack of Brackets	$14.99
1	Kit of Laser and Photoresistors	$13.99
2	2x4 96 long wood board	$12.240
1	5 inch Touch Screen	$56.99
1	HDMI	$12.99
1	Kit of Breadboards	$12.49
1	Breadboard Jumper Wires	$7.98
1	Raspberry Pi Power Supply	$10.99
2	Replacement Laser	$6.29
1	Replacement Photoresistors	$5.150
1	Omars Power Bank	$89.94
Total		**$385.54**

As mentioned throughout the paper, a Raspberry Pi 4 was used to power the system. Due to the current chip shortage, Raspberry PIs are extremely hard to find and could cost as much as the project's budget. With the help of the ECE department, the team received a Raspberry PI that was previously purchased by MSU free of charge. This provided an opportunity for the team to offer different solutions with various cost to performance ratios to the objectives mentioned in the paper.

Schedule

Figure 26 represents the schedule and duration of each of the major steps in this project. These are divided by objective where the purple bars represent the timeline of the operations objective, red represents the timeline of the chute shield objective, and blue represents the timeline of the depth sensing objective. Each objective’s steps span from the beginning of the semester to the end of the semester.

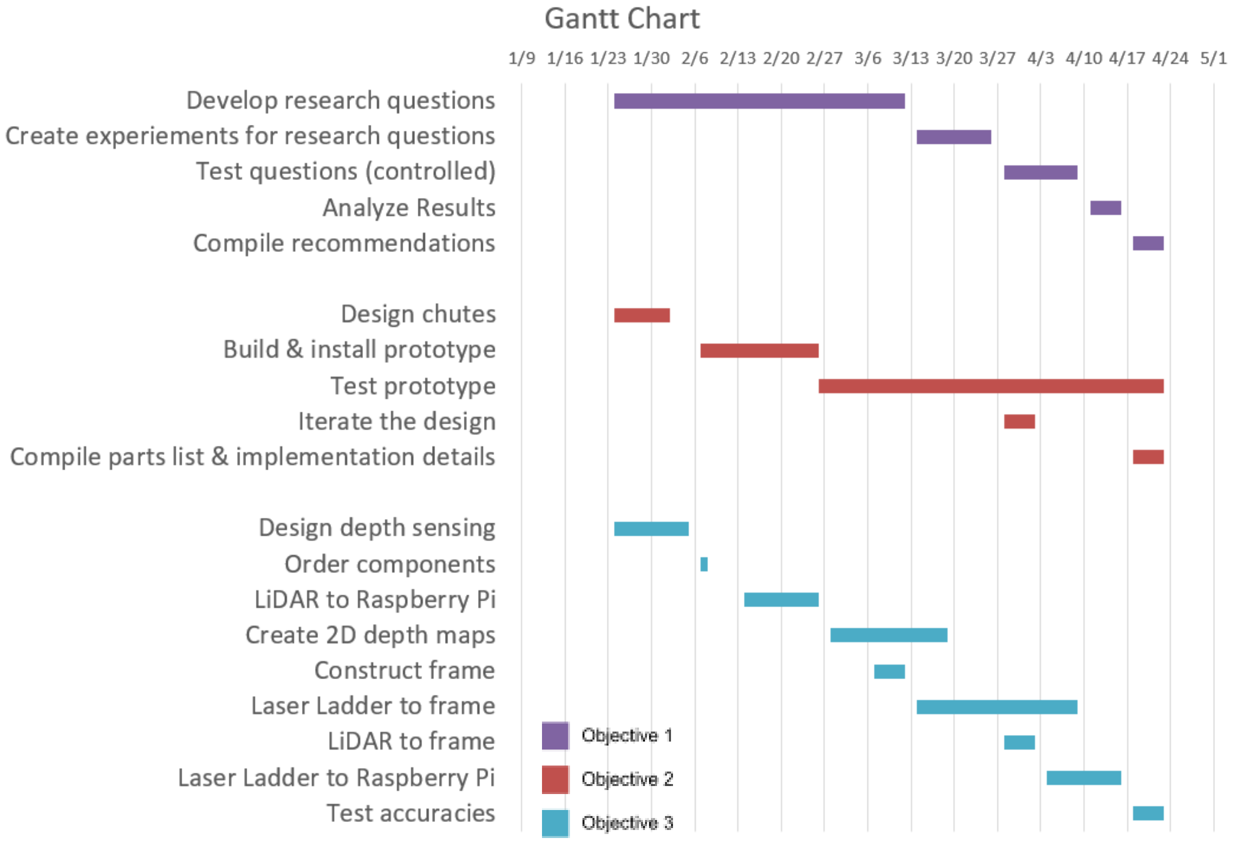


Figure 26: Gantt chart outlining the major steps in each objective.

