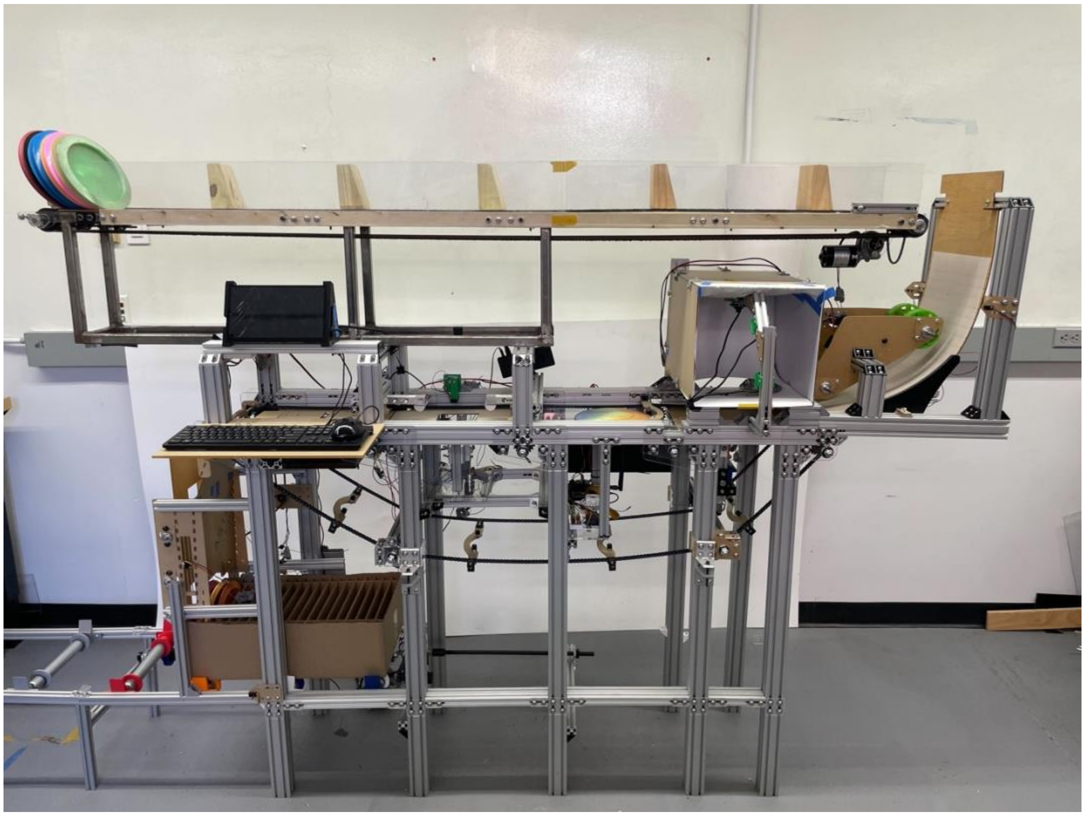
AUTOMATED DISC ANALYSIS AND INVENTORY SYSTEM



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Automated Disc and Inventory System

A Major Qualifying Project Report
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Abstract

Maple Hill Disc Golf is a world-class disc golf organization, featuring a premier course and a reputable on-site pro-shop. To reach more customers in the community, Maple Hill intends to establish an online store; however, disc golfers traditionally prefer to purchase discs through physical examination of their features. Therefore, the team has constructed the second iteration of an automated machine that measures the necessary features and inventories them. The machine implements modular design principles to record, maintain, and store information about each disc including the diameter, wing width, flexibility, weight, height, while also taking cosmetic photos. With this automated machine, Maple Hill aims to provide customers with comprehensive product information in order to replicate a traditional in-store shopping experience.

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Glossary of Terms

- **Disc alignment tool** - in reference to the object that centers discs on the conveyor system and pushes them along from module to module.
- **Box conveyor** - in reference to the conveyor on the underside of the machine that moves boxes along via rollers.
- **Upper conveyor** - in reference to the conveyor belt that discs are initially loaded onto. This top conveyor moves along incrementally and drops discs down the intake ramp.
- **Main conveyor** - in reference to the conveyor system that moves discs from module to module.
- **Dome height -** in reference to the height of a disc, measured from a surface to the highest point on the disc, with the disc lying flat on said surface.
- **Wing width** - in reference to the distance between the inner diameter and the outer diameter of a disc.
- **Edge profile -** in reference to the outer edge of the disc, the area between the inner and outer most diameters.
- **Intake** - in reference to the assembly responsible for queuing and advancing discs between the top conveyor and the main conveyor.
- **Outtake -** in reference to the assembly responsible for advancing discs from the main conveyor to the slotted inventory boxes on the box conveyor.

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Paper Formatting – Tristan Andrew and Jonathan Whooley

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Executive Summary – Tristan Andrew

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Executive Summary

Maple Hill Disc Golf and their Expansion Efforts:

Maple Hill is a world-class disc golf organization located in Leicester, Massachusetts. Their venue includes a professionally designed disc golf course, capable of accommodating recreational play as well as national championship level competitions. In addition to the course, they also manage an on-site pro shop. Here, prospective players can try out and purchase a wide variety of disc golf discs.

Traditionally, disc golf customers use physical examination of discs to make purchasing decisions. At higher levels of disc golf, professionals are able to accurately predict the flight behavior of a disc simply by analyzing the disc in their hands, through an understanding of how the full profile, the dome height of the disc, the weight, and other disc characteristics affect its flight behavior. Therefore, many disc golfers avoid online pro shops as they are not able to simulate the in-person experience. Maple Hill's goal is to create an online shopping center that emulates the in-person shopping experience by creating standardized measurements that allow accurate comparison between discs.

One of the main issues with disc golf manufacturing is slight inconsistencies between discs of the same model. Color and graphics can vary from what's advertised to what is delivered to the customers. Physically, the measurements given by the manufacturers are not useful as there is no standardized way of labeling a disc's flight speed, weight, or flexibility, all of which are determining features in how the disc flies. Our team set out to improve upon a design that will autonomously collect the standard measurements examined during an in-person shopping experience, while also providing cosmetic photos and an inventory system to ensure a worthwhile online shopping experience.

Our Approach:

The goal for our team was to construct a machine which autonomously moves a disc through various implemented modules, which obtain measurements from the disc, takes high quality cosmetic images of each disc, and then inventories the discs in boxes. To achieve our goal of creating a machine to autonomously measure, photograph, and inventory discs, our team developed the following objectives:

- Enable measurements upon button activation.
- Achieve disc motion through the machine’s conveyors.
- Prototype mechanical and electrical module designs.

Through interviews and focus sessions with the client, we were able to determine the standard measurements needed to simulate an in-person shopping experience. We validated these standardized measurements by consulting with a disc golf professional and gaining insights into their approach to selecting discs.

Design and Development of the Machine:

From the research and discussions with the client, the team was able to design and develop a machine to align with the objectives set at the beginning of the project. The machine, although not fully autonomous, can be used to accurately measure, photograph, and inventory discs through use of controls on the user interface (UI). This functionality is achieved mainly through the motion of the three conveyor systems and the communication between multiple microcontrollers and a Raspberry Pi communicating via Robotics Operating System (ROS). The machine is a modular design to ensure adjustability when Maple Hill inevitably expands its warehouse. Each module’s function, whether it be motion or measurement, is executed via digital buttons on the user interface. Overall, the data that can be collected includes height, dome height, weight, and flexibility while also providing cosmetic photos that can be used to create a 3D rendering. Finally, each disc can be placed in an independent slot to ensure easy accessibility once inventoried.

Conclusion:

Through the development process the team was able to create a sufficient solution to the client’s needs, while also learning invaluable information on engineering in industry. The machine will provide a valuable baseline for further improvement and eventual shift in the disc golf online shopping experience.

Recommendations:

For future development of the machine, we recommend:

- Adding additional modules to increase measurement data of discs.

- Improved user interface.
- Exporting data directly to the online shop.

These changes will make the necessary improvements to bring this product fully to market.

Chapter 1: Introduction

1.1 Maple Hill Disc Golf Problem Overview

Located in Leicester, Massachusetts, Maple Hill Disc Golf is a local 18-hole disc golf course which sells discs via their in-person pro shop. Maple Hill prides itself on being a leader within the disc golf community and hosts the Most Valuable Player (MVP) Open every year with spectators and professional disc golfers coming from all around the world to watch and compete.

At Maple Hill's pro shop, customers are encouraged to physically examine discs before purchase as the factory ratings of each disc are often insufficient. Parameters that customers examine include the aesthetics of the disc as well as its physical characteristics, such as the full profile, dome height, weight, and flexibility. Without having the equipment to measure many of these qualities, customers are forced to rely on physical examination and their own knowledge of disc characteristics. Therefore, buying discs online becomes a challenge as customers do not have physical access to discs, and online disc retailers provide unstandardized information and measurements of the discs. Being a leader of the disc golf community, Maple Hill wants to improve the online shopping experience for discs by providing a concrete way to communicate these disc characteristics to their customers.

Maple Hill is eager to expand their outreach by offering an online store in which disc golfers from all over the world can buy discs from their website. Their efforts to expand into the online store community are influenced not only by their ambition to sell more discs, but to provide a superior online shopping experience for disc golfers. To compete with other online disc golf stores and better satisfy customer needs, Maple Hill needs to not only provide information other online retailers do but provide quantifiable and understandable ways to express sought after disc qualities among various types of discs.

Maple Hill is looking to substantially increase their sales to their large global consumer base by providing repeatable and accurate measurements of the large variation in disc makes and models. Manually recording disc measurements would be inefficient and raise reliability concerns for Maple Hill's large-scale operations aimed at processing hundreds of discs quickly. Therefore, the autonomous data collection and inventorying machine was created to save time for workers and provide accurate and standardized data about discs for online customers.

1.2 Background Research

To understand the objectives of the client, we toured Maple Hill, inspecting both the client's course and the pro shop to evaluate the customer experience and gain a deeper knowledge of disc golf. To better understand how to simulate the shopping experience online, we met with and questioned disc golf professionals, and held client meetings to discuss the qualities customers look for when shopping for discs in person.

When shopping for discs online, customers would like to see the disc's aesthetics and physical features. Pro disc golf customers typically seek information that is required for discs to pass Professional Disc Golf Association (PDGA) standards, including diameter, wing width, full profile, weight, flexibility, and dome height (Figures 1 & 2). These measurements also collectively inform the customer on the flight characteristics of the discs. While PDGA standards provide information about what disc measurements are acceptable for professional disc golf, the methods of measurement collection are only guidelines for users to follow and therefore can produce a wide variety of measurement results. For example, the way to measure the flexibility of a disc involves holding the disc "on its edge in a vertical position perpendicular to a scale… The upper rim of the disc is then gradually pressed down" (PDGA, 2021). However, when performing this test at home, many different types of scales and variations of pushing down on the disc can occur, leading to inaccurate results compared to when the test is done properly with a high precision scale. Therefore, we sought to collect flexibility as well as other disc measurements in a standardized way that could then be transparently communicated to customers online.

In addition to its physical characteristics, customers are also interested in the disc's cosmetic appearance. The client emphasized a need for a 3D, or 360-degree view of the discs, where users online could click and spin the disc image to see different views.

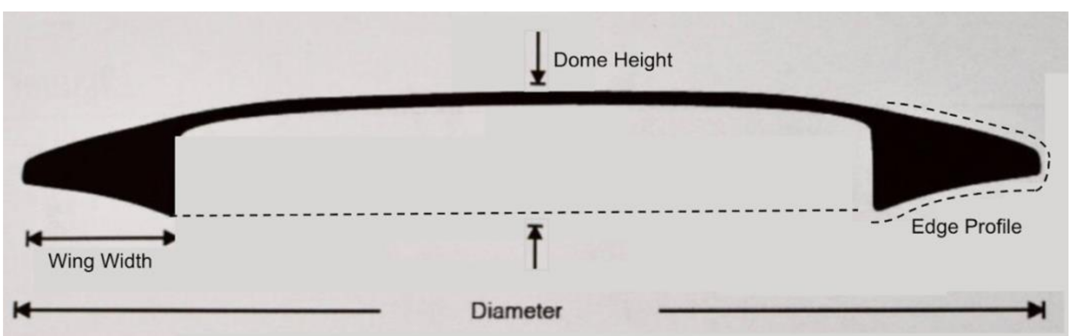


Figure 1. Desired measurements of a disc

Figure 2. Wing width and diameter example

1.3 Previous Work

In order to obtain the desired information from the discs, prior efforts led to a modular machine, with each module focusing on a different task or measurement. These measurements would then be communicated to a central computer, where they would be compiled and saved.

To determine the weight of the disc, a custom weight module was designed and assembled, incorporating four load cells hooked to a ST Nucleo F303K8 microcontroller. The diameter and wing width were obtained by a diameter module that used a camera positioned underneath the discs with the goal of using vision processing technology to calculate the measurements from the resulting images. Additionally, the full profile module passed discs under a line of acrylic probes, utilizing the displacement of these probes to characterize the discs curvature. Finally, while lacking a dedicated module, cameras were mounted throughout the system to obtain cosmetic pictures of the discs as they passed through.

Due to limited space at the client's workplace, a stacked conveyor system was designed where discs could be loaded on an upper queue, transferred to a middle conveyor housing the measurement modules, guided through each module, and finally dispensed into a box on a lower conveyor system. The upper queue dropped discs down one at a time through an intake system, ensuring a steady supply to the main conveyor and measurement modules, with the main conveyor integrating a disc alignment tool to consistently align and center discs within each module. Upon completion of the final module, discs descended through an outtake ramp into a waiting slot in a specially designed slotted box. The lower conveyor was planned to move the box along, allowing each new disc to be placed into an empty slot in the box.

The machine was designed to process upwards of 100 discs without user input, recording the weight, diameter, wing width, and full profile of each one, as well as acquiring cosmetic pictures of their appearances. Unfortunately, the prototype fell short of its design goals in a number of areas. The weight module was unable to accurately weigh the discs, the full profile fell short of the necessary precision, and the camera module failed to take quality photos of the discs. There were also several problems with the electrical, communication and motion systems. The electrical and communication systems were based around a Controller Area Network (CAN) bus system, which did not work as intended and proved difficult to integrate and debug. In addition, the upper conveyor could not properly hold the required number of discs, the main conveyor used a motor that could only communicate using CAN, and the box conveyor implemented complex geometry that was unfavored by the client. The intake and outtake systems also lacked consistent functionality and structural integrity. As such, these modules had to be either fixed, or in many cases, completely redesigned.

