ENPH 454 Advanced Engineering Physics Design Project – Group 8 Final Report

Resistor Sorter

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Abstract

An autonomous resistor sorter would be a valuable tool in physics labs, as it would save time and reduce errors incurred by manual sorting of resistors. This paper presents the design and development of such a device, with the intention of accurately and efficiently sorting resistors without human involvement. The design uses gravity and motors to transport the resistors through the system and determines resistance values for sorting. The design process was organized by dividing the group into four sub-teams, each focused on a specific component of the device.

The development of the resistor sorter required the group to overcome two main challenges: accurately reading the resistors and sorting them into correct bins. To solve the first challenge, one sub-team produced a program to detect resistance values based on colour bands. The other three sub-teams focused on the second main challenge of building a system to transport and sort the resistors once inputted into the device. The tasks for these teams to accomplish included building a mechanism to dispense resistors using a conveyor belt, constructing the framework and transportation mechanisms in the structure, and programming motors to control the moving parts in the system.

The final product requires the user to manually straighten and input 12 resistors at a time into the device for sorting. The resistor sorter has an accuracy of 60% for determining the resistance values using camera detection and 40% at sorting them correctly. Further adaptations that could improve the accuracy of the current design components include improving the set-up of slides and chutes that transport the resistors, modifying the size of the bins into which resistors are sorted, and implementing a higher torque motor. The device could also be re-designed to accept a large quantity of tangled and unsorted resistors rather than requiring the user to manually straighten each resistor and place it on the conveyor belt in small quantities at a time. This modification would allow the device to achieve complete autonomy and would provide the best user experience.

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1. Introduction

1.1. Background and Motivation

The resistor is one of the most fundamental electronic components in physics and engineering, used every day by staff and students. Resistors come in a variety of different values that require sorting for ease of use during lab time, but the sorting process is tedious and error-inducing. Since the resistance values are determined based on colour bands, it is quite common for a person to misread a colour band and place the resistor in the wrong bin. Furthermore, there are accessibility issues for colour blind individuals who have trouble distinguishing the colours on each resistor. In this case, one is forced to manually measure and read the resistance value using a multimeter. Unsorted resistors lead to errors in lab work that could easily be avoided. To reduce the error associated with sorting resistors and increase the efficiency of the process, this project was proposed to automatically sort resistors without human error. The most vital component of the system must allow a computer to recognise the color bands to correctly determine a resistor value.

1.2. Stakeholders

The main stakeholder of this project is the Queen's Department of Physics, Engineering Physics, and Astronomy. This department includes students, professors, and employees who use resistors in Stirling Hall. Implementing an apparatus for sorting resistors will eliminate the need for tedious labor and allow students and faculty to use their time more efficiently during labs, projects, and when conducting research. Not only will this device reduce the time taken for sorting, but it will also prevent students from wasting time in-lab by using an incorrect resistor, placed in the wrong bin. Additionally, any people who are colour blind will also benefit from the resistor sorter as it will allow them to organize resistors without the need to identify individual bands. The project will therefore meet an accessibility need in addition to increasing efficiency for those in Stirling Hall.

1.3. Problem Statement

This project aims to develop an autonomous tabletop apparatus that will sort resistors into appropriate bins based on their resistance value. To be considered successful, the following design criteria must be met, shown below in Table 1:

Table 1: Summary of all key criteria, constrains, and relevant stakeholders with rationale.

Criteria	Constraint & Metric	Rationale
Size and Mass Restrictions	• Must be "tabletop" size • Easily transportable within a physics lab (under 10 kg)	• Since the design will be primarily utilized within a physics lab, it must be easily transportable and not occupy an unreasonable amount of space within a lab.
Financing and Costs	• Budget of $1000	• Constraint set by ENPH 454 administration for all capstone projects.
Time and Resources	• Minimum viable product completed by end of the fall term, 2022	• Constraint set by ENPH 454 administration for all capstone projects.
Accessibility, Intuitive Nature, and Ease of Use	• Easily configurable and initiated with the push of a button	• The basis of the design is that it should enable users to operate the machine easily and effectively without prior training so resistors can be sorted properly.

	• Intuitive and easy to operate for all students and staff (undergraduate and graduate) • Resistors are easy to mount onto the system	
Safety Considerations	• Requires no extra safety training to operate properly • Emergency stop button/power switch	• If only certain students/staff can use it, or it requires additional training to use, it defeats the purpose and adds additional levels of operational complexity.

Based on the design criteria described in Table 1, the following broad quantitative goals were identified. First, the resistors must be sorted with a minimum efficiency of 80% and resistors should be detected in under one second. These objectives, combined with the aim of making an autonomous system, ensure that the resistor sorter device is more efficient than having a human sort resistors manually either by colour band or by measurement with a multimeter. For these objectives to be achieved, the apparatus must be able to accurately select, identify, and sort only one resistor at a time.

2. Design Decisions

To meet the goals and design criteria outlined above, the group decided to use a camera to detect resistors and read the bands, rather than running a current through the resistor to measure the value. The camera was selected because it had the ability to sort crooked or tangled resistors, and because the project stakeholders within the Physics Department requested this method as it would allow the system to read the nominal resistance value, rather than the true value. The rest of the design decisions were made around the camera detection plan with an overall outline as follows:

1. A conveyor belt was chosen as the entry point for resistors into the sorting device so that multiple pre-loaded resistors could be inputted and then deposited one at a time to be read by the camera.
2. The camera needed to accurately classify resistors within a very short time frame so that the resistor sorter would achieve the goal of being faster than manual sorting.
3. A carousel of rotating bins was chosen to be the destination of the resistor after its value was determined. Depositing the resistors directly into bins allows them to be easily accessed by the user and the decision to have a rotating carousel was determined to be the easiest and fastest method of sorting. This design takes advantage of gravity to drop the resistor into the appropriate bin.

This design framework was selected based on the design criteria identified in Table 1 as the best way to achieve the quantifiable goals of the project.

3. Safety, Environmental Concerns, Ethical Concerns, Equity

3.1. Safety

Safety was considered both during construction and operation of the resistor sorter. Safety was especially important during construction since multiple components required milling, lathing, and soldering. Risk factors were mitigated by having all team members complete safety training at the beginning of the term. During the operation of the resistor sorter, the device uses a series of motors and moving parts, which may present a safety hazard for long hair, jewelry, and loose clothing. The team was sure to keep any hair or loose items away from the device during operation and a sign was posted alongside the sorter to alert any other users. Team members also ensured that motors were turned off before trying to remove any resistors caught in the system. In event of emergencies, the entire system could be shut down by using the switch on the power supply.

3.2. Ethical Concerns and Equity

Given that the system does not collect any data from users and does not provide a morally questionable service, the primary ethical concern for the project was accessibility. The device is currently accessible for anyone who can straighten resistors by hand and place them on the conveyor belt. In future design iterations, modifying the system to accept tangled and bent resistors would be the best method of improving accessibility so that users could simply place a collection of unsorted resistors into the device. An additional ethical consideration is that the device may be useful for those with colour blindness. Colour blindness presents an obstacle in determining resistance values and can necessitate the use of a multimeter. In future iterations, the speed of the sorting process could be improved to make the device faster for a colourblind individual than using a multimeter.