Summary

The operations objective of this project was to develop recommendations on how to maximize the use of the robotic sorting technology by increasing the number of picks per minute performed by the robot. The manual presorting and AMP’s pick priority system are the main variables that affect the efficiency of the robot. Presorting plastics based on their size and location relative to chutes resulted in an increased pick per minute rate. Also, modifying the pick priority to reflect which types of plastics is seen on average yields an increased pick per minute rate as well.

The chute shield objective was met by prototyping and providing a supply list for chute shields and diverters. This reduced the clogging of recyclable materials in the caged area and reduced the amount spillover from non-targeted material.

The depth sensing objective of this project was to determine the optimal placement of additional sensors in order to obtain a volumetric estimate of the objects on the recycling line. This objective aims to identify a burden depth of each recyclable on the line to prevent unintended collisions with the Cortex arm and with other recyclables on the line. Within the context of this project, two unique approaches to potentially solve this problem were explored.

The first being a simple and cost effect method referred to as the Laser Ladder. Which used a combination of laser diodes and photoresistors to give a burden depth estimate of recyclable materials on the conveyor belt. How it gathers the relevant depth data is lasers going up incrementally on a post shoot across the belt onto the matching photoresistors on a seperate post. When an object blocks the laser's path the Raspberry Pi connected to the photoresistors detects that blockage and then produces a burden depth estimate displayed on the device's local monitor.

The second approach uses LiDAR to identify burden depth which is more expensive technology but produces more accurate data than the Laser Ladder. The LiDAR device used for this prototype was a Slamtec A1M8 RP LiDAR sensor. Which scanned 360 degrees around its mounting point. For its use in this design, the concern was with the data collected from the conveyor belt directly below the device. The LiDAR device was programmed to use trigonometry and other digital libraries to identify the height of materials on the belt. The relevant burden depth information would then be displayed alongside the Laser Ladder data on the local monitor.

Conclusion and Future Work

Through this project we were able to successfully assist the MSU Recycling Center in some of its immediate needs (helping them understand how to load the recycling line for the MRF robot to be most efficient, creating a design for chutes to improve sorting capability and reduce contamination), as well as provide AMP robotics with prototype supported suggestions on how they can incorporate depth estimation into their identification and sorting system. With all things considered, we consider this project a total success.

Further work still persists, however, on further improving the logistics of the MSU Recycling Center, as well as improving our depth estimation approach. Regarding the chute design, we believe that no future work remains there, but could be wrong depending on how the chutes perform over an extended period of time.

In terms of improving the logistical aspects of the Recycling Center, further study must be done on how the robot performs and ways that they can make the robot perform better. We provided immediate suggestions on what we think human sorters should prioritize and how they should organize material, as well as suggestions on optimizing the MRFs sorting parameters, but these are suggestions that can be immediately incorporated. We offered no drastic suggestions to presorting techniques; this would likely be a longer term project with a larger budget, offering the ability to make large logistical changes, not something that we would have been able to do in only a semester. Therefore, we believe further work still needs to be done to research and explore MSU’s ability to sort plastics and optimize the robots performance. Our suggestions will definitely be helpful, but even with our suggestions, MSU’s pick per minute rate of their robot is far below large commercial recycling plants. Further study may allow MSU to narrow the gap and become increasingly efficient.

The chute shields are ready for final implementation in the coming weeks by the SSRC.

In regards to depth estimation, a prototype was successfully implemented and tested using LiDAR and the laser ladder. This yielded both a high and low cost potential solution. The LiDAR is the ideal choice, as it provides many readings along the width of the belt.

The next step for depth sensing would be to interface with the AMP robot. By adding the depth information to the current machine learning process, the robot would be expected to be more accurate, efficient, and risk averse. This would include decreasing latency by reading from sensors on a separate thread and increasing the LiDAR scan rate to 10 Hz.