1.4 Project Goals & Objectives

To continue previous work as well as meet the needs of the client, goals were established including achieving autonomous collection of accurate disc data for use in an online store, seamless interaction with a machine operator, and efficient storage of each disc along with its corresponding data. The development process included designing or redesigning modules to measure the flexibility, weight, full profile, and dome height of discs, and a module to take cosmetic pictures. The design of the disc motion within the machine involves loading discs onto an upper conveyor and subsequently dispensing them onto the main conveyor, where they pass through the measurement modules. The discs are then dropped into the outtake to be labeled with a barcode and then stored in a slotted box on the box conveyor. However, due to time and monetary constraints, we specifically focused on ensuring the design and implementation of the upper and lower conveyors, intake and outtake systems, camera, weight, and flexibility modules, as well as the higher-level communications, control, and electrical systems. These elements would then be operated semi-autonomously through buttons on a simple graphical user interface (GUI).

Chapter 2: System Design

2.1 System Overview

The automated disc inventory machine was designed with an upper conveyor, middle conveyor, and lower box conveyor for discs to travel through. The top conveyor, loaded by an operator, holds, and dispenses discs through an intake and onto the machine. The main conveyor system moves discs between data collection modules, including the camera, diameter, flexibility, and weight modules. Discs are then dispensed through an outtake into a specially slotted box on the box conveyor (Figures 3 & 4). These systems were designed and prototyped using axiomatic design, and further details about this design process can be found in Appendix B.

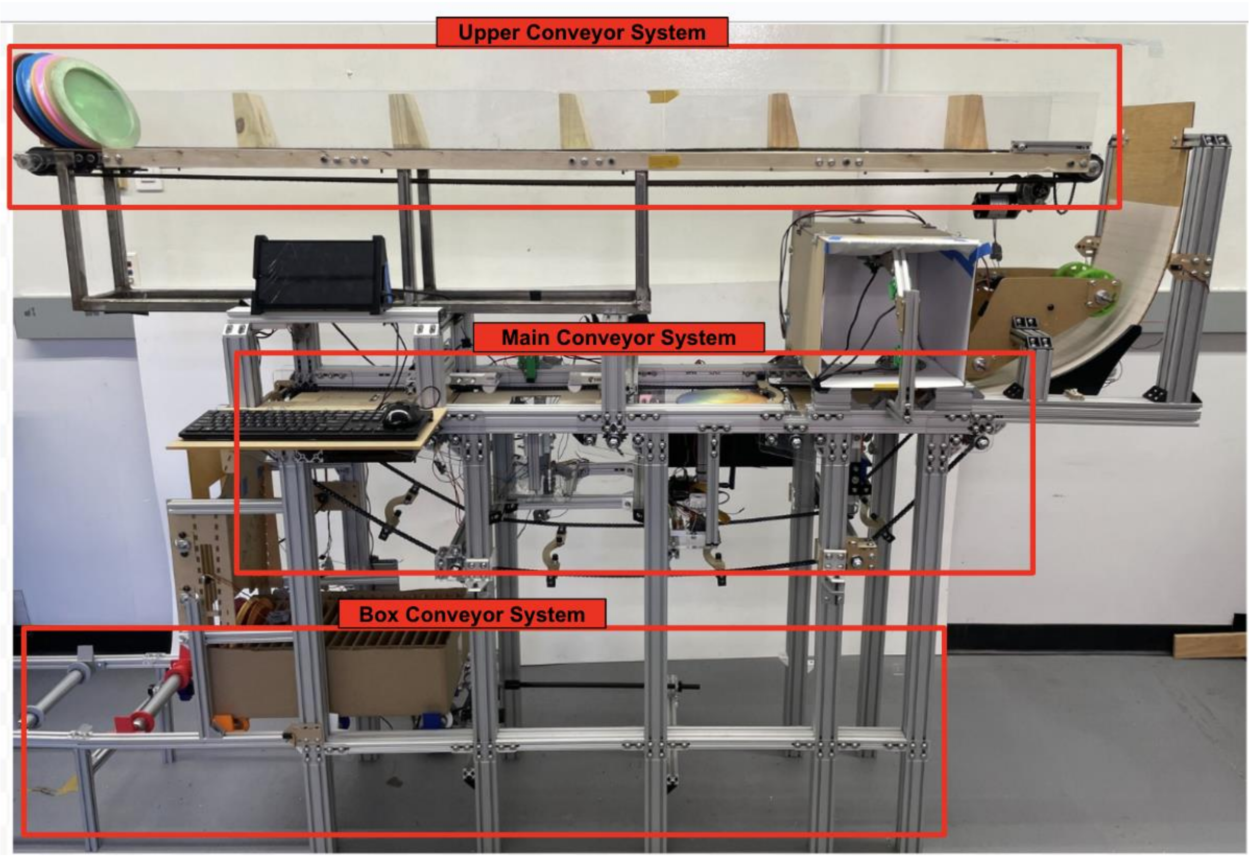


Figure 3. System overview of conveyors on the machine

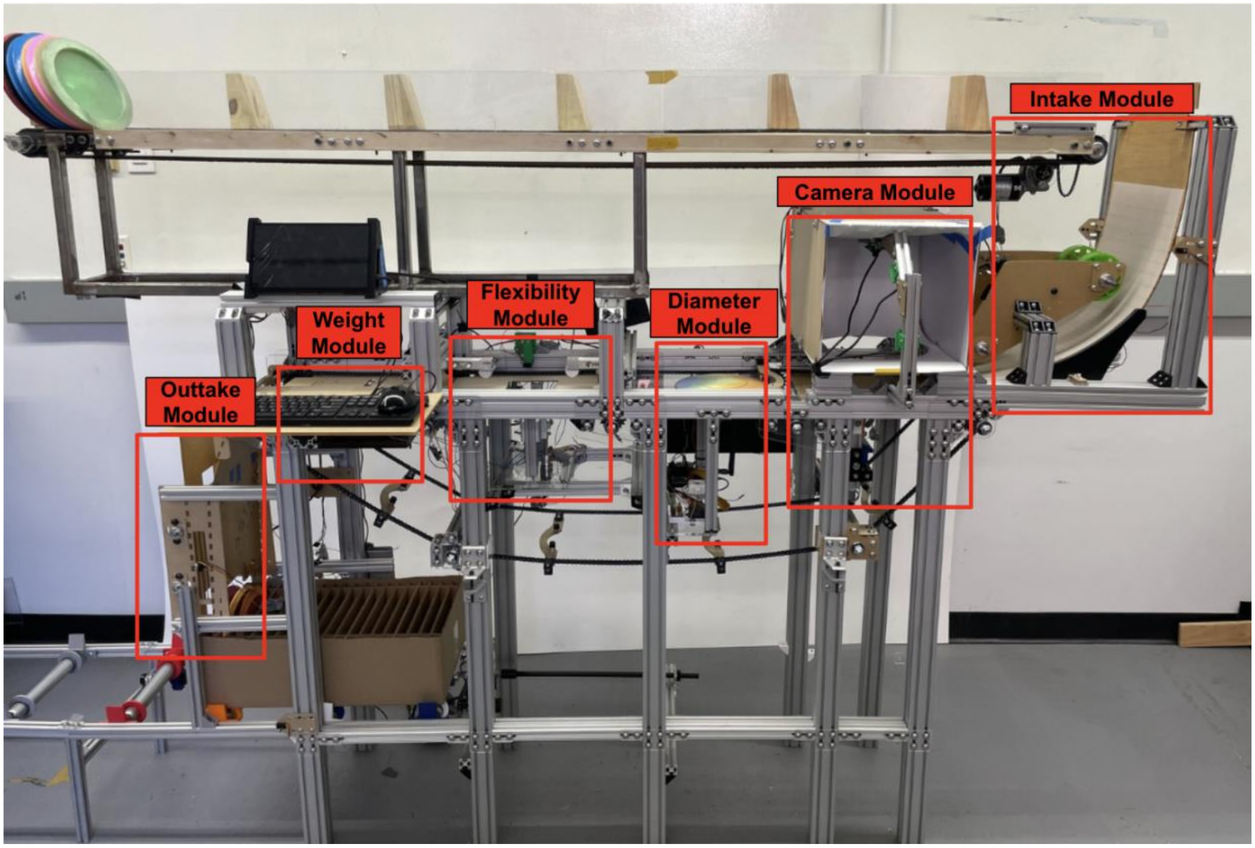


Figure 4. System overview of data collection modules

The system architecture for the machine was then designed to be modular, expandable, reliable, and simple for an end user with minimal training. The machine implements a Raspberry Pi 4B as the main control system that communicates to three ST Nucleo F303K8 microcontrollers with the ROS Noetic Serial package over serial USB (Universal Serial Bus) connections. The Nucleos are then used to control data collection and motion throughout the machine. Users can operate the machine via a touch-screen tablet, or with keyboard and mouse, powered by the Raspberry Pi, that displays a simple, interactive, graphical user interface.

2.2 System Communications and Control

The machine is composed of three subsystems, each architected around a Nucleo microcontroller, which can be implemented, tested, and debugged independently of each other. The Nucleos were labeled A, B and C, with Nucleo A controlling the upper conveyor, intake, and parts of the camera system, Nucleo B controlling the flexibility, weight, and main conveyor systems, and Nucleo C powering the outtake and box conveyor. Each subsystem can communicate with the main Raspberry Pi and with any connected actuators or sensors, creating a level of encapsulation, and simplifying the testing of each module by reducing dependencies.

Previously, the system was designed to use a CAN bus to connect all microcontrollers. In initial testing, the CAN bus implementation proved unreliable due to electrical part selection issues and software bugs. There was a custom CAN bus software implementation developed by the previous team which did not prove robust or easy to debug. Therefore, the connection and software strategy switched to ROS due to its reliability, built-in troubleshooting tools, ease of expansion, and numerous online resources. Previous electrical components, such as the Nucleos, or previously used sensors, were kept and used due to cost restrictions as they still proved to be viable throughout the project.

2.2.1 Electrical Control Systems

For this machine, the control logic sequences are implemented as state machines. Each motion and data collection module has its own low-level state machine and there is a machine-wide state machine, currently still in development, governing high-level functions. Architecting the system this way is helpful in ensuring that each module can be developed independently of each other. The overall system electrical architecture, as well as wiring diagrams of each subsystem, can be found in Appendix C and D.

2.2.2 Function of Main Raspberry Pi

The main Raspberry Pi serves three primary functions: user interface, communication hub, and data handling. Three ROS nodes are run on the main Raspberry Pi, in addition to the ROS Serial connection nodes (Figure 5). The main ROS node handles all communication with microcontrollers, tracking machine state, and data logging. The UI ROS node handles transmitting user input and displaying key data published from the microcontrollers, while the camera ROS node handles capturing and saving photos from the USB cameras.

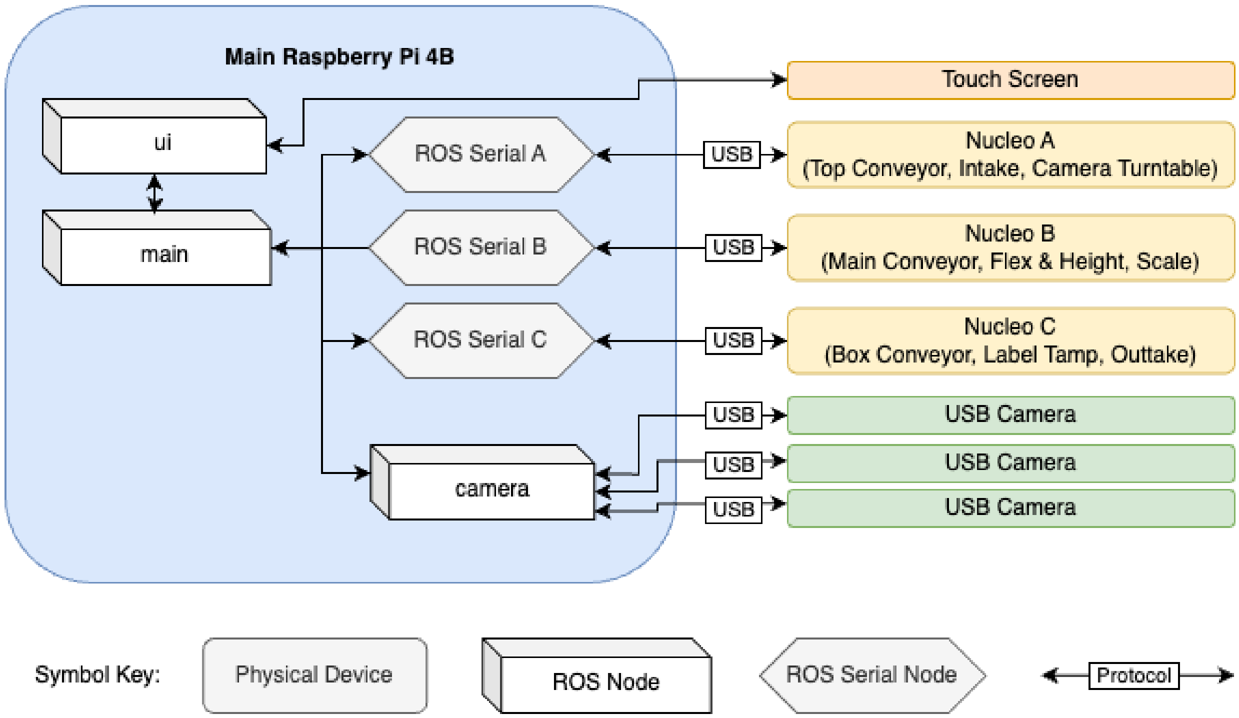


Figure 5. Raspberry Pi and ROS communication with Nucleo subsystems

The main ROS node uses a state machine to track the progress of the machine and issue commands to the microcontrollers with correct timing and coordination. Communication with the microcontroller for each module is divided into classes which are inherited from a base module class to reduce code duplication throughout the project. All module classes expose methods to start a module and check for completion, which are triggered based on the high-level state machine. Because this implementation of the machine runs semi-autonomously with button control, the main ROS node is still in development to implement this autonomous state machine functionality.