3.3. Environmental Concerns

Many portions of the design make use of recycled and scrap materials that were available in the physics lab. The major sources of material waste are incurred from purchase of bins and from 3D printing. Small quantities of bins were not available for purchase and the extra containers may be used in other projects or applications around the lab. The 3D printed parts were necessary for the customized construction of the design and are tailored specifically for this device; however, the conveyer belt may be applicable for a future design project requiring a method of transportation for small parts. Additionally, there is a possibility of a group working to improve this design next year, in which case none of the parts will be wasted. Also, the operation of this device does not produce waste apart from the initial materials and it does not consume an excessive amount of electricity.

4. Methodology

The solution development and labour were divided into four sub-teams: the conveyor belt, machining and constructing parts, motors and mechatronics, and camera detection. Details of the design process for each sub-team are provided below along with a description of each sub-team's final design.

4.1. Division of Labour

The team consisted of seven members, each with their own skillset. With a group this large, it was imperative that all members had a task to work on during each lab period. Each group member was assigned to a sub-team based on their individual skillset. For example, Seiji and Melanie both worked as accelerated master's students in Stirling this past summer, and therefore had extensive experience working in the machine shop. For this reason, Seiji and Melanie did most of the machining, milling, and soldering throughout the project. Michael G. had previous experience with image processing, so he was assigned to the camera detection portion of the system. The remaining roles were divided between the rest of the group according to the expertise and interests of everyone.

4.2. Sub-Teams

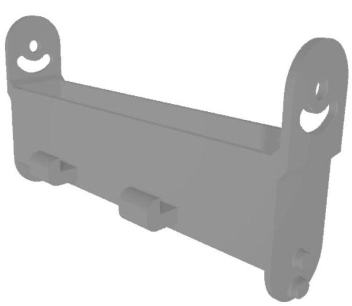
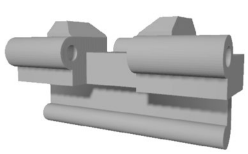
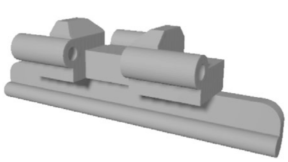
4.2.1. Conveyor Belt

The first sub-team of the project focused on making a conveyor belt to mount onto the system. The user can manually straighten a resistor and set it on a link in the belt to be dropped into the reading station. The quantitative objectives for the conveyor belt are as follows:

- Load and hold a minimum of 10 resistors at a time
- Spin fast enough to not hold back the camera readings
- Weigh less than 1 kg so that it does not place undue strain on the components for mounting
- Have a turning radius and chain link width of no more than the width of a straightened resistor (i.e., ~ 5.5 cm)

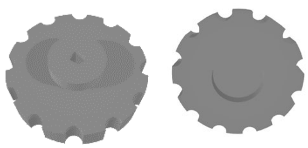
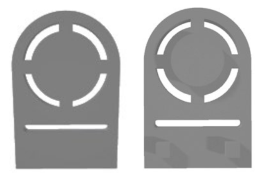
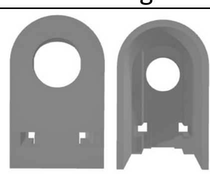
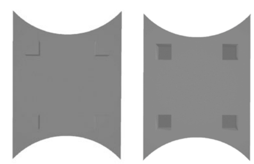
Several prototypes were developed in SolidWorks, 3D printed, then evaluated according to the table below.

Table 2: Evaluation of conveyor belt link prototypes against design criteria.

CAD Models for Prototypes	**Prototype Criteria**		
	Ability to connect to neighboring links	Ease of holding resistors while vertically mounted	Size compared to the overall design
Iteration #1 	• Difficult to connect plastic links to one another • Turns with a large radius of curvature	• The scoop that holds the resistors has a hole in the centre that allows resistors to fall out during rotation or if improperly placed by the user	• The belt links are too large for a tabletop device and need to be reduced in size by at least 50%
Iteration #2 [1] 	• The links can be joined using steel wires which allow for a small radius of curvature	• The shelf that holds the resistors is still slightly small but significantly improved	• The size is appropriate for a tabletop design
Iteration #3 	• The links were maintained from the previous iteration	• The shelf that holds the resistors was increased in size to ensure no resistors fall during operation	• The size was maintained from the previous iteration

Based on the above evaluation, the third design was determined to be optimal for the conveyor belt. Several links of the second model, however, had already been printed, so they were incorporated into the final design to limit the need for additional 3D printing. It was possible to use this combination of designs as both had the same dimensions and were able to fit together seamlessly. The links were printed during reading week to ensure the group was making the most effective use of time. After printing links, components about which to rotate the belt and to attach the motor were also printed. All parts were assembled using superglue, set screws were added to secure the motor, and the entire structure was mounted onto the apparatus.

Table 3: Front and back views of each additional 3D printed component on the conveyor belt with brief explanation of how parts fit together [1].

Gear	Casing
 Two gears were printed, and the links rotate around these. The gears are slightly too small which leaves a small amount of slack in the belt, but it was not enough to consider reprinting.	 Two of these parts were printed, and they fit into the other side of the gear. On the back of the casing are two extrusions which fit into another component to hold the whole structure together.
Housing	Joint
 This housing protects the device from the moving parts.	 This piece joins together the different components in the design.

Once all the components were printed, they were assembled and mounted onto the scaffolding. The final assembly is displayed below in Figure 1. This assembly acted as the entry point and user interface for the device.

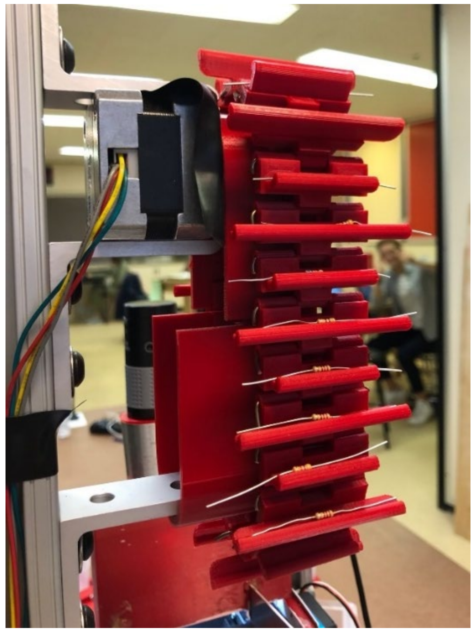


Figure 1: Image of the final assembly of all conveyor belt components.