While high accuracy was achieved for depth sensing, other options could still be pursued. Ultrasonic sensors could be used to increase the accuracy and consistency of sensing clear plastics. Looking into a combination of LiDAR and ultrasonic sensors could lead to the highest accuracy implementation. Further studies would illustrate where the need for accuracy was (e.g., clear plastics) to better outline the path that should be taken in the future.

Appendix 1 - Technical Roles

Figure 27: Team photo with members from left to right - Jarrett Blumke, Sepehr Rahgozar, Jacob Honer, Austin Anthony, Katie Albus, and Sam Church.

Katie Albus

This semester, Katie's main technical focus was the chute shield objective. For this, she began by eliciting the requirements from the sponsors at the SSRC. She learned a lot about the recycling process that the SSRC followed to understand more about the root of the problems tackled in this project. After eliciting requirements, she built a timeline with main goals for the chute shield objective and worked with the team members to build a timeline for the remaining two objectives. Katie installed a prototype version of the shields on a visit to the SSRC. They were created using corrugated board and duct tape. Katie learned CAD and created the components of the chute shields in CAD to send off to the sponsor, AMP Robotics, to validate their safety. This process ended with a few design iterations that needed to be made for the safety of the robotic arm. After figuring out that the AMP CAD model was about 3" shifted downstream, Katie created changes to the design to create a variable sloped shield that stayed under the 1.5" maximum suggested within the 72" diameter circle of the working zone of the robotic arm. Katie then compiled a list of materials for the welders to use at the SSRC to purchase and build chute shields out of steel and plexiglass. She also suggested a slight change to that design in padding the outer edge in a soft plastic material to prevent rattling and scratching on the cage. This installation will happen at their nearest availability.

Katie also worked closely with Austin to understand the processes at the recycling center to support him with his responsibility of changing the operations of the facility to improve the functionality of the robot. With this, she took multiple visits to the SSRC and watched students on the line and tried experiments while the students were not present. She helped analyze and compile the data in the report above.

A bulleted list of the contributions of Katie in this project:

- Designed the chute shields and diverters for proposal to the sponsors in PowerPoint.
- Iterated to a hinge design for the chute shields and defined initial measurements for components.
- Drew up the components in CAD for validation from AMP Robotics.
- Cut and Installed prototype chute shields out of cardboard and duct tape.
- Validated with SSRC sponsors improvement in the contamination levels and prevention of clogged materials.
- Iterated to a variable sloped design to accommodate AMP Robotics recommendations of 1.5” max height within a 72” diameter working region.
- Designed and ran experiments for the operations objective.
- Created graphic representation of the data from SSRC experiments.
- Rewired the photoresistors on the Laser Ladder to be color consistent.
- Cut the photoresistors down to size and repositioned them in the Laser Ladder.
- Helped align the lasers with the photoresistors.
- Ran testing on the functionality of the depth sensing prototypes.

Sam Church

Sam worked on the depth sensing objective. This work can be split into two categories: interfacing with the Raspberry Pi and real-time visualization of data. Interfacing with the Raspberry Pi refers to reading LiDAR data using the LiDAR SDK and reading GPIO pins corresponding to the laser ladder outputs. Most of the work was spent updating the visualization library to have the necessary features needed for real-time visualization and converting the data to the appropriate structure to be visualized. There was much collaboration between Jacob and Sam on these tasks, especially the beginning stages of LiDAR visualization.

Sam’s specific technical contributions to this project listed:

- Compiled LiDAR SDK on the Raspberry Pi.
- Read and filtered the LiDAR input data (360 degrees) to correspond to the desired region below the LiDAR.
- Used Matplotlib for C++ for visualizing object height information.
    - Plotted the current LiDAR scan and the current laser ladder output on top of each other for comparison.
    - Implemented real-time updating of LiDAR plotting.
    - Real-time Image updating was not available for Matplotlib for C++, so the source code of the library was updated to add this feature.
    - Modified Matplotlib for C++ library to allow improved customization (e.g., labeling of colorbars).

  - Designed layout of the visualization and implemented labeling, legends, color choices, etc. to create a visually appealing and intuitive program.
- Read GPIO pins using pigpio library to visualize laser ladder data.
- Masked GPIO pin readings to isolate readings from each laser ladder circuit.
- Converted LiDAR data from (angle, distance) pairs to (x, y) pairs, which allowed more intuitive visualization of objects passing underneath.
- Created a script that recompiled the program, killed any previously executing processes, and started the visualization program.
- Made program script executable from the Raspberry Pi Desktop.
- Setup program to run on startup of the Raspberry Pi.
- Assisted in debugging and design of the laser ladder circuitry.
- Ran testing of LiDAR and laser ladder to determine effect of transparency on accuracy.