The UI ROS node uses the CustomTkinter package to render a simple GUI, which includes buttons for various machine operations and data display. The node subscribes to various data publishers from the microcontrollers to receive the data and updates the GUI whenever new data is received. Additionally, the Camera ROS node connects to the USB cameras and saves photos when triggered via a message from the main ROS node. This functionality is separated into its own node so that it runs in a separate thread and long operations such as file saving do not impact the main thread responsible for machine motion.

2.2.3 User Interface

The machine has a low-level GUI for ease of use and ease of debugging (Figure 6). The interface is designed to implement buttons to activate each motion or measurement module, as well as stop all modules. Using buttons to control modules was a simple way to program the machine for overall testing while also keeping user control of the system easy and straightforward. With multiple different debugging buttons, each component can be tested independently of the other modules. However, overall knowledge of the system is required to operate the machine, as each module button has to be run in order for the machine to function as intended.

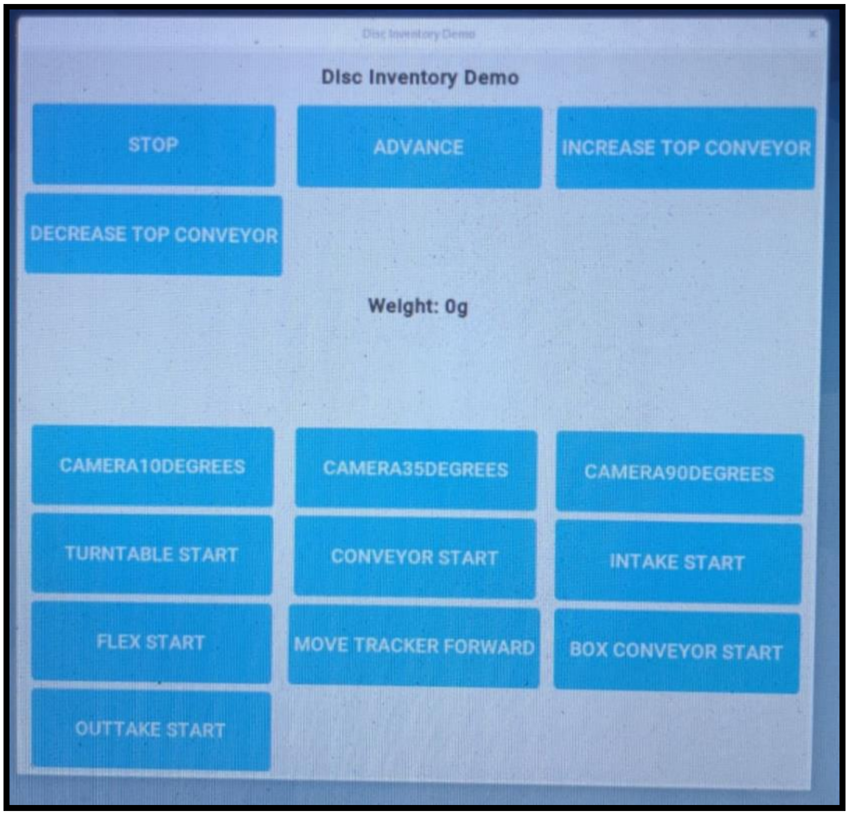


Figure 6. Low level user interface

2.3 System Modules

The overall communications and electrical system architecture controls the motion and data collection modules of the automated disc inventory machine. Many of these modules were redesigned, created, and/or tested to ensure that the machine can collect and store disc data and inventory discs. The upper conveyor, intake, and main conveyor systems were evaluated and refined for better functionality and consistency. A dedicated camera module was designed and developed, as well as a flexibility module. The weight module, as well as the outtake and box conveyor systems, were redesigned to achieve the required functionality. Additionally, some theoretical system modules were researched and developed, such as dome height and full profile modules, and a disc labeler system.

2.3.1 Upper Conveyor and Intake System

The upper conveyor and intake system together are responsible for the process that takes operator-loaded discs and puts them onto the main conveyor for photos and measurement modules to perform.

The upper conveyor comprises a lengthy conveyor belt mechanism with the end of the belt aligning with the intake module (Figure 7). Attached to the conveyor belt are wooden blocks that hold discs in place when loaded by the operator. The spacing of the wooden blocks can hold about 20 to 30 discs between each of them. The fundamental operation of the system revolves around a slow and deliberate advancement of the belt which allows one disc at a time to drop into the intake.

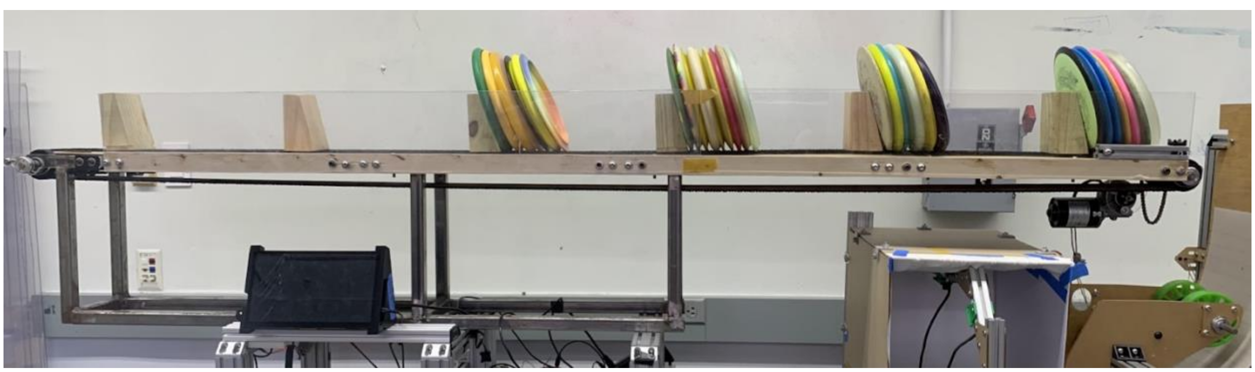


Figure 7. The upper conveyor loaded with all the discs available to the team

From here, one disc at a time is held in place by the upper compliant wheels of the intake until the first module is open for another disc. When discs are dispensed from the intake, they need to reach the main conveyor, but not overshoot the center of the first data collection module, the camera. The centering device will align the disc for the camera turntable (Figure 8).

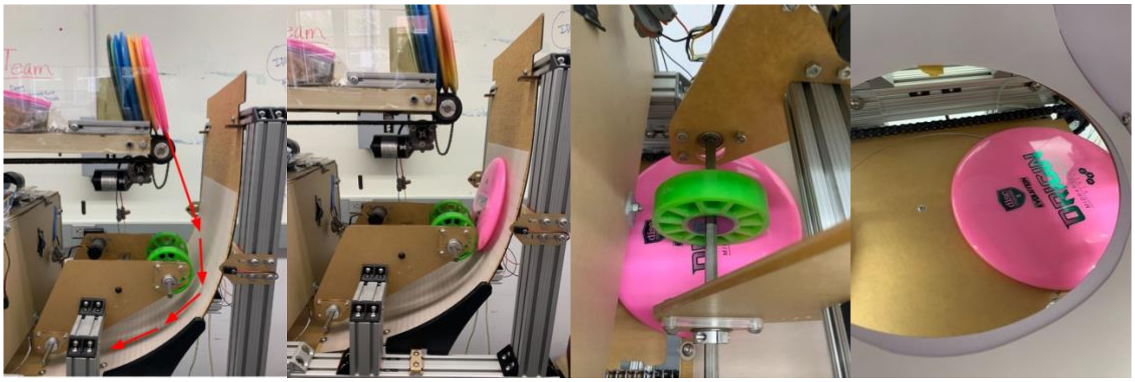


Figure 8. Demonstration of disc motion from top conveyor through the intake

Inherited Work and Early-Stage Design

The previous design of the upper conveyor required an operator to load discs stacked against each other, like books on a bookshelf, to ensure discs are dropped into the intake vertically. The previous design also used only one wooden block to hold discs in place on the conveyor. This loading method posed disc slipping issues if too many discs were stacked onto the upper conveyor, resulting in inconsistent drops into the intake (Figure 9). Discs were also at risk of falling off the edges of the conveyor as there was no side walling. The previous design also created the conveyor structure by welding together a large stainless-steel frame, constricting vertical space for modules on the main conveyor.

Figure 9. Inherited design with loaded discs showing slippage

The inherited intake design consisted of a low friction wooden ramp where discs from the upper conveyor slide onto and two sets of compliant wheels which moved the disc into the conveyor. Using all the discs available to the team, manual drop tests were performed to simulate the top conveyor supplying a disc. The intake motor was run while discs were dropped down the ramp to test the success rate of discs advancing onto the main conveyor. The system was very inconsistent due to varying flexibility, sizes, and dome heights. Most discs that were unsuccessful failed when approaching the lower compliant wheel, as they were not pushed far enough by the first wheel to make contact (Figure 10).

Figure 10. Three instances of a failed intake test with the inherited system

Final Design and Fabrication

The upper conveyor went through modifications to address issues found with the previous design. To address the issue of discs slipping from their vertical position due to overloading, additional wooden blocks were incorporated along the conveyor belt's path. Transparent polycarbonate walls were installed to the upper conveyor to enhance safety and provide protective barriers without obstructing visibility. The transparency of the side walls also allows the operator to visually confirm the number of discs they have loaded at a time so that they can reload the machine as needed. Additionally, sections of the stainless-steel frame were cut out to make room for a new camera module that required more vertical space above the main conveyor. Along with these cuts, the entire upper conveyor was raised a few inches to accommodate the size of the camera system. These enhancements not only optimize functionality but ensure smooth integration and prioritize safety within the system.

For the intake to function more reliably, the compliant wheels were repositioned such that they contacted the thinner discs, while still allowing discs with greater dome height to pass through. To consistently center discs entering the intake from the upper conveyor, various options were considered. The addition of side walls proved to be a sufficient safety feature and stopped potential discs from falling out of the intake completely but was unsuccessful in ensuring the disc was centered entering the intake module. Ultimately, the top axle of compliant wheels was designed to contain two wheels which balance the disc on either side as it falls, resulting in a centered disc. The lower set was left with one compliant wheel as two wheels proved to be redundant through repeated drop tests. The speed of the intake motor was also altered so that discs processed by the intake would not overshoot placement on the main conveyor. Discs needed to be placed onto the main conveyor and just before the first data collection module, to allow the disc alignment tool to center and align the disc properly in the first module (Figure 8).

To facilitate the coordination of the upper conveyor and intake with the rest of the machine, a state machine diagram was created (Figure 11). This diagram outlines the communication process between the Nucleo responsible for the upper conveyor and intake, and the Raspberry Pi.

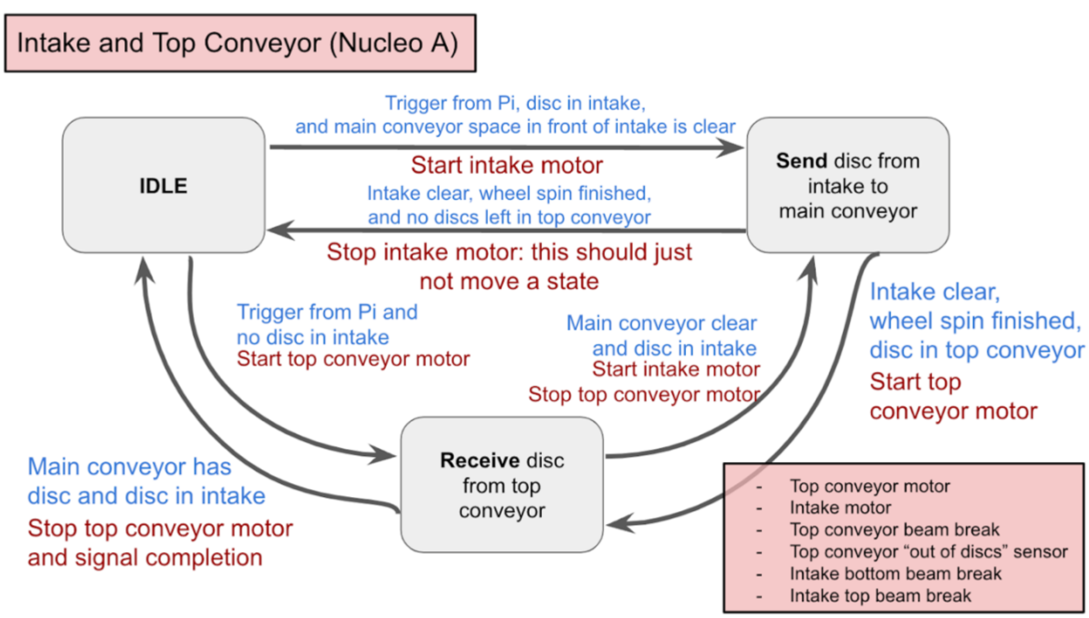


Figure 11. State machine diagram for the upper conveyor and intake system

Unit Testing

Several repeatability tests were performed to ensure the reliability of the intake system. Sixty different discs were dropped by hand, simulating the upper conveyor's function, into the intake. The intake motor was initially idle to ensure the disc could be queued in the upper set of compliant wheels. Power was then supplied to the motor so that the disc would advance to the main conveyor. This process was done twice per disc and achieved a 100% success rate in the placement of the discs.

2.3.2 Main Conveyor System

The main conveyor is responsible for transporting the disc through the machine while allowing the modules to execute their functions. The requirements of the system include centering the disc in the direction of motion, proper placement of discs for measurement modules, and remaining non-intrusive to the measurement modules.

Inherited Work and Early-Stage Design

The inherited main conveyor design featured a chain and sprocket system that included two chains driving a disc alignment tool guiding the discs (Figure 12). Each bar used two contact points to move the disc to each module. A tab extruding from each section of the disc alignment tool was used to trigger a beam break switch that communicated the position of the alignment tool to the control system. The conveyor was driven using a C610 Brushless Direct Current (DC) Motor. This motor had several electrical flaws because it only communicated via the CAN Bus protocol.