4.2.2. Machining and Constructing Parts

4.2.2.1. Rotating Resistor Bins

To hold all the bins and rotate them with a stepper motor, a bin holder was 3D printed and machined. Given that the goal was to sort nine resistor values and have a tenth discard bin, the dimensions of this piece were constrained by the dimensions of the bins that were purchased. To lower the moment of inertia of the system, the design was made to be as small and as light as possible while still maintaining its structural integrity. The center piece was constrained by the width of the bins and the overall radius of the component was constrained by the length of the bins. This resulted in a total radius of 27 cm. Since the 3D printer could only print components up to roughly 8 inches in length or width, the center plate was printed separately from the trays. Holes were then tapped in all the trays and the center plate and bin holders were screwed together, which is shown in Figure 2 and Figure 3. The final assembly is shown below in Figure 4.

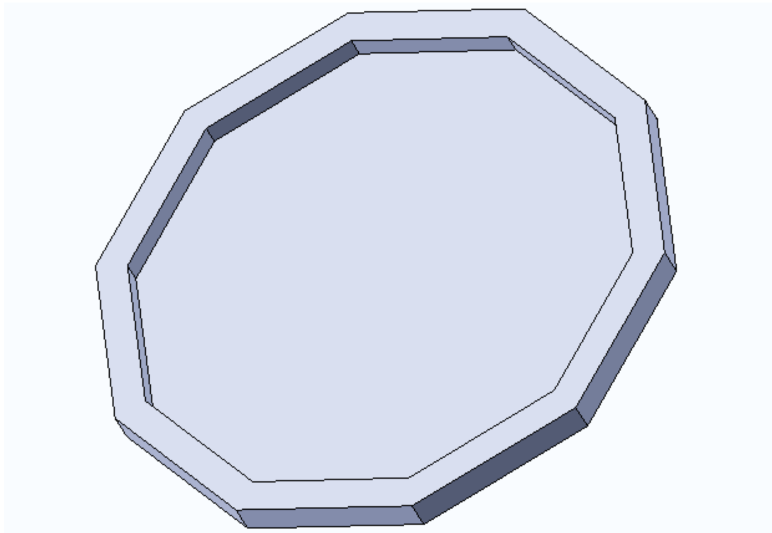


Figure 2: CAD model of the center plate.

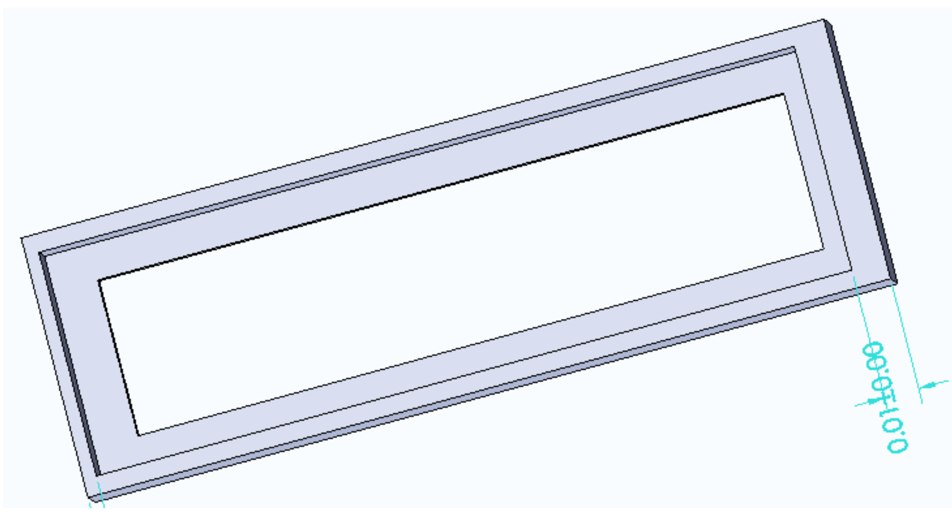


Figure 3: CAD model of an individual tray.

Figure 4: Final assembled revolving tray.

To determine the torque needed for the stepper motor, a moment of inertia calculation was completed approximating the bin holder as a disk. The moment of inertia was determined to be 0.043 N·m, therefore the stepper motor was more than adequate to rotate the bins.

4.2.2.2. Camera Enclosure and Drop Chute

The goal of this system was to have 95% of the resistors in the field of view of the camera with good enough lighting to be readable. To create diffuse and consistent lighting for the camera to read the resistors, an enclosure was 3D printed. This was also made to mount the servo motor to the structure. An aluminum tube was then machined and inserted into the top of the camera enclosure, which allowed for an adjustable height of the enclosure, as machining the tube is easier than re-printing a new enclosure. The interior of the box was painted white, then certain sides were covered with black paper to absorb some of the light. Once the resistors slid into the camera enclosure, the base plate had ridges on it to catch the resistors. Since the resistors picked up too much speed being moved from the belt to the enclosure, their landing point had a high variability. The resistors landed in the field of view of the camera with a 40% accuracy which was below the desired value.

4.2.2.3. Funnel and Slide for Resistors

To ensure smooth transitions between the conveyor belt, camera, and storage boxes, slides were used. The slides were machined using scrap aluminum that was cut using the shear, and walls were bent upwards to ensure resistors would not fall off the track. Some slides acted as quasi-funnels, tapering in on the edges to force the resistors to slide into smaller spaces more precisely and repeatably. The mounting techniques to the scaffolding varied largely, some parts were held using hot glue, but the non-tapered slide was fixed using a cantilever-like support, fitting into the slot of the extrusion as seen in Figure 5.

Figure 5: Final slide attached to the scaffold. The slid is meant to funnel the resistors off the conveyor into the camera detection area.

4.2.2.4. Scaffolding Apparatus

The main structure of the build was made using extrusions taken from the lab. These parts were bolted together using L shaped brackets. Some pieces were mounted on both sides if they needed to support a greater load. The scaffolding was built taller to ensure the slides were at a steep enough angle to prevent any catching or stopping in transit. This enabled the use of a taller stepper motor which had a large enough torque that the revolver could spin without external intervention. Given the modular nature of the extrusions, new portions were added as needed such as the extension supporting the camera mount. This feature was greatly beneficial to the project as it enabled the team to iteratively build the structure to change aspects as needed. This variability was key as one of the slides was too steep, causing the resistor to overshoot the slot in the box used to read the colour values. The grade of the slide was then flattened, and its length was shortened, followed by an adjustment of the camera enclosure position to ensure more consistent operation.

4.2.3. Motors and Mechatronics

4.2.3.1. System Overview

The sorter uses two stepper motors and one servo motor, all of which are controlled by one Arduino. One stepper motor turns the conveyer belt to drop resistors onto a slide. The other spins the revolver at the base of the device so the resistor can fall into the appropriate bin. The servo motor acts as the base of the resistor reading station and then rotates the base plate to drop the resistor down a ramp. The motors need to be able to perform their required actions sequentially, which is why the system uses one Arduino to control all three. This system is shown below in Figure 6.