Austin Anthony

Austin led group sixteen's operations objective. This objective required finding recommendations that maximize the use of the robotic sorting technology by increasing the pick per minute rate. To achieve this objective, he first had to gather requirements from the project stakeholders to determine what approach to take to increase the pick per minute rate of the robot. This required many meetings with the SSRC's Sean Barton and Dave Smith. He also did research to discern how other Materials Recovery Facilities (MRF) approached using robots to sort plastic materials. This required reading research papers, and presentations on how other recycling companies use their recycling-sorting robots. After this Austin designed experiments to identify possible methods that would increase the pick per minute rate of the SSRC's robot. Running these experiments also required many in-person visits to the MSU's recycling facility. Austin and Katie led these experiments, and also manual presorted the materials needed for their experiment much like an actual worker the MSU's SSRC would.

Austin's technical contributions to this project are listed below:
- Researched industry-standard practices of recycling centers that use robots to sort materials
- Explored different experiments to increase pick per minute rate and efficiency of the robot:
  - Highest Priority - Change pick priority by which plastics it are seen more often
  - Lowest Priority - Change pick priority by which plastics it are seen more often
  - Changing the way the line of materials should be loaded
  - Which materials are best sorted by the robot
  - Which materials are worst sorted by the robot
  - Should another robot be added to also presort the materials
- Conducted experiments in MSU's recycling center to see the pick per minute rate and efficiency of the robot can be increased
- Analyzed data from experiments and created graphs to show results
- Outlined and designed the experiments for objective one to the sponsors in powerpoint slides

Sepehr Rahgozar

Sepehr focused on a variety of tasks during this project. He was mainly responsible for researching and identifying the necessary parts for the laser ladder system while maintaining a balanced price to performance ratio of the components. Sepehr worked closely with Jarrett to provide general assistance regarding the potential design elements of the Laser Ladder. Throughout the project, Sepehr implemented different features to the Laser Ladder structure to improve the system's functionality while providing a better experience for the users. An example of such an improvement in the system's functionality was implementing a touch screen on a 3D designed stand that provides live feedback to the users. Sepehr did extensive research to identify the correct, safe way of delivering mobile power to the Laser Ladder structure. With the implementation of such a feature, the system became mobile, making it possible to provide a live demo.

Sepehr's technical contributions in bullet format can be found below:

- Identifying the necessary parts for the laser ladder and LiDAR system.
- Maintaining a necessary price to performance ratio of the components.
- Reinstalling and wiring of the lasers.
- Identifying new suppliers for the replacement parts such as lasers and photoresistors.
- Implementing new features to the Lasser Ladder structure such as display and mobile power.
- Research regarding different components of the structure. Such as identifying a Raspberry Pi-approved system to power the Pi while having it mobile.
- Implementing new design changes to install the replacement batch of lasers.
- Designed a structure to mount Raspberry Pi to the display.
- Ordering, handling, and testing equipment to ensure their quality prior to installation.
- Supervising and ensuring the safety of the team members in the lab areas.

Jacob Honer

Jacob worked primarily on the depth sensing objective of this project. This meant interfacing the Raspberry Pi with the LiDAR sensor and working on all visualization aspects of the project. This includes interfacing with the open source LiDAR sensor SDK, writing code to format the data appropriately, and then, through the graphing and visualization library Matplotlib for C++, creating real-time visualizations. These visualizations visualized both the LiDAR scans and the laser ladder readings. The majority of software related work was a joint effort with Sam.

Additionally, Jacob designed all relevant circuits for the laser ladder. This meant that Jacob handled the circuit design, tuning, and final touches in the construction of the transmitter and receiver circuits. Through his efforts, the laser ladder became not only functional, but also robust to ambient light from the environment.