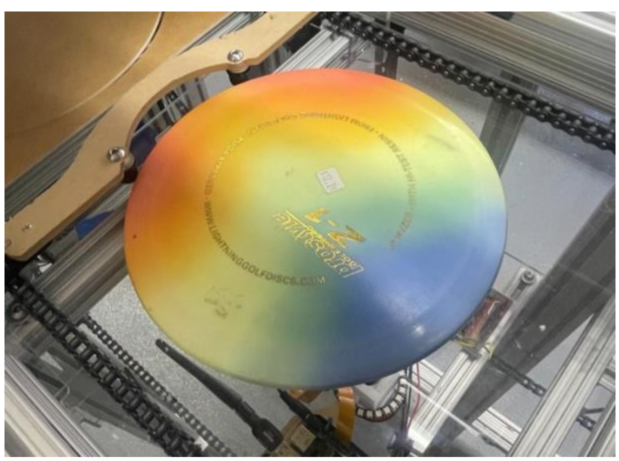


Figure 12. Picture of the chain and disc alignment tool system of the main conveyor

Final Design and Fabrication

To implement ROS as an integration system, a new motor was chosen to fit with the electrical and control system of the machine. A 12V 37D Metal Gearmotor with a 30:1 gear ratio was chosen to replace the previous motor. To ensure that the motor on the main conveyor functions properly, an analysis of the new motor was performed.

Tests were performed on the mechanical system, including performing an in-depth analysis of motor requirements. The amount of force applied to the main conveyor, as well as the required torque were calculated to properly evaluate the motor being used. Calculations can be seen in Appendix D. With a factor of safety of two, the target force applied to the conveyor was found to be 8.44 Newtons (N). With this information, the torque required by the input mechanism was calculated and showed that a gear ratio chain system was needed to increase the applied torque of the motor. The machine features a geared increase in torque from the input motor to the conveyor belt, allowing the DC motor to move the entire conveying system with a full load of four discs (Figure 13). The team was able to calculate the maximum torque required by the motor to achieve the rotation of the conveyor system.

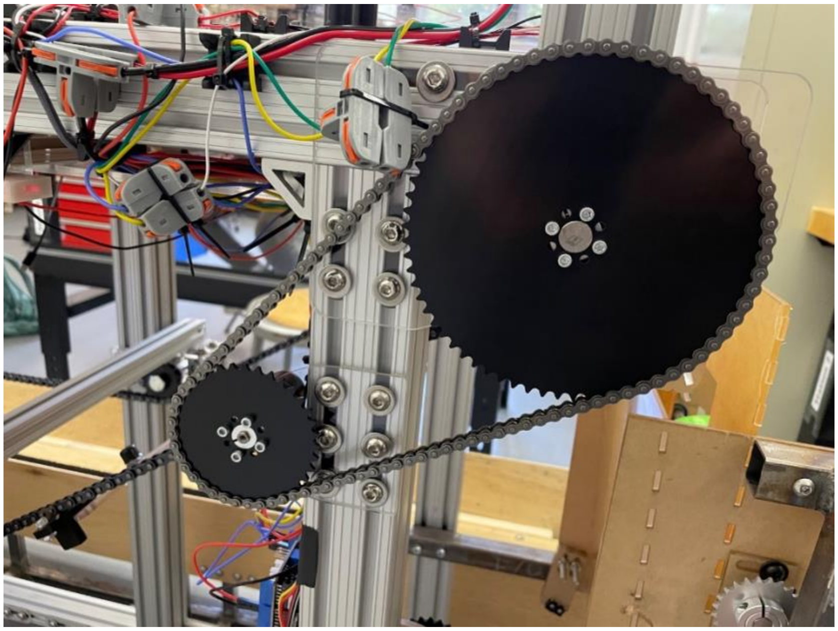


Figure 13. Geared conveyor driver

A motor specification diagram was used to make sure that our selected motor, a 12V 37D Metal Gearmotor with now a 30:1 gear ratio, would function with the calculated 0.295 Newton-meter (Nm) load of the motor (Figure 14). The diagram shows the current, speed, power and efficiency of the 12V Metal Gearmotor when operating with this 0.295 Nm of torque on the system. This motor can provide sufficient current and power to operate the conveyor at a fast speed, ensuring acceptable efficiency (See Appendix E).

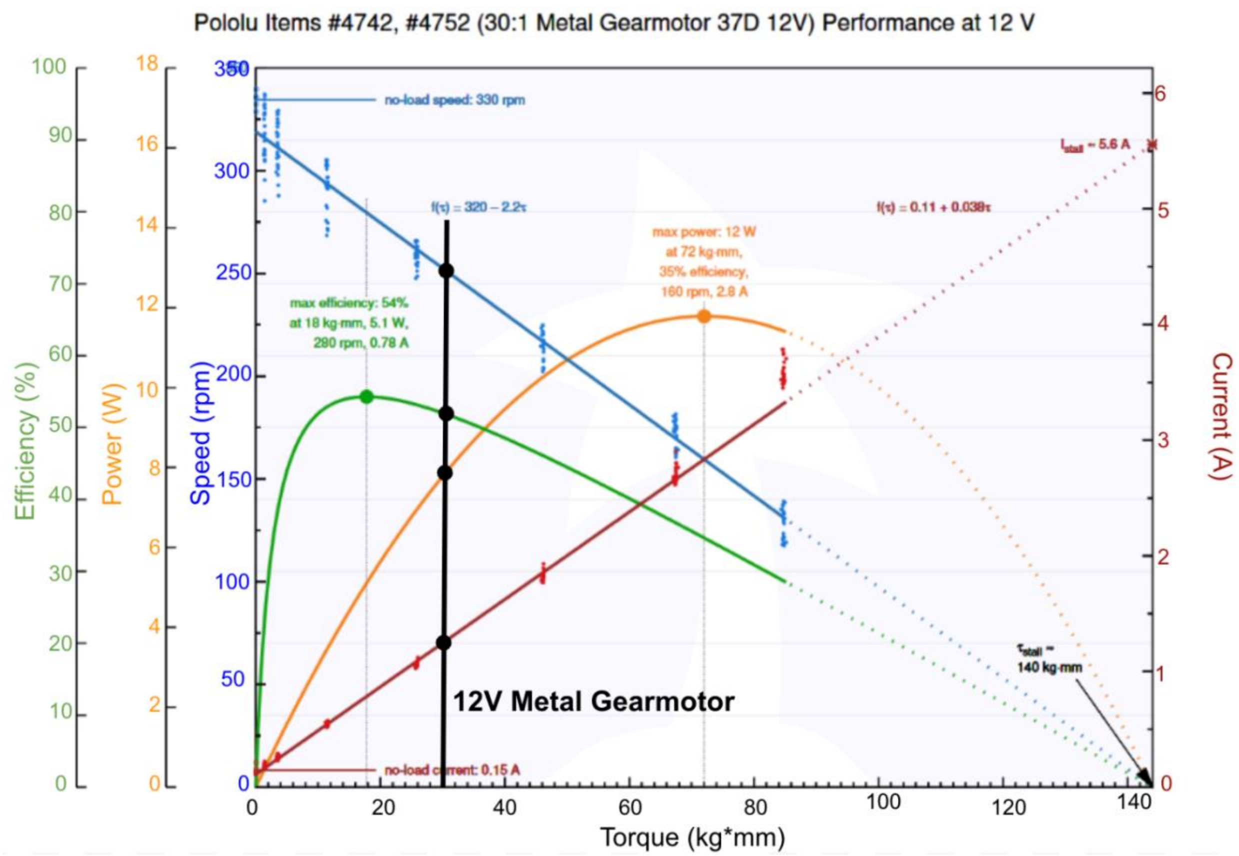


Figure 14. Motor specification diagram for the 12V 37D Metal Gearmotor

The state diagram was used to program the logic of the main conveyor can be seen, showing how the main conveyor can communicate with the Raspberry Pi to advance discs from the intake through the data collection modules (Figure 15).

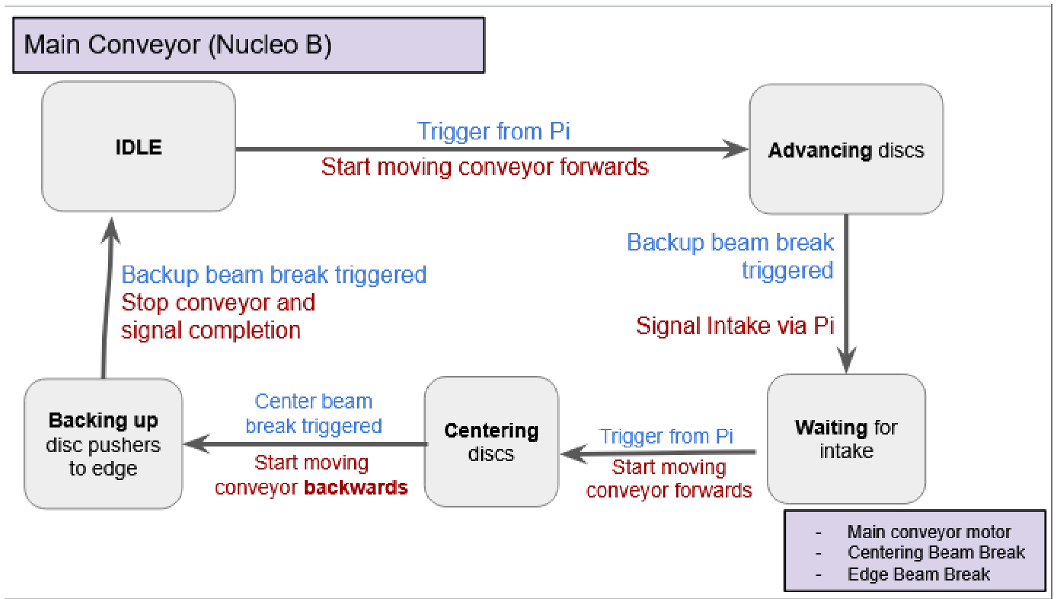


Figure 15. State machine diagram for the main conveyor system

Unit Testing

Along with the analysis and calculations of the inherited motor for the main conveyor, repeatability tests were run with the newly chosen motor. The 12V 37D Metal Gearmotor was run backward and forward with a full load of discs. After running the conveyor for 50 discs, the chain and sprocket system had a 100% success rate with no signs of wear. Subsequent testing involved assessing electrical integration via the UI to ensure seamless communication between the Raspberry Pi and the Nucleo C microcontroller.

2.3.3 Camera System

As a part of the requirements, high quality images of the discs were needed so that they could be displayed on the company's online store. The client wanted a 3D, or 360-degree view of discs so customers could have a better viewing experience online. Therefore, a dedicated camera module using a photo booth area accessed by a turntable system was created to take pictures of discs. The isolated photo booth is a few inches above the main conveyor. Discs enter the booth from the main conveyor via a turntable system which raises and lowers discs into and out of the photo booth, as well as rotates discs in place to photograph all sides of the disc for the 360 views.

Inherited Work and Early-Stage Design

Prior work done on the camera module included a setup for taking cosmetic images of the disc using a series of cameras mounted throughout the machine rather than a dedicated module. This setup, however, had numerous issues. Images taken had low resolution and poor lighting due to poor camera choice and a lack of measures taken to provide dedicated illumination and limit ambient light conditions. Camera angles were also very limited, and pieces of machinery were oftentimes visible, if not outright obstructing the images taken. To improve image quality and better meet the needs of the client, we constructed a dedicated camera module consisting of a raised photobooth and turntable mechanism.

Final Design and Fabrication

Photo Booth

To create a high-quality image of a disc, the pictures needed to have high resolution, proper lighting, a neutral background, and no obstructions. With many different processes and parts moving on the machine constantly, it became apparent that to take proper images of each disc that it would have to be done in an isolated module where factors like lighting and background could be controlled and other machine parts would not cause obstructions. Therefore, a small photo booth was created, built a few inches above the main conveyor system. The booth is accessible via the turntable mechanism, which raises the disc into the photo booth, and then spins in place to capture images for a 360-degree view.

To create the desired 360-degree online view, discs needed to be photographed from three different angles to capture the edge, isometric, and top views of the disc. After experimenting with different camera angles and showing the results to the client, we used 10-, 35-, and 90-degree camera angles. To photograph the disc from the desired three angles, we created a stationary camera arm to mount three cameras at the different angles needed. The cameras would then take pictures simultaneously while the disc spins in place. An alternative solution to a stationary arm was using one camera that moved to the different angles of the disc to take pictures, however, this would have involved creating a separate mechanism to move the camera in an arc around the disc, which would then have to be timed with the rotation of the disc in the booth. Adding this extra motion would cause taking pictures to implement a more difficult functionality while also taking more time to complete, which is an issue as the camera module already has the longest completion time. To achieve the 360 views with stationary cameras, all three cameras need to take photos simultaneously as the disc rotates, so that photos from the 10-, 35- and 90-degree angled cameras line up on the same vertical axis of the disc, producing a consistent 360 image view when rotated between photo angles.

Global shutter USB webcams were used because they were the most cost-efficient option that were still capable of capturing quality photos. They also specifically minimize object blur when taking photos of objects in motion, which will allow for clearer photos when the cameras are taking pictures as the disc is spinning on the turntable. The fact that they are USB webcams also made for easy implementation. They connect to the main Raspberry Pi via a USB hub.

The material for the photo booth needed to be sturdy and matte to reduce reflections and glare in the photos, and the background needed to be white to easily match the background of a standard web page. The photo booth was therefore built out of acrylic, a low-cost material that is easily machined. Brackets holding the booth together were 3D printed or laser cut with acrylic material (Figure 16). White matte acrylic was difficult to find, and expensive, and so white matte sticker paper was stuck to the inside walls of the photo booth as well as white photo booth paper to minimize the harsh corners of the booth in the image and provide the desired white background.