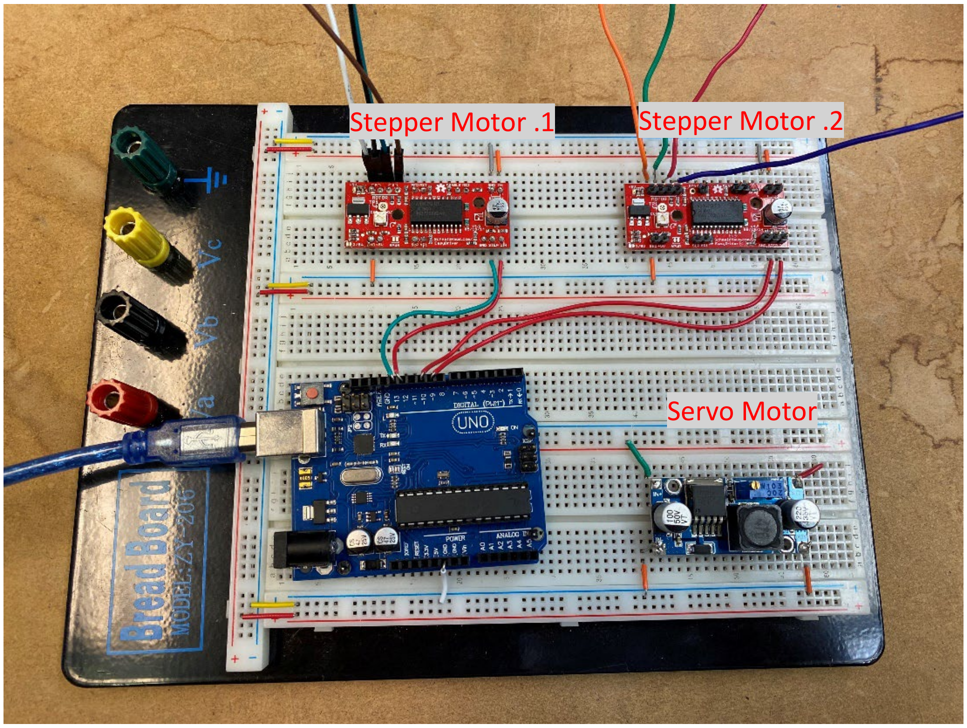


Figure 6: Final project circuit showing Arduino control of the three motors. All red rails are 12V, all blue rails are ground, and the buck converter supplies 6V to the servo (see Figure 8).

The system begins with the conveyer belt servo rotating 134 steps. The number of steps corresponds to the number of steps required for the belt to perform one revolution divided by the number of shelves the belt has. The conveyer belt servo then stops and waits for the rest of the system to complete tasks before dropping the next resistor. After the conveyer belt stops moving, the Arduino tells the detection program to read the resistance.

The resistor then drops into the reading station where its resistance is read (see section 4.2.4). Once the value is determined, a program sends a bin number from 0 to 9 to the Arduino. The Arduino then tells the revolver motor to rotate until the correct bin sits under the slide.

Once the revolver motor is done stepping, the servo acts as a drop chute. It rotates the base plate of the reading station by 90 degrees. The resistor then falls down the slide and into its bin. Once the servo is back in its original spot, the system starts from the beginning with the conveyer belt stepper. Once there are no more resistors left to be sorted, the revolver returns to its starting position with bin 0 under the ramp.

4.2.3.2. Circuit Components

The motors are run off a power supply set to 12V to support the specifications of all three motors. The servo motor has a 6V rating, so a buck convertor was used to drop the 12V down to 6V as seen in Figure 7 below.

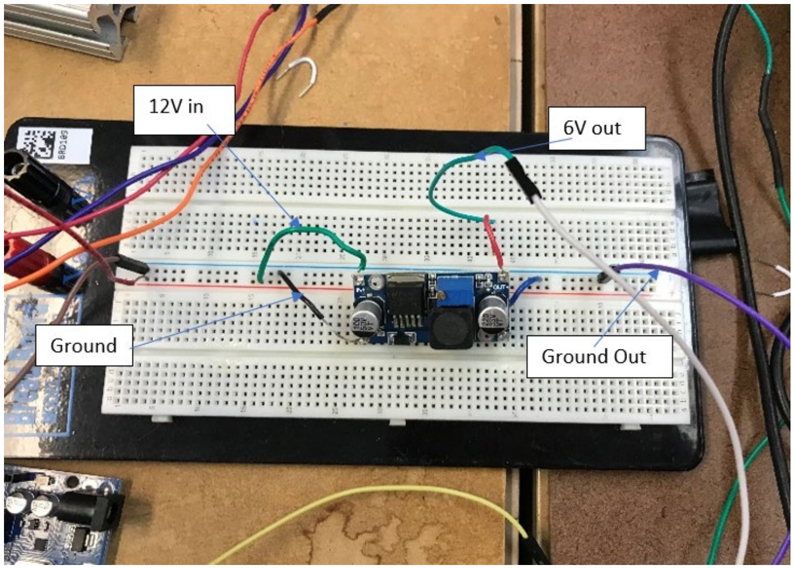


Figure 7: Buck convertor design used to drop voltage from 12V to 6V to fit needs of the Servo

Note the Arduino and the motor components needed to be connected to a common ground so the current can flow back to the power source.

The two stepper motors are run off two identical drivers as shown in a circuit schematic below. Originally, the stepper motors were chosen by comparing the base torque of the motor to the minimum torque requirement to move their respective components. These motors did not have the power to move their components from rest because their ramp torque values were below the minimum torque values resulting in slow acceleration and step skipping. As a result, new stepper motors were chosen with ramp torque values greater than minimum torque which significantly increased accuracy. A complete circuit diagram is shown below in Figure 8.