Jacob’s technical contributions in bullet format can be found below:

- Figured out the interfacing of the LiDAR sensor for taking the sensor generated data and passing it to the Raspberry PI using the open source LiDAR SDK provided by the supplier.
- Created prototype version, writing data to system files in C++ program and then visualizing data in an independent Python program, as a proof of concept demo for the LiDAR sensor depth sensing ability.
- Took 1D scan data from the LiDAR sensor and created continuous 2D depth maps through Matplotlib for C++, a C++ wrapper for Python’s matplotlib plotting library.
    - Modified the Matplotlib for C++ library to work with continuously updating images.
    - Figured out subplotting capabilities of Matplotlib for C++ library.
    - Made graphs look nice with appropriate limits, labels, titles, etc, and downsampled LiDAR scan data so that data could be feasibly processed in real-time for 2D depth maps.
    - Protted 1D LiDAR scan in real-time concurrently with laser ladder scans for comparison of the two approaches. This graph also provides further information pertaining to the resolution, characterization, and accuracy of each scan.
- Created all circuit schematics for the laser ladder. This included designing the circuitry for turning on and off the lasers, while making sure that they do not burn out due to too much current being fed through to the lasers. Jacob additionally designed, tuned, and constructed the circuitry for the laser light receiver circuit, used to indicate whether there was something blocking the laser light or not, to be used by the visualization program running on the Raspberry PI.

Jarrett Blumke

This semester, Jarrett’s main technical focus was on the Laser Ladder portion of height sensing objective. For this he began by coming up with the Laser Ladder design idea. That design idea was obtained after visiting the MSU Recycling Plant and observing the challenges of the robotic sorting arm operating without height data. Once the concept of the Laser Ladder was approved by the team and facilitators he produced several design concepts. The final design was submitted to the group in a CAD drawing which was then approved for construction. He then played a role in the selection of materials required for the construction of the laser Ladder along with a rough timeline of prototype construction. Jarrett constructed the Lasser Ladder in a Northern Michigan machine shop. It was there that he learned how to use an industrial manual mill and drill press to manufacture the parts for the prototype. It was upon the first assembly of the prototype that he noticed flaws in alignment and stability of the design. He then corrected the majority of those flaws by adding additional components and support methods. He then completed the first stage of the wiring by adding in the lasers and photoresistors and wiring them in. After the next several stages of the design process he assisted various members in additional wiring to the photoresistor circuit board and color coding the input/output wires for various components. In the final stages of the Laser Ladder prototype design he applied cosmetic alterations to the frame and wiring to make it look more visually appealing.

Jarrett also worked closely with team members to add a method to mount the LiDAR device to the frame in an efficient manner. He worked with Sepehr, Jacob, and Sam to find a location and a method to mount the Raspberry Pi device and its Monitor to a location that would not interfere with the device's operational capabilities.

Jarrett’s technical contributions in bullet form can be found below:

- Designed the Laser Ladder structure and created several drawings including CAD blueprint.
- Selected materials used to build prototypes including wood, waders, photoresistors, brackets, etc.
- Learned how to operate an industrial manual mill and drill press to manufacture structure parts.
- Assembled Laser Ladder frame and made alterations to design to fix stability and alignment issues.
- General wiring to Laser Ladder:
    - Installed lasers
    - Installed photoresistor input ports
    - Wired lasers around frame to a local connection point
- Assisted teammates in rewiring of lasers power connections and photoresistors:
    - Color coded wires to be fame across relevant connections
- Assisted teammates to mount Raspberry Pi and its local monitor
- Cosmetic improvements to laser ladder
    - Removed glue that was all over frame from earlier designs
    - Added wire covers
- Manufactured LiDAR mounting bracket

Appendix 2 - References

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Appendix 3 - Technical Attachments

For access to code of the laser ladder and LiDAR visualization software, please contact Sam Church or Jacob Honer at sam.church99@gmail.com or jsh1999213@gmail.com, respectively.

Figure 28: Photographs of the prototyped chute shields labeled by the components in the CAD.