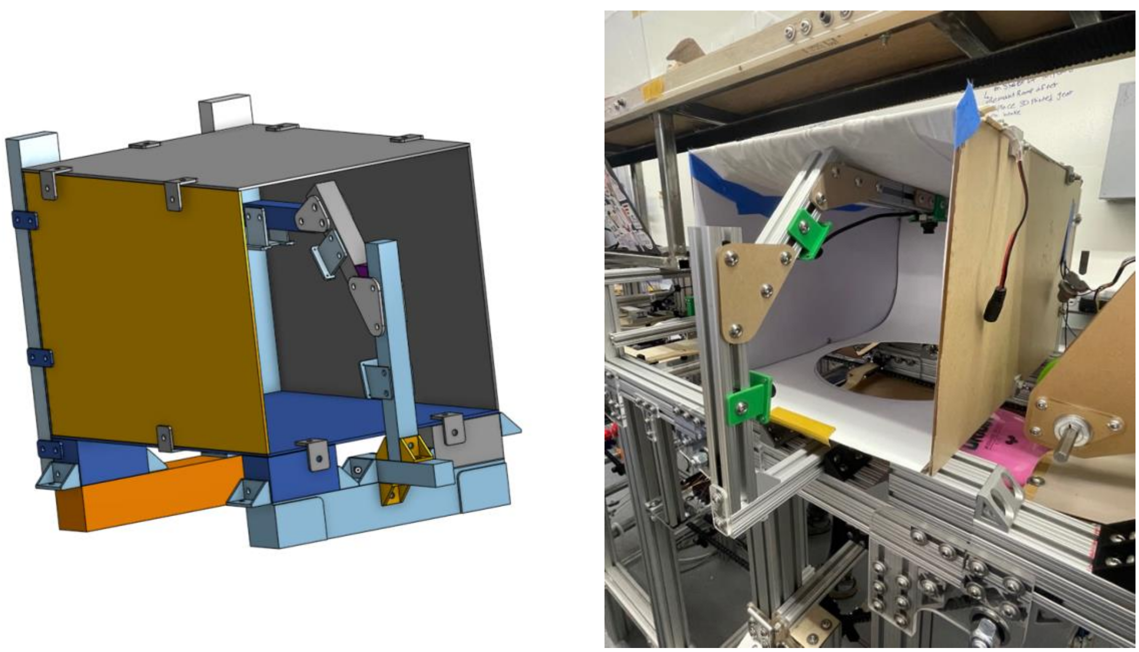


Figure 16. CAD model (left) and final design (right) of photo booth

Lighting for the photo booth must be bright and diffuse to minimize any shadows or reflections. Diffuse LED strip lights provide ample light with easy application and are stuck to the roof and upper sides of the photo booth. More LED strips were added to the roof of the photo booth, as well as white fabric to try and add brighter lighting while eliminating glare caused by lights on more reflective discs.

Photos can be taken and saved from the USB webcams using OpenCV video and image processing libraries. Using OpenCV, video streams from the webcams can be started and images can be captured from the stream over time. However, this method causes USB bandwidth problems when running three USB webcam video streams simultaneously. When investigating other image processing libraries to use to take individual images as opposed to starting video streams, such as pygame, ffmpeg, or imagio libraries, none proved to perform how desired. Storage of photos is a concern as photos are large files and each disc will have many different pictures. Images can be saved to the local computer system using OpenCV, and therefore, an external storage drive could also be plugged into the USB hub for greater storage capacity and accessibility.

Turntable System

To transport discs from the main conveyor into and out of the photo booth, as well as aid in taking photos of discs, a camera turntable was designed. Discs are dispensed from the intake onto the main conveyor, centered onto the turntable plate, then raised into the photo booth, where they are rotated in place to take pictures from all sides of the discs. After the images are collected, the discs are lowered back onto the main conveyor to advance to other data collection modules.

The design of the turntable implements a lead screw, two motors, and a limit switch, to perform the desired functionality. The plate of the turntable was designed with white matte acrylic to seamlessly blend into the photo booth when raised. The DC motor moves the turntable assembly up and down a series of guide rails to reduce friction between the motor mount and rails, as well as prevent wobbling. The limit switch controls how far up the turntable assembly travels, and a stepper motor rotates the plate in place while inside the photo booth (Figure 17). Calculations were done to determine the torque required to rotate the lead screw (See Appendix F). A Pololu 10:1 Metal Gearmotor was eventually selected for this task; though the 0.54 Nm of torque was well in excess of our requirements, its use throughout other parts of the machine-made troubleshooting and integration significantly easier.

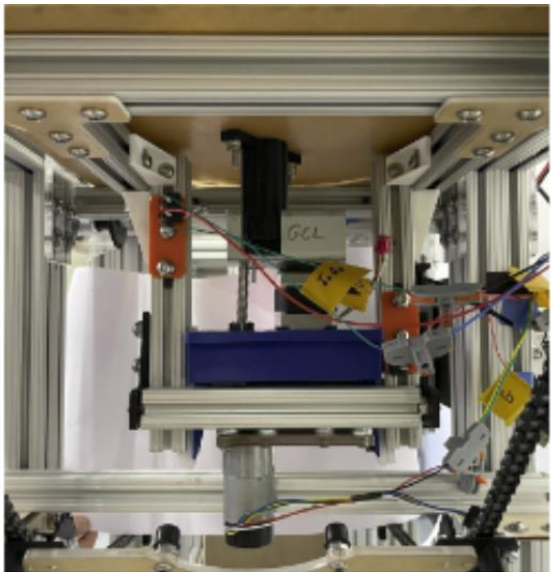


Figure 17. Photograph of final design for turntable assembly

The overall logic of the camera module can be seen in the state diagram detailing how the camera and turntable function and communicate with the main Raspberry Pi computer (Figure 18).

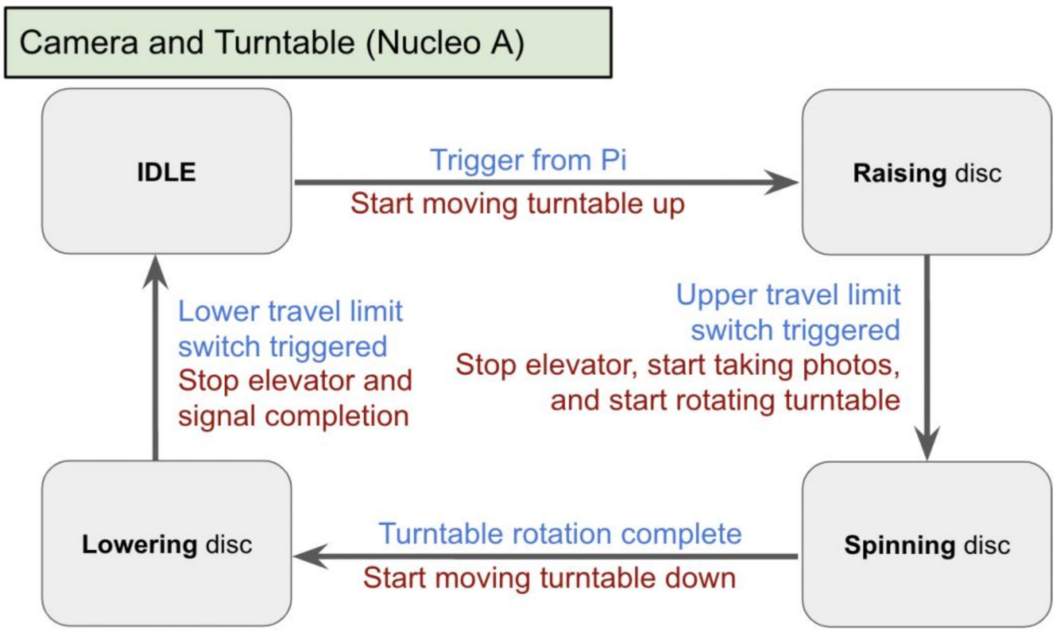


Figure 18. State machine diagram for camera and turntable system

Unit Testing

To test the camera module, different camera parameters and lighting environments were tested to achieve the highest quality photo with the USB webcams. The focus of the camera can be adjusted manually via the camera lens, and the resolution and frame rate of the camera can be specified in the camera code. The maximum resolution of the cameras is 1920x1200 pixels and the maximum frames per second is 90, producing a strong photo quality (Figure 19).

Figure 19. Photo of disc in photo booth with cameras and lighting at best quality

Many lighting environments were tested, including large panel lights, thin panel lights, and LED strip lights. Both types of panel lights, placed in the front and top of the photo booth, did not provide adequate lighting for discs and caused too much glare. Mounting LED strips along the top of the photo booth provided the greatest amount of light but still caused significant glare with more reflective discs. To attempt to mitigate this issue, white fabric was placed over the lights to diffuse the light and reduce glare, producing a well-lit photo, however, more reflective, and holographic discs still cause glare and reflection issues.

2.3.4 Flexibility System

To measure the flexibility of discs, disc golfers typically use a hands-on test, in which the edges of the disc are held in both hands whilst pushing one's thumbs upwards in the center of the underside of the disc (Figure 20). Therefore, a new module to emulate this flexibility measurement was created. Since this measurement module is entirely new, it does not build off inherited work or designs.

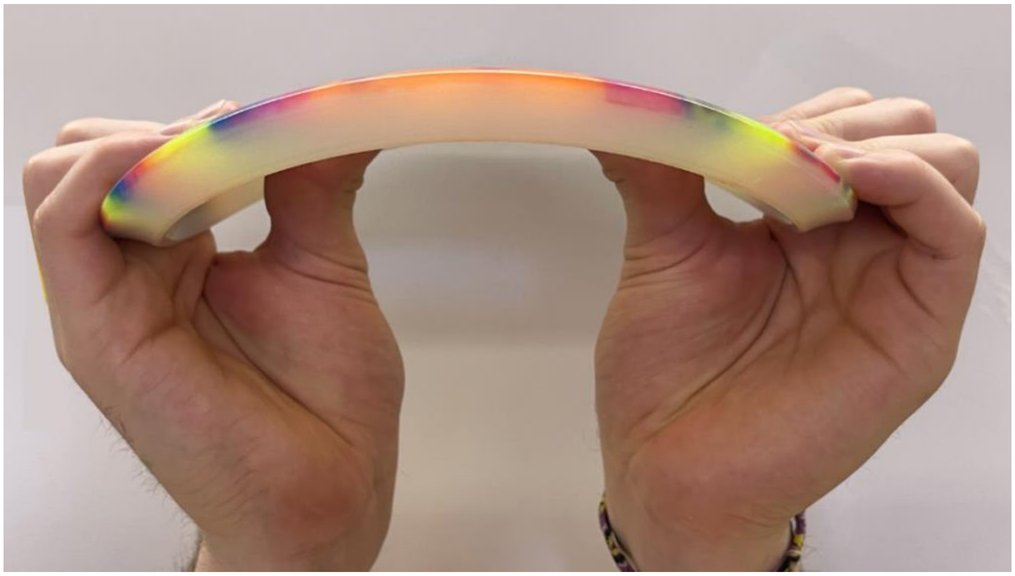


Figure 20. In-person disc flexibility test

Inherited Work and Early-Stage Design

The flexibility module was designed purposefully to emulate the disc flexibility test performed by disc golfers while shopping in-person (Figure 20). To do this, the disc needed to be bent in a similar motion and produce measurable results of disc flexibility. To create a flexibility module on the machine, the disc alignment tool needed to center the disc in this module so that a disc could be bent a measurable distance with a measurable force. The resulting distance and force measurements of each disc could then be used to create a graphical relationship between the amount a disc deflected at a given applied load. Using this relationship and cross comparing it with other measured discs could allow for a numeric scale to be created to rate the flexibility of a disc. Current disc manufacturers perform varying methods for testing a disc's flexibility, which means that there is no standardized numeric scale rating for how flexible a disc is.

In designing how to implement the flexibility module, we originally planned to apply a downward force on the edges of a disc to emulate the in-person flexibility test performed by disc golfers (Figure 21).

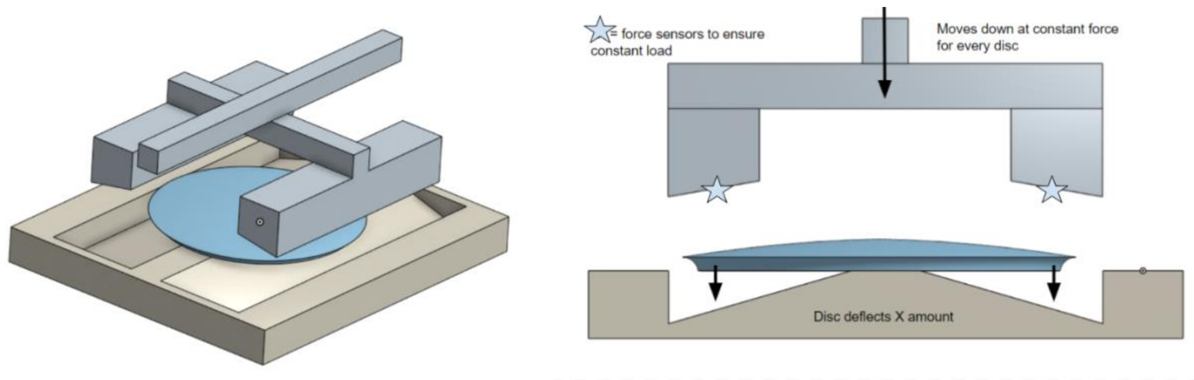


Figure 21. Isometric view (left) and side view (right) of first flexibility's prototype

After careful consideration, the application of the force was changed such that the load was applied from the underside of the disc. The orientation of the load application was changed for two main reasons. Firstly, the art and graphics on discs are extremely important to buyers and are sometimes even a deciding factor when purchasing a disc. Due to this, there were concerns about objects applying loads to the top of the disc scratching or distorting these graphics. In addition, applying the load from the underside of the disc was not only easier given the adequate space underneath and limited space above the main conveyor, but it appeared to better imitate the in-person flexibility test, with the thumbs pushing upwards under the disc. As a result, a system was created such that an assembly would rise from underneath the main conveyor to contact the underside of a disc and continuously raise it into contact with two stationary load cells. The application of the force from underneath the disc, while the disc is held on its edges by the load cells, would create an achievable and measurable deflection (Figure 22).