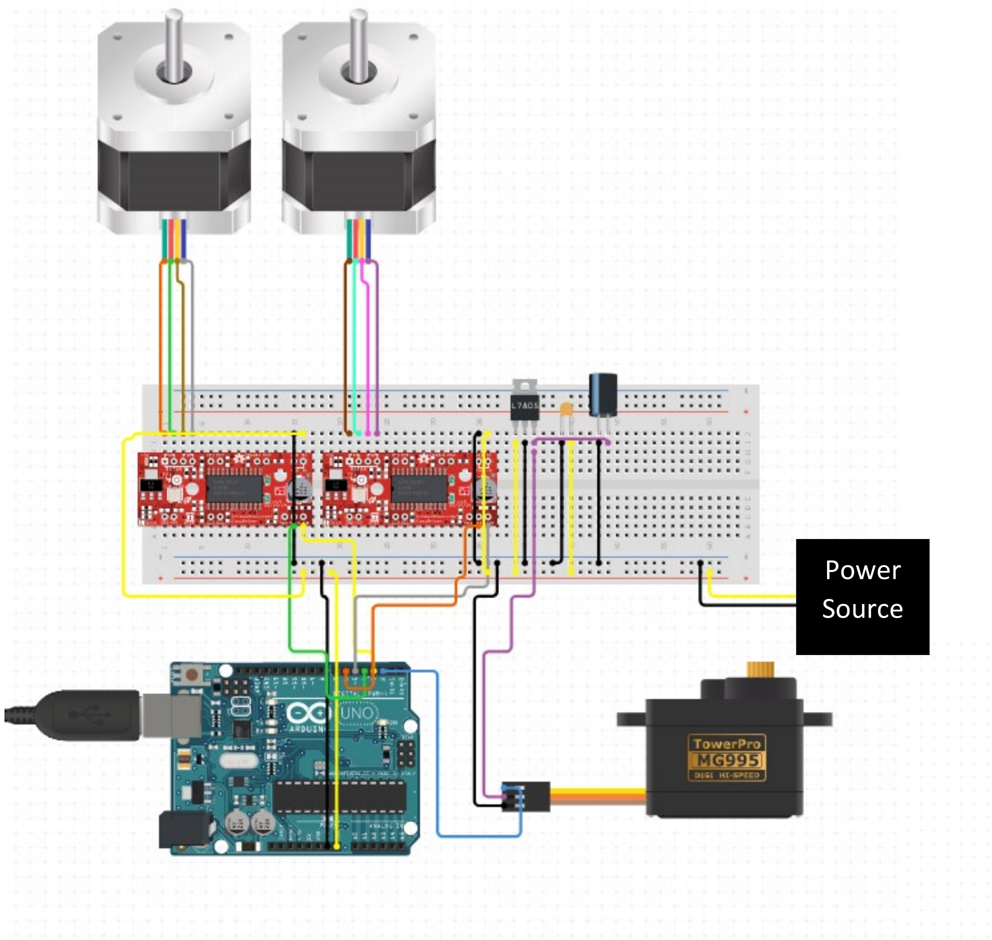


Figure 8: Circuit schematic of the motors, the drivers, and the Arduino.

The driver is connected to two analog Arduino pins, one which controls direction and one which controls the stepping of the motor. Its output is four stepper pins connected directly to the motor. The Arduino receives information from the camera detection system connected by a USB cable.

4.2.3.3. Arduino Code

The motors are programmed using Arduino and the code can be found in Appendix C. The program starts with the conveyer belt stepping 134 steps to drop one resistor into the reading station. The program then waits to receive a signal from the detection system which sends a digit to the Arduino based on the resistance read.

Each digit (0-9) is associated with one of the 10 bins shown in Figure 4. Once the digit is received, it is converted into a step number. Since one revolution is associated with 160 000 steps, the step number for each bin is its bin value multiplied by 16000. So, bin 0 has as step value of 0 (it starts under the ramp), bin 1 is 16 000 steps, bin 2 is 32 000 steps, etc.

The step number is then used as a condition in a loop which steps once per loop. The loop counts down the step number and stops when the step number gets to zero. So once the loop stops the appropriate bin is under the ramp and ready to receive a resistor.

There is a condition at the end of the step loop which sets a variable ("servo") to true. Once this variable is true, the servo drops the resistor and returns to its original spot to wait for the next resistor. It then sets the "servo" variable back to false to await the next reading. The code then starts with the belt stepping 134 steps.

An important part of the code involves storing a variable to remember how much the revolver motor stepped in the previous cycle. In each loop the step number is stored in a variable called "oldPos". The code then checks if the difference between the two is greater than half of a revolution. If it is greater than half a revolution, then it is quicker for the motor to spin in the opposite direction than the default direction. Once the required direction is known, the two step variables are subtracted and outputted into a new variable called "diff". Diff is the variable used in the loop condition previously mentioned to countdown the step number.

4.2.4. Camera Detection

The camera detection works using a three-step process that begins with isolating the resistor from the rest of the image, detecting the colour bands in the isolated image, then decoding the colours [2]. See Figure 9 for the code flow diagram.

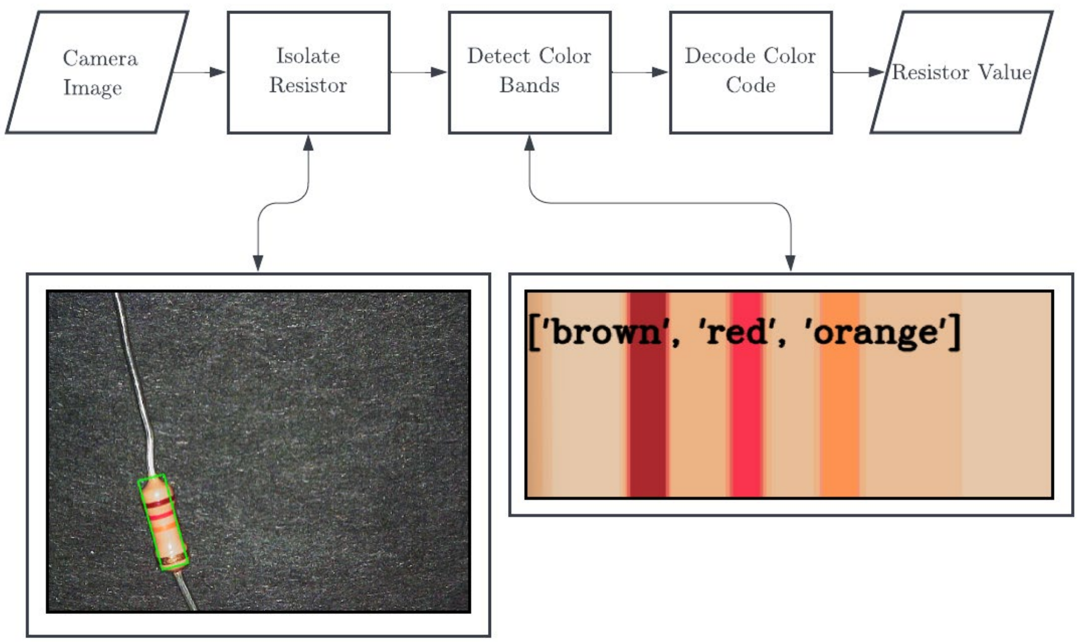


Figure 9: Flow diagram illustrating the process for the resistor detection software program.

4.2.4.1. Resistor Isolation

The matte black background was chosen so that resistors can be distinguished from the background purely based on pixel brightness. Since the lighting and camera exposure are held constant, the image is threshold to a binary representation based on a set brightness. This approach alone is insufficient because the leads of the resistor would also be detected and dark bands would split the resistor in half. To solve both these problems, a median filter is used to remove these thin elements. Like a mean filter (gaussian blur), a median filter removes fine detail, however the median filter also preserves sharp edges. Contour detection is then used and a minimum-area bounding rectangle is fit to the body of the resistor. This corrects for the rotation of the resistor. The image is then cropped to a rectangle and sent to the next step.

4.2.4.2. Colour Band Detection

The initial design for this component used a traditional image processing approach, similar to the one used the previous step, but was found to be unreliable. If two close bands were different colours but similar in intensity, they were detected as a single band. It became clear that a more sophisticated approach that made full use of all three color channels was required.

Before the cropped resistor image is processed, the image can be simplified to a one-dimensional image, taking advantage of the radial symmetry of the resistor package. Taking the mean of the pixels in the radial direction, reflections can be supressed to reduce the dataset. Reducing the number of pixels is useful for speed as the original target device was a Raspberry Pi 4 with limited RAM and computing power.