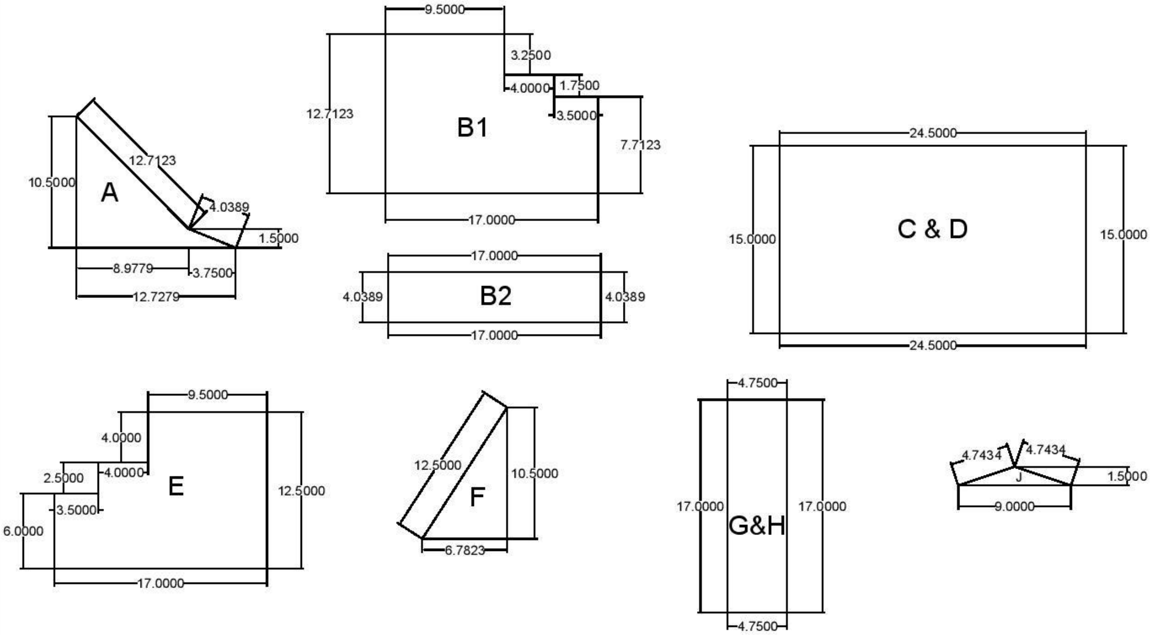

Figure 29: CAD drawings of each of the components creating the chute shields.

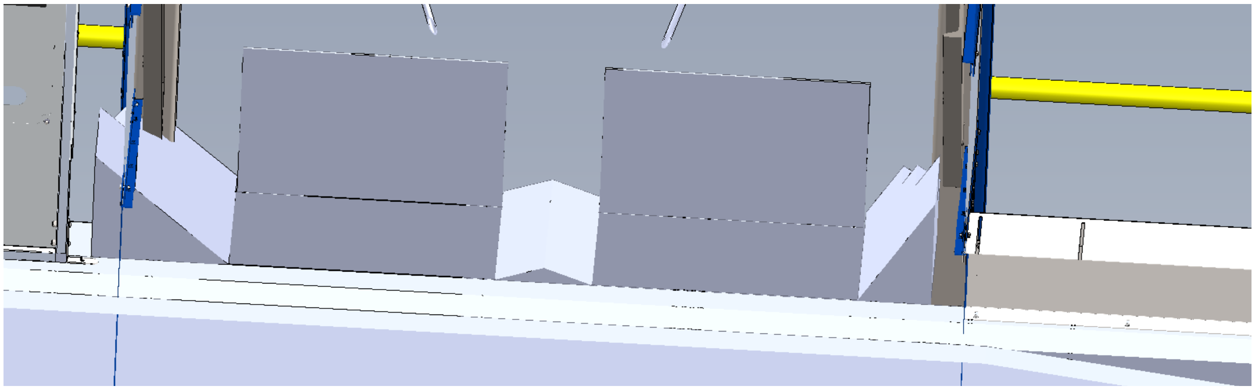

Figure 30: 3D depiction of the chute shield design as provided by AMP Robotics. Note, the chute openings are actually about 3” downstream from the location provided in the diagram.

Table 2: Proposed costs of components for the chute shields as sent to the SSRC.

Name	Part Number	Quantity	Cost per item	Total Cost
800 lbs. Capacity Zinc Plated Steel Tie-Down Ring	3076T35	2	1.08	2.16
Extra-Flexible Coated Wire Rope—Not for Lifting	8923T517	1	1.47	1.47
Mortise-Mount Entry Door Template Hinges	1494A43	4	7.60	30.40
High-Strength Grade 8 Steel Hex Head Screws	91268A503	2	9.23	18.46
Low Carbon Steel Sheet	6544K17	2	37.10	74.20
				$126.69