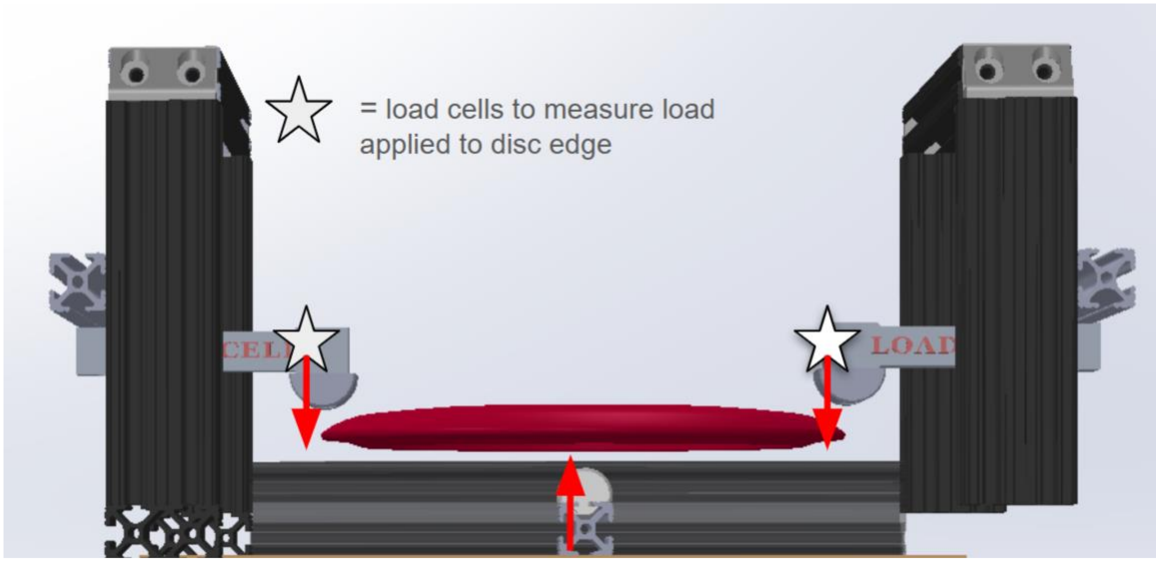


Figure 22. Side view of final flexibility module design

Final Design and Fabrication

The final design of the flexibility module implemented the stationary load cell assembly above the main conveyor to measure the deflection force and a center lead screw carriage assembly below the main conveyor to push the discs into the stationary load cells (Figure 23).

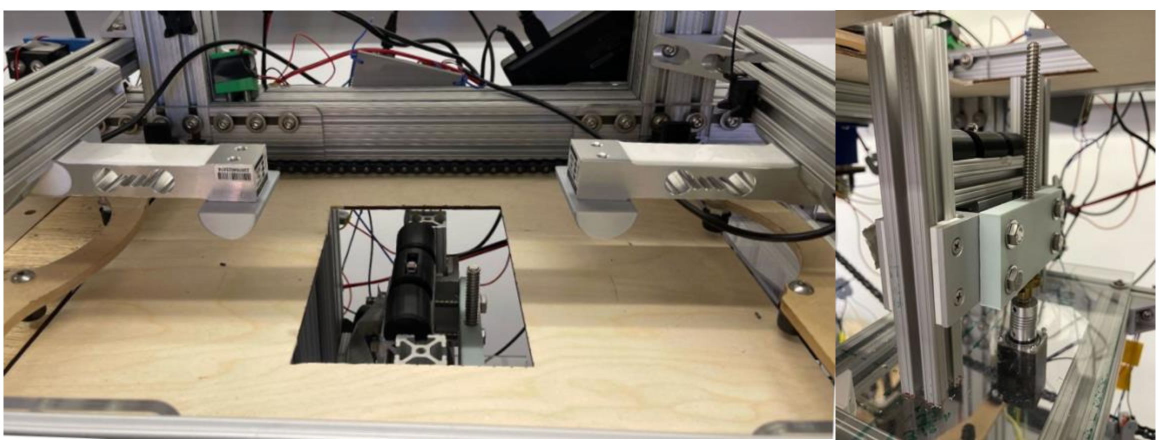


Figure 23. Flexibility module assemblies above (left) and below (right) the main conveyor

To create the load cell assembly, two load cells were mounted on the extrusion frame of the machine. To determine the rating of load cells needed, manual disc flexibility tests were done according to PDGA guidelines to see the average force applied when pushing discs down vertically on a kitchen scale. The measured force did not exceed 30 kilograms (kg). Therefore, 30 kg load cells were used. Rounded 3D printed components were attached to each end of the load cells, aimed at preventing disc deformation when subjected to a load. Polyethylene Terephthalate

Glycol, a thermoplastic polymer, (PETG) was selected as the material for manufacturing these 3D printed components due to its durability and strong impact resistant properties.

To create the carriage assembly, a DC motor was mounted to an acrylic base plate, supported by multiple extrusion struts on the underside. These supports serve to ensure the stability of the lower assembly of this module as loads are being applied to discs. The overall lower assembly comprises two linear guide rails, made from extrusion strut, mounted to the acrylic plate. The lead screw is connected to the motor via a flexible coupling, which offers greater lateral movement tolerance in case the lead screw was to deflect in a specific direction. The carriage assembly has an extrusion bar running across it that has three 3D printed semi-circular pieces on it. These semicircle shaped objects are designed to replicate a person's thumbs, as individuals purchasing discs will push their thumbs into the center of the disc's underside (Figure 23). These 3D printed thumbs are easily replaceable if size adjustments are required. As the assembly moves upwards, the thumbs encounter the underside of a disc. The assembly continues to push the disc upwards into contact with two load cells, which measure the force being applied to the rims of the disc (Figure 24). A limit switch is implemented to allow discs to travel constant distances from the main conveyor into the load cells.

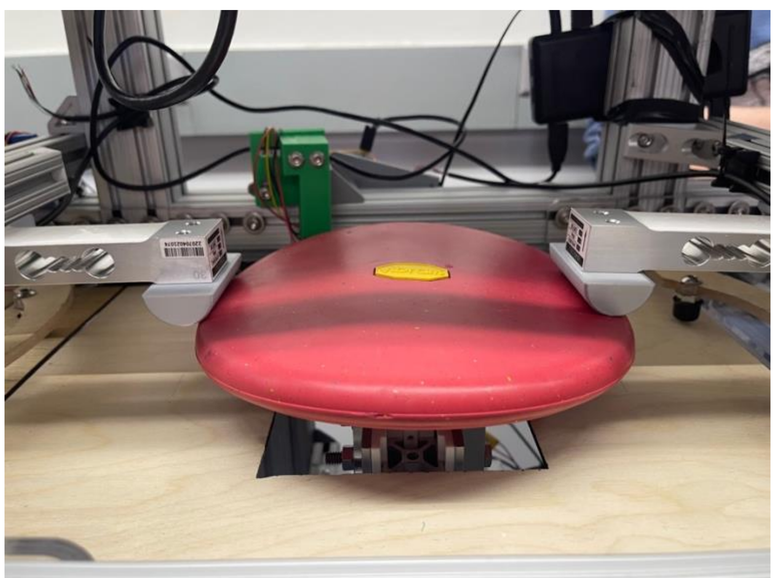


Figure 24. Successful bend of a disc in the flexibility module

To control the final flexibility system, all electrical components were wired to a Nucleo which communicated a state machine to the main Raspberry Pi (Figure 25).

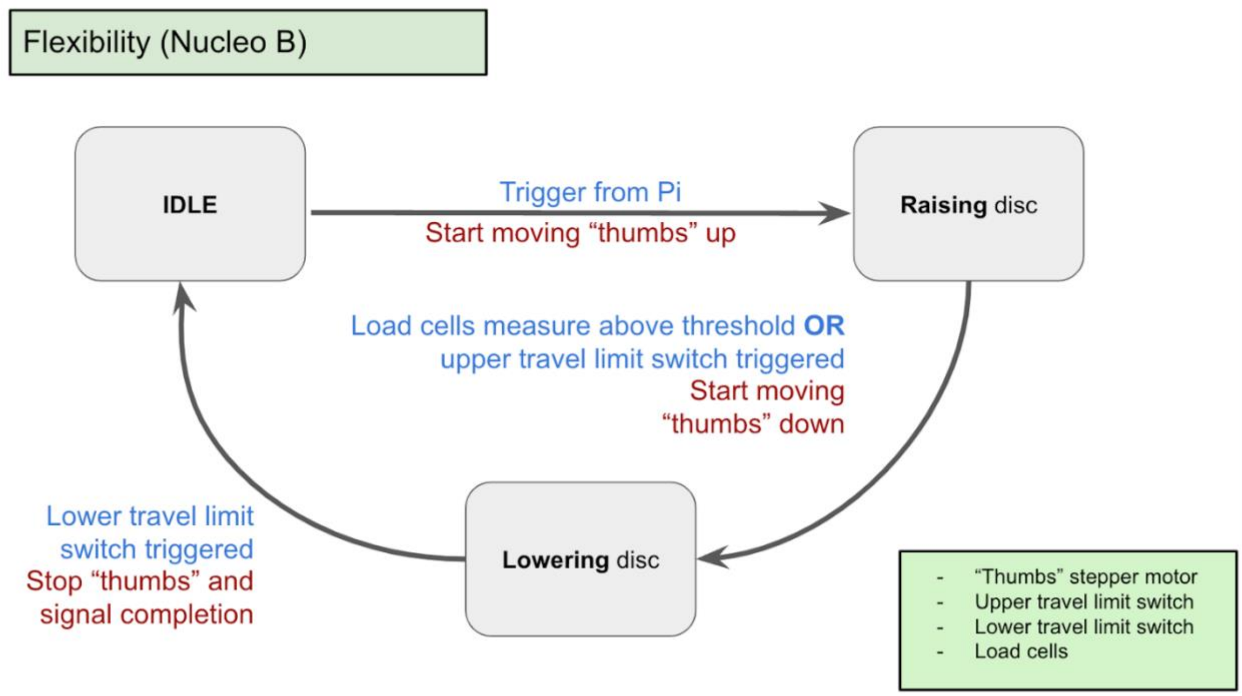


Figure 25. Flexibility module state diagram

Unit Testing

To ensure a disc can lift into the load cells for a force reading on the flexibility module, tests were done on the motor and assembly as a whole. The main purpose of these tests was to ensure the load cells were transmitting proper and accurate readings to the Nucleo, and discs did not fall off the assembly or move when traveling up and down. The motor and load cells were first tested separately to ensure seamless operation of both the upper and lower assemblies prior to full-scale testing of the system. Discs were pushed semi-autonomously into the flexibility module, utilizing the machine's module button activation. After being centered with the disc alignment tool, the raising and lowering of discs was performed repeatedly to ensure seamless operation of the system's vertical motion. No changes were required after performing this repeatability test as discs were raised into contact with the load cells and lowered back down onto the main conveyor without issues.

In order to test the load cells, precision weights were used on each load cell to properly calibrate their readings. Using the calibration data, calibration curves for each load cell were created. These curves show the relationship between a known weight and the voltage output from the load cells, which allows for the output voltage of the load cells to be converted into a force measurement in kilograms (see Figure 26 & 27).

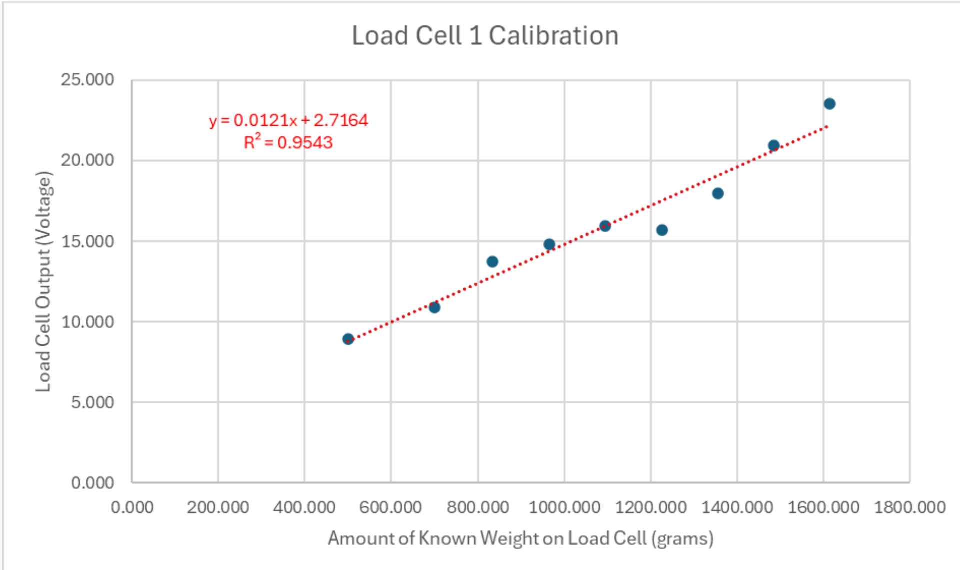


Figure 26. Calibration curve for load cell 1

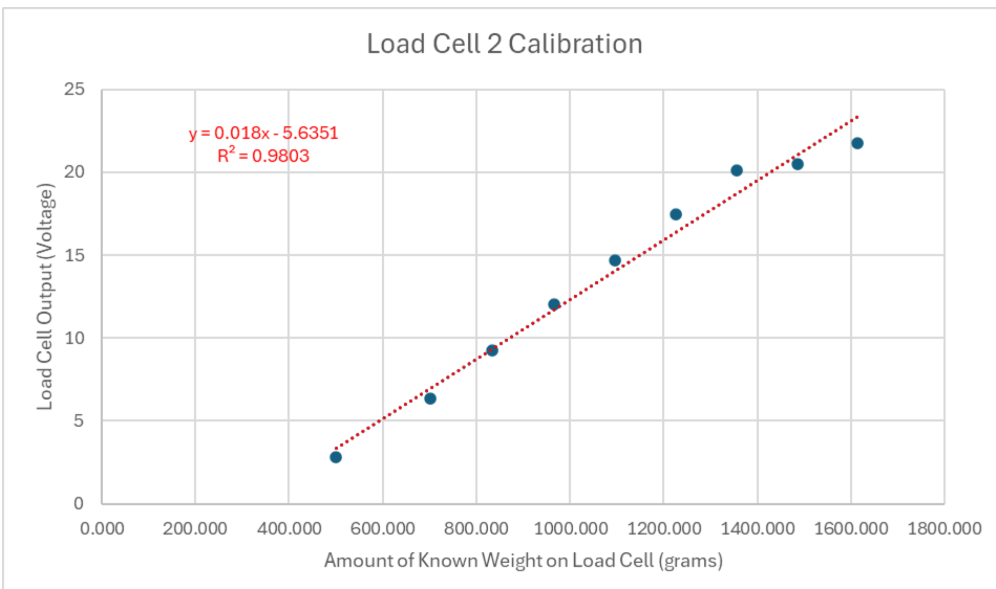


Figure 27. Calibration curve for load cell 2

After calibrating each load cell, quick tests of the force readings were performed on two discs, a driver and a midrange model. These discs were manually pushed into contact with the load cells to obtain a general idea of disc readings. The discs were pushed into the load cells ten times with an estimated equal distance and force applied to each trial, and the corresponding load cell voltage and reading was measured and recorded. Manipulating the linear slope equation $y = mx + b$ and using the values of slope, the y-intercept, and voltage output for each load cell respectively, an accurate force measurement was found (see Appendix G). Overall, the data suggests that the driver disc was stiffer than the midrange disc, as the average forces measured by the load cells for the driver were overall higher, meaning that it did not deflect or bend as much. This data appears to be relatively accurate as drivers are meant to be stiffer than midrange discs.