For the final design of this step, the resistor is treated as a collection of datapoints, rather than an image. Pixels can be converted to vectors with 4 components: red, green, blue, and x-position. Y-position is redundant due to symmetry. To isolate the bands, groups of pixels that are similar in both color and position must be found and an algorithm called k-means clustering is used [2]. K-means clustering returns the centroids of the clusters it finds. For this application, the first 3 components define the average color of the band, and the last gives its center position. The clusters are sorted based on position, and then the colors must be classified. The program contains a set list of color names along with their average RGB values. The RGB values are interpreted as a 3-component vector, and the distances (in cartesian RGB space) from the average cluster color and each named color are computed. The band is assigned whichever named color it is closest to.

The main flaw of this implementation is the lack of automatic background detection and removal. The previous iteration of this design had this feature. Dropping it and moving to the new design allowed for an increase of accuracy, but a loss of generality. Reinstating it would greatly increase the scope of the resistors that the algorithm is able to classify.

4.2.4.3. Resistor Decoding

The resistors are then decoded according to the IEC 60062 standard [3]. The gold or silver bands are used to identify whether the sequence should be read forward or backward. These bands are always at the end of the sequence for four-band resistors. A bin is then selected and a message is sent over serial to the mechatronics subsystem.

5. Final Design

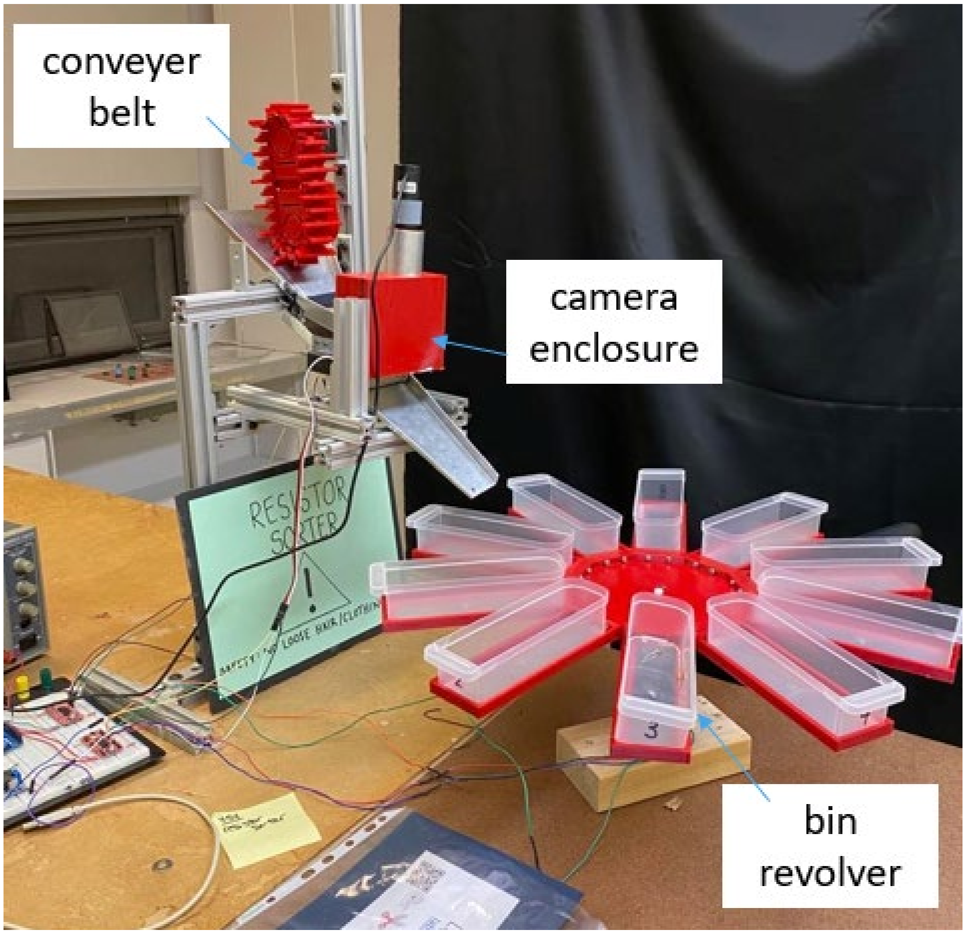


Figure 10: Final constructed design with annotations for each of the respective sub-components.

The three main components of the final design are the conveyer belt, the camera enclosure, and the bin revolver. The resistors are pre-loaded in the conveyer belt. They then slide down into the camera enclosure where they are read. Once the resistors are read, the bins are rotated to the assigned bin, then the drop chute in the camera enclosure drops the resistor into its bin. After a cycle, the system resets and the conveyer belt and drops another resistor.

6. Testing, Validation, and Iteration

6.1. Determining a Baseline

Timed tests were conducted to compare the performance of the autonomous resistor sorter to manually sorting resistors. There were three main methods identified of sorting resistors: an inexperienced user, an experienced user, and a multimeter. An "inexperienced" manual sorter is defined as a user who sorts resistors by comparing the colours of the bands to the colours listed on the drawers, shown below in Figure 11.

Figure 11: An image of the Stirling Hall fifth floor resistor bins, displaying their colour codes.

An “experienced” manual sorter is a user who sorts by converting the colour bands to resistance values while referencing the colour chart shown below in Figure 12.

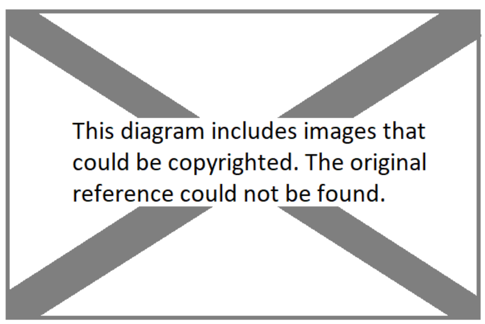


Figure 12: Resistor colour band decoder, as used by an "experienced" user to sort resistors.

Lastly, the multimeter method is defined as a user who measures resistance values with a portable multimeter, shown below in Figure 13.

Figure 13: An image of the digital multimeter used for the third method of testing.

Each of the methods were tested three times. For a trial to be considered, four resistors had to be sorted accurately. The results of the tests are shown below in Table 4. Note that there are no values for the “Resistor Sorter Device” since the final prototype was not able to sort even a single resistor reliably, and hence could not be compared to the other sorting methods (see Section 6.2). However, this is how the device would have been tested had it been able to perform properly.

Table 4: Testing matrix to compare the speed of each resistor-reading method. Note that there are no values for the “Resistor Sorter Device” since the final prototype was not able to sort resistors with 100% accuracy, and hence could not be compared to the other sorting methods.

Trial Number	Inexperienced User Manually Sorting [s]	Experienced User Manually Sorting [s]	Resistance Measurement Using Ohmmeter [s]	Resistor Sorter Device
Trial #1	147	108	149	N/A
Trial #2	164	121	134	N/A
Trial #3	132	69	118	N/A

When the resistor sorter did perform successfully, it was able to sort one resistor in approximately 15 seconds. Assuming that this is how long it would take to sort each resistor, and assuming that sorting could occur with consistent accuracy, it would take approximately 60 seconds to sort the four resistors. This proves that with additional development of the prototype, the resistor sorter would hypothetically be the fastest method of sorting resistors. Note that the time required to straighten the resistors and place them on the conveyor belt has not been considered here.

6.2. Testing the Overall System

The overall testing of the resistor sorter had poor results as expected based on the varying success rates for individual sub-team designs. The conveyor belt and system of slides were only able to transport the resistors one at a time to the correct location within the camera enclosure with an accuracy of 40% and the camera was only able to detect the resistance value correctly with an accuracy of 60%. The product of these two success rates gives the system an overall accuracy of 24%. In the one test of the entire system that the team completed prior to the end of term, only two of ten tested resistors were successfully sorted. Given that the assembly of the final design did not occur until the last week of the project, there was very little time for testing of the overall system.

System	Success Rate
Proposed System	>80%
Product of the Subsystem Success Rate	24%
Actual System (Single Test)	10%

Given more time to improve the design, the team would have completed tests as follows. Ten tests would have been completed, each with ten resistors loaded on the conveyor belt. During each trial, the resistors would have been catalogued as: successfully sorted, unsorted due to camera reading, or unsorted due to field of view restrictions. Once these trials were completed, an overall success rate could have been determined by the number of successfully sorted resistors. The group would then have been able to determine which of the two major design flaws to focus on in future refinements: either the resistor placement in the camera enclosure or the inconsistencies in camera reading. Each trial would also have been timed from the point at which resistors were loaded onto the conveyor belt to the time when the last resistor was placed into the bin. This data could have been averaged to estimate the sorting time per resistor and then compared to the baseline tests described above to determine whether the device was faster than manual sorting. This comparison would enable the group to determine if the initial project objectives were met and if a success rate of greater than 80% was achieved.

6.3. Iteration of the Overall Design

Considering the late completion of the first iteration of the overall system, the team did not have the time to iterate upon the overall design. It should however be noted that iterations to the subsystems are described in the Methodology section and suggestions for possible future improvements are outlined in the Discussion section below.

7. Discussion

7.1. Discussion of Design

Limitations and suggested improvements that can be made to the design are discussed below in order of most to least impactful on device performance.

First, the device cannot sort more than about 12 resistors autonomously before requiring manual reloading. The limitation on the number of resistors inputted means that a user must straighten resistors by hand, place them on the conveyor belt, and remain near the device to continue reloading as sorting occurs. As a result, the design is not yet any more efficient than other methods of resistor sorting. The next step to eliminate this issue and improve the system accessibility is to design a resistor dispenser that allows the user to dump a large quantity of tangled and unsorted resistors into the device. This improvement would make the system fully autonomous and helpful for users.

Second, the inaccurate sorting can be addressed by ensuring that resistors land within the field of view of the camera. To reduce this error, the slides directing resistors into the camera enclosure can be tapered to force all resistors to slide down sideways with the leads entering the enclosure first. This modification would require adjustments to the servo mechanism and the construction of a new camera housing. Additionally, if the slides were constructed from a single piece of curved aluminum rather than several, the disruption to resistor movement caused by the lips between slides would be eliminated. Once these adjustments were made to the slides and the camera detection program was refined, the accuracy of the sorting would be greatly improved.

Third, there are several improvements that could be made to the design of the revolver. Smaller bins would allow the system to be more compact and would make room for the addition of more bins, and therefore a wider range of resistors that can be sorted. A higher torque motor would also be beneficial to help accomplish these tasks. The team had planned to add a limit switch to center revolver, and although the motor was sufficient for spinning the bins, there was not enough torque to push a limit switch. Although the current rotation speed was acceptable, adding a higher torque motor would have allowed the button to be pushed and set the starting point automatically instead on relying on the best guess of the user.

Finally, other small improvements that would help meet the design criteria include adding a shield onto the conveyor belt, reducing the slack in the belt, shrinking the overall size, and constructing a casing for the entire system. The shield on the conveyor belt would prevent resistors from falling out before sorting and becoming trapped in device components. It would also protect long hair or loose items from catching in the moving parts. Reducing the slack in the belt would ensure that it does not drop more than one resistor at a time. Shrinking the overall size of the device would allow for easier placement and storage in a laboratory space. A casing around the entire system would protect users from moving components and improve the aesthetic appearance of the device.

7.2. Discussion of Design Success

Based the analysis of limitations and suggested improvements presented above, a large portion of the work required to construct a fully autonomous resistor sorter has already been completed. As it is right now, the device is not considered successful, but with suggested improvements implemented, the design will be appropriate for achieving the goals identified at the project outset.

7.3. Discussion of Design Process

At the end of the term the group completed a brief reflection on how the design process worked well for the team and how it could have been improved over the course of the term to achieve a better result. There were three major factors that contributed to the design process and are discussed below:

1. Since weekly meetings with TAs took place at the end of Friday lab periods, there was no opportunity for the group to discuss the feedback received together before people had to leave for other classes. The group should have scheduled an additional meeting time for reviewing the feedback received and discussing how best to implement it. This would have allowed the team to better organize a solution.

2. The iterative process taken by the group was very effective for the design process of individual sub-teams and allowed opportunity for the teams to assess design flaws and make refinements. However, if additional time had been taken at the beginning of the term to focus on the project planning, then it may have allowed the team to proceed with a more sophisticated design.
3. The team could have significantly benefitted from setting improved quantitative objectives at the beginning of the term. The overall objectives were mainly qualitative and vague; it was only the separate sub-teams that set specific quantitative goals. While this allowed the sub-teams to work effectively on improving their designs, the overall team would have benefitted from having more clearly defined goals in mind from the project outset.

The team functioned well in the separate sub-teams, but improving the aspects of the design process outlined above would have allowed the group to achieve better overall communication to work toward a more unified goal.

8. Economic Analysis

As discussed in Section 1.3, the budget for this project was $1000. The total cost of the project came out to $298.89 after tax. This considered any new purchases and materials for the project and did not consider materials provided by the Physics Department. To see a comprehensive breakdown of the project costs, please see Tables S1 and S2 in Appendix B.

If the project was scaled past the prototype stage, additional funding could have gone towards further iterating various 3D-printed parts, as well as constructing/building a more compact scaffold to hold all the components together. As discussed in Section 7.1, one of the main improvements to the device would be to read the resistor values directly off the conveyor belt. If this was implemented, additional funding would need to go towards 3D-printing or painting the conveyor belt in black, thereby providing the black background required for the camera to read. The conveyor would also require an enclosure to create consistent lighting for the camera. This would bring on additional costs for either reprinting or painting the pieces. The total cost for further developed device approximately comes out to an additional $387.98. For a full cost breakdown, please see Appendix B, Table S3.