2.3.5 Weight Measurement System

To be able to measure the weight of each disc, the team incorporated a high-precision commercial scale with a digital communication interface. This was the most reliable option to accurately collect the specified data.

Inherited Work and Early-Stage Design

The previous weight measurement system used four small load cells connected to an acrylic plate, custom-fitted within the dimensions of the machine's main conveyor. However, this setup proved highly flawed, primarily due to the load cells' sensitivity and inability to withstand the weight of the discs. Consequently, the load cells frequently malfunctioned and eventually broke.

Furthermore, the design resulted in an inability of the load cells to provide precise readings of the disc weights. The four load cells were attached to each corner of the acrylic plate, with each load cell theoretically measuring one-fourth of the disc's weight. This placement of the load cells failed to distribute the load evenly, leading to inaccuracies. In addition, the load cells lacked calibration, and this, coupled with the uncertainty of each one's accuracy, compromised the reliability of the measurement process.

Final Design and Fabrication

An off-the-shelf digital RS232 scale was used for this module as it is easier to replace in case repairs are necessary. The scale also provides sufficient capacity and accuracy while remaining affordable. A custom weight plate was designed as the plate that came with the scale was too small to accommodate varying disc sizes (Figure 28). The custom plate simply screws into the existing plate's mounting holes. A small shelf was installed to hold the scale perfectly flush with the main conveyor, such that discs are able to slide on and off without any interference (Figure 28).

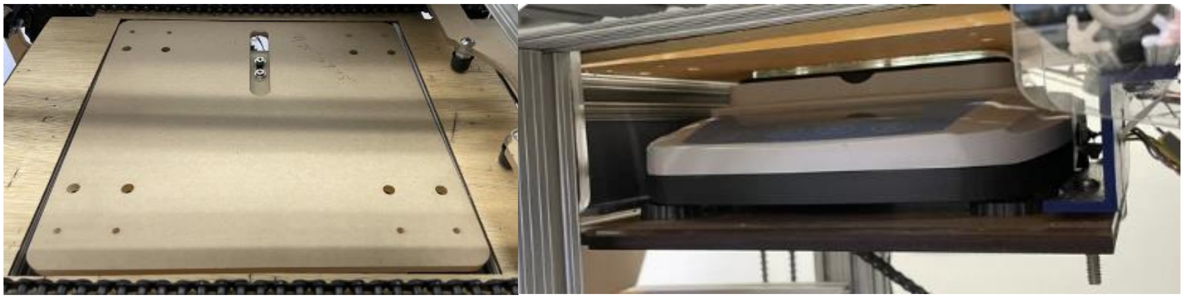


Figure 28.The RS232 scale custom acrylic plate and mount assembly

Though the scale is designed for a human interface with physical buttons to power and tare the scale, we added electrical interfaces to simulate this human interaction. Specifically, the buttons were rewired using transistors to receive a command from the microcontroller to trigger the power and tare buttons. The circuitry is shown in the Nucleo B wiring diagram in Appendix C. The power and tare buttons are initially triggered when the machine is turned on. However, further implementation of taring the scale in between disc measurements is required. The current system control of the scale and its communication with the Raspberry Pi can be seen in the state diagram (Figure 29).

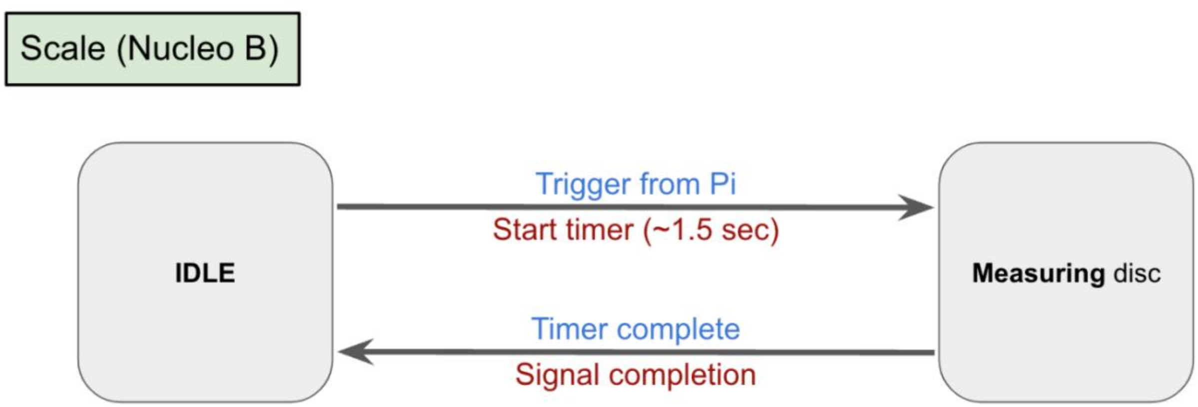


Figure 29. State diagram of scale module

Unit Testing

A series of repeatability tests were conducted on the RS232 scale. The goal of these tests was to determine the reliability of the scale and the accuracy of its measurements. In addition, these tests analyzed the calibration drift of the scale following each measurement, aiming to determine the frequency of taring required to maintain the necessary precision to meet the design specifications.

In the first of two trials, a disc was placed upon the scale and after five seconds the weight was recorded, and the disc was removed. After another five seconds, the disc was placed back on the scale. This procedure was repeated one hundred times, with the recorded weights being compiled into a spreadsheet.

The second trial's procedure was largely similar to the first, however after the five seconds following the disc's removal, the scale was zeroed. As with the first trial, this process was repeated one hundred times (Figure 30).

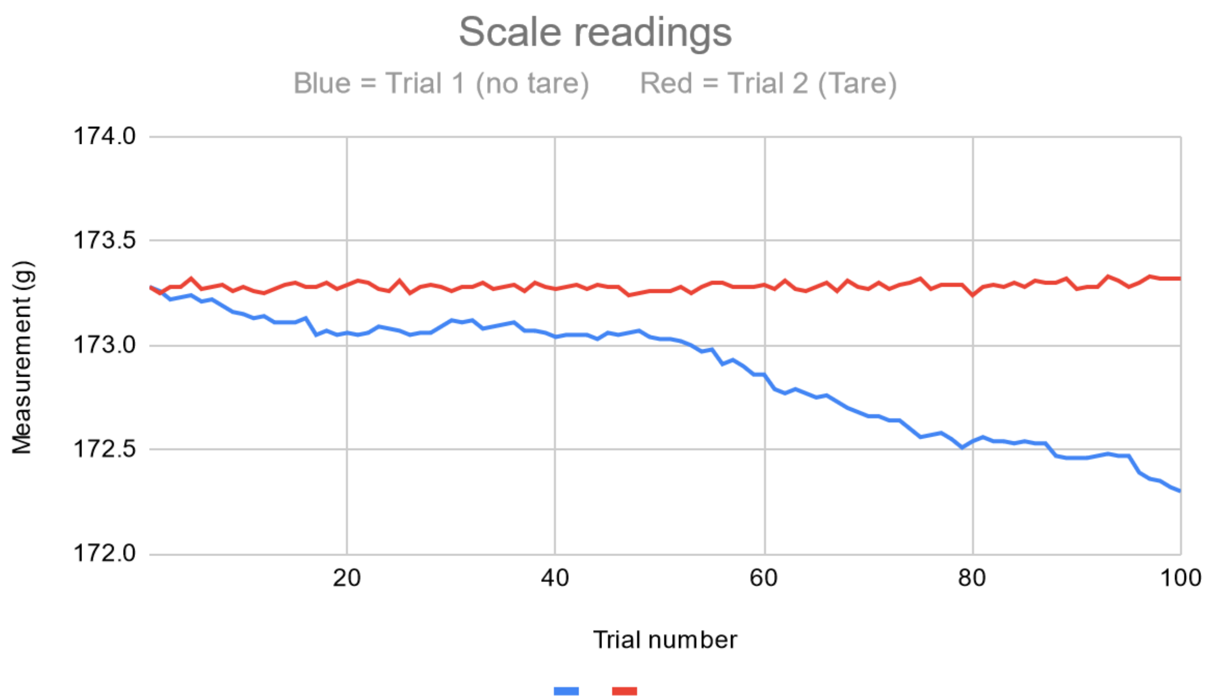


Figure 30. Scale repeatability testing recorded measurements over course of trials

While both trials started with roughly the same readings, in trial one the scale experienced a sharp decline in accuracy over the course of the trial, with the last result deviating from the first by nearly a full gram. In both trials, measurements deviated from the prior test by an average of 0.019 grams, with fewer than 4% of tests deviating by more than 0.05g and no tests exceeding a deviation of greater than 0.09g.

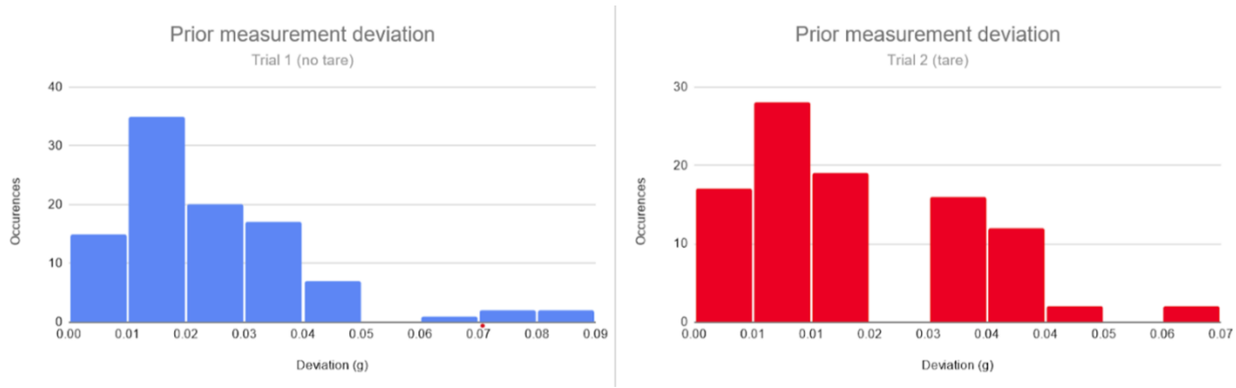


Figure 31. Scale repeatability testing prior measurement deviation

From these trials we were able to conclude that while the purchased scale was able to match the 0.1g precision requested by the customer, the scale would require taring after each measurement. This contributed to our decision to wire the tare button such that it could be directly triggered by the microcontroller.

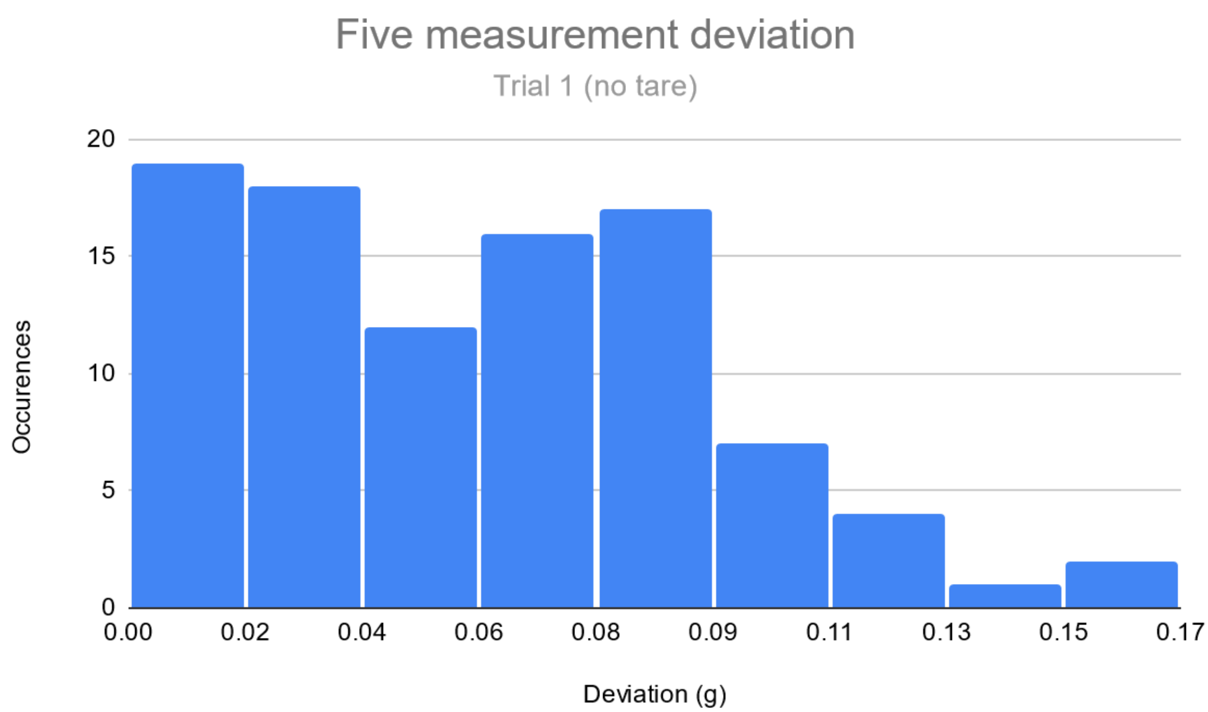


Figure 32. Scale repeatability testing deviation after 5 measurements

2.3.6 Outtake System and Box Conveyor

The outtake system of the machine allows the discs to be distributed and sorted into boxes for accessible inventory. Autonomous sorting removes the need for an employee to spend time categorizing measured discs and putting them into boxes themselves. The design ensures seamless transition of discs between the main conveyor and the storage boxes through a ramp and conveyor design.

Functioning as the link between the machine's main conveyor system and the awaiting boxes, the outtake ramp was engineered with acrylic, compliance wheels, hex shafts, and motor-driven chain and sprockets. The design facilitates accurate disc placement into designated box slots, with multiple sensors monitoring disc progress to ensure no potential backups.

Below, the box conveyor, driven by a hex shaft and motor, serves as a queue for awaiting boxes. The assembly is composed of modular sections and aluminum rollers, each outfitted with specially designed helical gears. To ensure synchronous movement, the hex shaft is outfitted with helical gears to mirror those on the rollers (Figure 33). This allows prompt stops and advances, while the modular sections allow for ease of adjustability. Additionally, the conveyor incorporates sensors to detect box presence, ensuring uninterrupted workflow by alerting the operator to add boxes as necessary.