9. Conclusion

Overall, the project failed to meet its accuracy performance goal, which is the most important metric by which it should be measured. However, the fact that it can outperform a manual operator in terms of speed demonstrates the viability of the concept. The accuracy of both the mechanical and imaging subsystems can be improved with additional development time. Although each of the subsystems did not meet all their individual performance goals, they were integrated together with only a minor additional loss in the success rate. The project's primary stakeholder, the Department of Physics, may decide to keep the apparatus for future improvements.

10. References

[1] T. Clark, "Drogerdy - Raspberry Pi Controlled Tank Bot," 26 January 2015. [Online]. Available: https://www.thingiverse.com/thing:652851. [Accessed 6 December 2022].

[2] Y. -S. Chen and J. -Y. Wang, "Reading resistor based on image processing," in *2015 International Conference on Machine Learning and Cybernetics (ICMLC)*, Guangzhou, China, 2015, pp. 566-571, doi: 10.1109/ICMLC.2015.7340616.

[3] International Electrotechnical Comission, "IEC 60062:2016+AMD1:2019 CSV: Marking codes for resistors and capacitors," International Electrotechnical Comission, Edition 6.1, https://webstore.iec.ch/publication/65655, 2019.

Appendix for:

Resistor Sorter

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Appendix A – Torque Calculations

A rough estimate of the torque required to turn the carousel of bins was done in order to choose the correct stepper motor. The center piece weight was 320.87g and each of the ten bins was 21.38g. This gave a total mass of 534.67g. To determine the moment of inertia, the carousel was approximated as a thin disk.

$$I = MR^2 \tag{S1}$$

$$I = (0.5347) * (0.25)^2$$

$$I = 0.03342 kg/m^2$$

The acceleration was approximated by assuming the carousel takes 5 seconds to do a revolution, starting from rest.

$$\alpha = \frac{2\pi - 0}{5} = \frac{2\pi}{5} m/s^2$$

The torque was the calculates as

$$\tau = I\alpha \tag{S2}$$

$$\tau = 0.035\ N * m$$

Appendix B – Project Budget

Table S1 below shows the total cost for all new materials purchased for the project.

Table S1: List of materials and costs for all new materials purchased for the project.

Item Name	Purchase Location	Unit Price	Quantity	Total Cost
USB Microscope	Amazon	$53.95	1	$53.95
Buck Converter	Amazon	$11.28	1	$11.28
Aluminium Rod	McMaster-Carr	$5.62	1	$5.62
64 Piece Drawer Cabinet	Amazon	$38.96	1	$38.96
3D Printing	Physics Department	$154.69	1	$154.69
			TOTAL	$264.50
			TAX	$34.39
			TOTAL WITH TAX	**$298.89**

Table S2 below shows the total cost for all items that were the required for the project. This includes any items that belong to team members or borrowed from the Physics Department.

Table S2: List of materials and costs for all materials used throughout the project.

Item Name	Purchase Location	Unit Price	Quantity	Total Cost
Computer	Dell	$1,500.00	1	$1,500.00
Aluminium Extrusion Pieces	Amazon	$149.99	1	$149.99
Stepper Motor	Amazon	$14.99	2	$29.98
Arduino Uno	Amazon	$23.99	1	$23.99
Stepper Motor Driver	Amazon	$6.99	2	$13.98
Pack of Wires	Amazon	$19.99	1	$19.99
DC Power Supply 1630	ValueTronics	$125.00	1	$125.00
Miscellaneous Screw Set	Amazon	$20.34	1	$20.34
Servo Motor	Amazon	$4.99	1	$4.99
Scrap Aluminium	N/A	$0.00	1	$0.00
			TOTAL	$1,888.26
			TAX	$245.47
			TOTAL WITH TAX	**$2,133.73**

Table S3 below displays the total approximated cost for additional items if the device was to be further developed past the prototyping stage.

Table S3: List of materials and costs for materials required if the product was further developed past the prototyping stage.

Item Name	Purchase Location	Unit Price	Quantity	Total Cost
3D Printing	Physics Department	$200.00	1	$200.00
Aluminum materials	Home Depot	$49.99	1	$49.99
Matte black paint	Lowes	$14.95	1	$14.95
Miscellaneous electrical pieces	Amazon	$19.99	1	$19.99
High-power motor	Amazon	$29.92	1	$29.92
Contingency (10% of total)	N/A	$28.49	1	$28.49
			TOTAL	$343.34
			TAX	$44.63
			TOTAL WITH TAX	**$387.98**

Appendix C – Arduino Code

```
#include <Servo.h>

Servo myservo;  // create servo object to control a servo

int pos = 0;    // variable to store the servo position

int servo = 0;

int beltnum = 134;

long oldPos = 0;

long newPos = 0;

int dir = 0;

long diff = 0;

long binNum = 0;

long stepNum = 0;

int belt = 1;

 void setup() {

         myservo.attach(8);  // attaches the servo on pin 9 to the servo object

        Serial.begin(9600);

        pinMode(9, OUTPUT);

        pinMode(10, OUTPUT);

        digitalWrite(9, LOW);

        digitalWrite(10, LOW);

        pinMode(12, OUTPUT);

        pinMode(13, OUTPUT);

        digitalWrite(12, HIGH);

        digitalWrite(13, LOW);

        myservo.write(85);

}

void loop(){

        if(Serial.available() > 0){

                binNum = Serial.readString().toInt();
```

```
                stepNum = binNum*16000;

                dir = My_Dir(stepNum, oldPos);

                diff = My_Diff(stepNum, oldPos);

                digitalWrite(9, dir);

                servo = 1;

}

if(diff > 0){

                digitalWrite(10, HIGH);

                delayMicroseconds(100);

                digitalWrite(10, LOW);

                delayMicroseconds(100);

                 diff--;

                }

if(diff == 0){

                oldPos = stepNum;

}

if(servo == 1 && diff == 0){

                myservo.write(20);

                delay(1000);

                myservo.write(85);

                delay(1000);

                servo = 0;


                belt = 1;

                }

if(belt == 1){

                while(beltnum > 0){

                   digitalWrite(13, HIGH);

                   delayMicroseconds(750);
```

```
                        digitalWrite(13, LOW);
                        delayMicroseconds(750);
                        beltnum--;
                        belt = 0;
                    }
            Serial.print('r');
            beltnum = 136;
            }
}
long My_Dir(long a, long b){
            long halfRev;
            long diff;
            int result;
            halfRev = 80000;
            diff = abs(a - b);
            if(diff > halfRev && a < b){
                    result = 0;
                    }else if(diff > halfRev && a > b){
                            result = 1;
                    }else if(diff < halfRev && a < b){
                            result = 1;
                    }else if(diff < halfRev && a > b){
                            result = 0;
                    }
 return result;
 }
long My_Diff(long a, long b){
             long half = 80000;
             long full = 160000;
```

```
        long diff1;

        long result;

        diff1 = abs(a - b);

       if(diff1 > half){

               result = full - diff1;

               }

       if(diff1 <= half){

               result = diff1;

               }

return result;

}
```