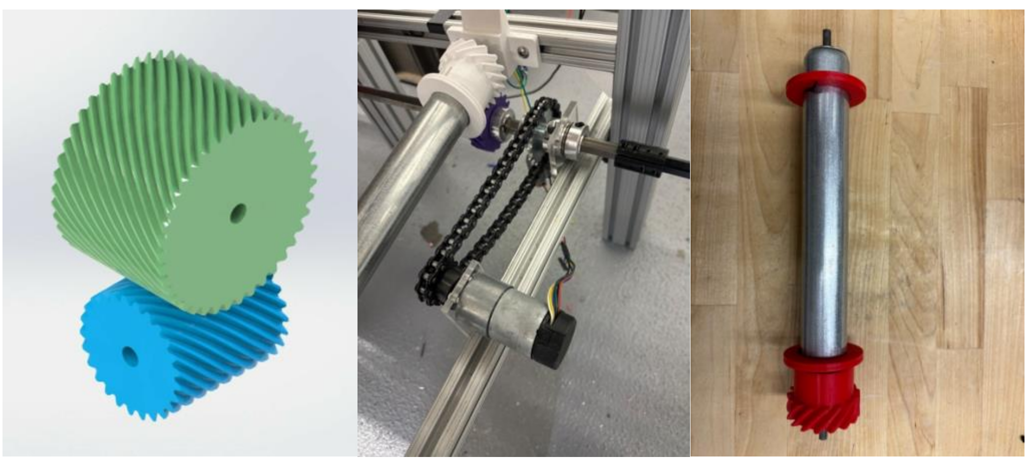


Figure 33. Box conveyor parts and driving mechanism

Inherited Work and Early-Stage Design

Upon analyzing the inherited outtake system, it was evident that modifications and redesign was necessary. While the first iteration provided the necessary link and inventory operations, it posed challenges in terms of manufacturability and integration with the machine. Although the outtake ramp remained largely unchanged in its overall design, minor modifications needed to be implemented. The slope leading into the outtake assembly needed to be re-fabricated due to height adjustments, while the acrylic components making up the side wall, and the front and back plates needed reinforcing to mitigate fragility issues. The outtake ramp also included a limit switch located at the bottom of the assembly that would detect an empty slot, like a ticker on a wheel. However, this proved inadequate, as the limit switch arm would eventually break due to the force exerted by the moving boxes. Finally, the stability and rigidity of the legs connecting the outtake ramp to the machine was not sufficient for long term use.

The box conveyor required a complete redesign to meet the client's needs. Initially, the conveyor featured a U-shaped design consisting of a standard straight conveyor with omni-wheels facilitating box movement between intake and outtake sections (Figure 34). Although this configuration met spatial constraints, it lacked mechanical and electrical efficiency. The reliance on multiple welded stainless steel box beam pieces and numerous motors for operation posed compatibility and reliability issues within the overall system. Additionally, using belts for friction between the rollers and boxes was impractical as tensioning the belts was not feasible and budget constraints did not allow for the purchase of custom belts. Two alternative designs were proposed, a straight design and an L-shaped design, both meeting client specifications. However, the added complexity of the L-shaped design led to a decision by the client to proceed with the straight design.

Figure 34. Previous box conveyor design

Throughout multiple iterations, adjustments were made to enhance the design efficiency, with a focus on reducing costs and complexity. Each iteration influenced the final design, creating a solution that met the client requirements.

Final Design and Fabrication

The outtake ramp incorporates three main structural components: the side plates, the front and back plates, and the ramp itself establishing the connection between the body of the machine and the outtake system (Figure 35). To regulate disc movement, compliant wheels were strategically positioned along the ramp. Two beam break sensors (Adafruit IR 3mm LEDs) and a distance sensor (Adafruit VL6180X Time of Flight Distance Ranging Sensor) are used to monitor disc progress through the system. The wheels are connected along a hex shaft, connected to ball bearings to allow full rotation. These shafts are driven by a Pololu 50:1 metal gearmotor via chain and sprocket. Subsequent coding will allow the motor to guide the disc through the outtake ramp and minimize the impact on the disc as it enters the box.

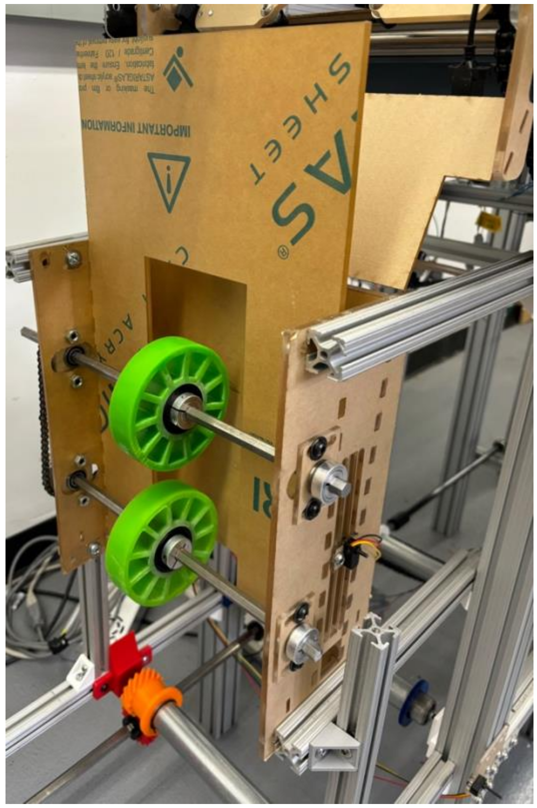


Figure 35. Outtake ramp assembly

The beam break sensors were incorporated into the design and development to mitigate possible backups in the outtake system. The sensors work through infrared (IR) emission and receiving, sending an invisible infrared beam to the receiving sensor, which is sensitive to that specific wavelength. Positioned at the midpoint of the outtake ramp, one sensor detects the presence of a disc in the ramp assembly, while the second sensor is situated above the box conveyor to identify boxes. Since a backup within the ramp will impede machine operation, the beam break sensors provide the necessary precautions to ensure no potential damages.

Similar to the beam break sensors, the rangefinder will serve to determine whether or not there is an empty box slot directly under the outtake ramp. Connected to the machine by a 3D printed component, the rangefinder will gauge the distance between itself and the box to determine the presence of a slot (Figure 36). This rangefinder is a reliable sensor with a 5mm to 100m measurement range along with high resolution and accuracy.

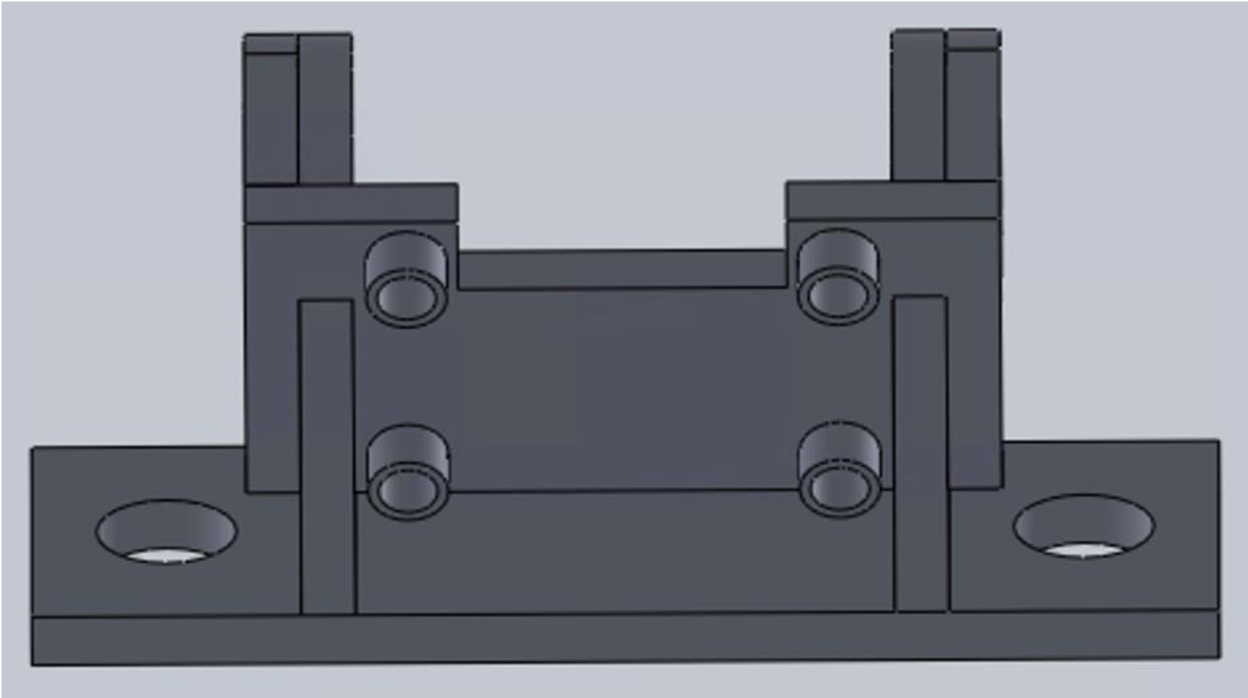


Figure 36. Distance sensor mount

The final iteration of the box conveyor system includes four sections, with three being modular, for adaptable length (Figure 37). One section beneath the machine remains fixed and the remaining conveyor consists of three 40-inch modular sections that can be easily added or removed to align with the client’s modularity requirements. The design accommodates the movement of two or three boxes with the flexibility to add extra modular sections to fulfill the client’s requirements of five boxes.

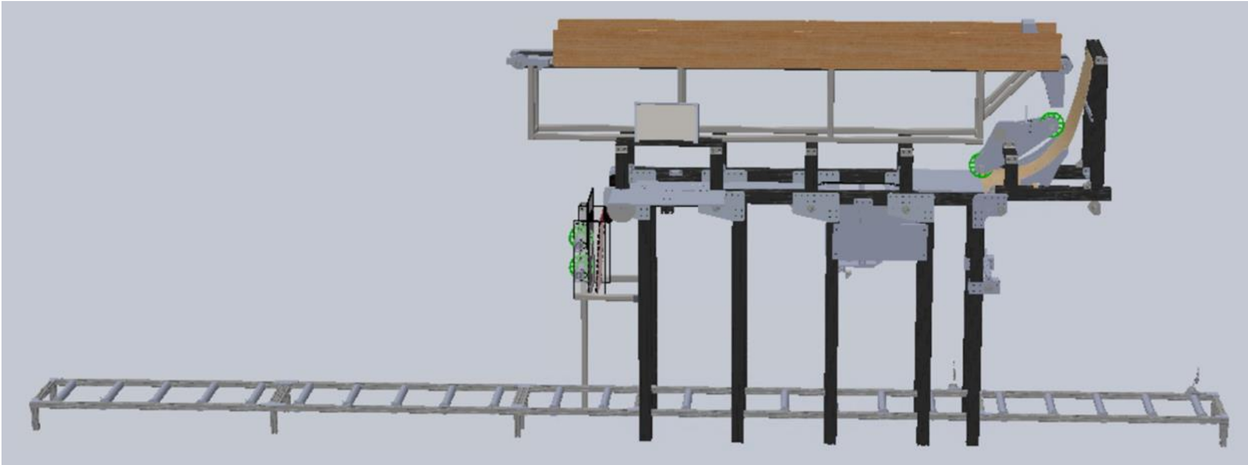


Figure 37. Full box conveyor with modular sections

Prioritizing cost reduction was imperative, encouraging a redesign focused on mechanical motion with little additional expenses for the driving conveyor driving mechanism. A final design consisted of intake sections of the conveyor being driven by either a shaft and pulley (Figure 38) or a shaft and helical gear design (Figure 33), with the box's momentum propelling it through the outtake section. Furthermore, the rollers from iteration one of the box conveyor were incorporated, and 8020 T-slot aluminum was procured to build the section underneath the machine for testing. The changes in driving motion significantly reduced cost while ensuring smooth operation.

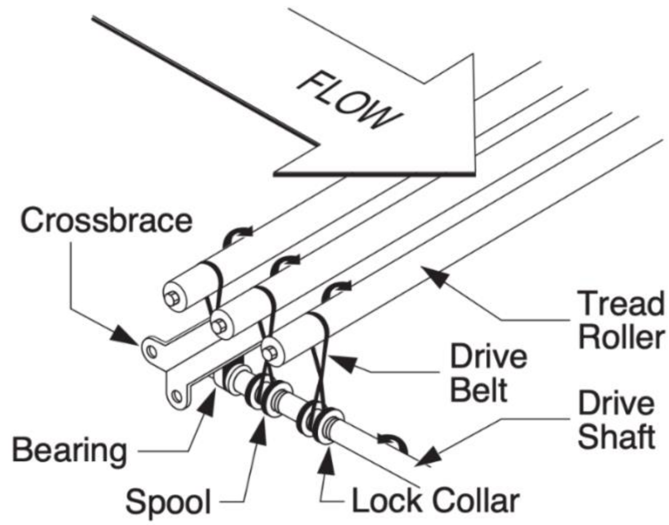


Figure 38. Shaft and pulley driving diagram

The shaft and pulley design was constructed using a ½" hex shaft accommodated with 3D printed driver wheels paired with a driven roller and aligned directly beneath. Each driven roller has a 3D printed part which encircles it, secured with rubber O-ring gaskets, and equipped with a notch for connection to the driver wheels via a polyurethane belt (Figure 33). Each roller is connected to the driven shaft, ensuring equal torque across all rollers. Conversely, for the helical gear and shaft mechanism each driven roller will feature a 3D printed helical gear attachment linked to a matching helical driving gear concentrically attached to the shaft. This design features 3D printed spacers concentrically attached to the driven rollers, secured by rubber O-ring gaskets to prevent damage to the box caused by direct contact to the gears. However, adding precise gear configurations and polylactic acid (PLA) 3D printed material added feasibility due to 3D printer tolerances and durability concerns due to wear and sliding.

To ensure smooth operation of the outtake and box conveyor systems, each assembly has a dedicated motor controller connected to Nucleo C. The diagrams below illustrate the different states each assembly can assume and how they function and communicate with the Raspberry Pi. This state diagram incorporates an additional state to include a labeling operation for eventual disc labeling using the data gathered during the measurement modules (Figures 39 & 40).

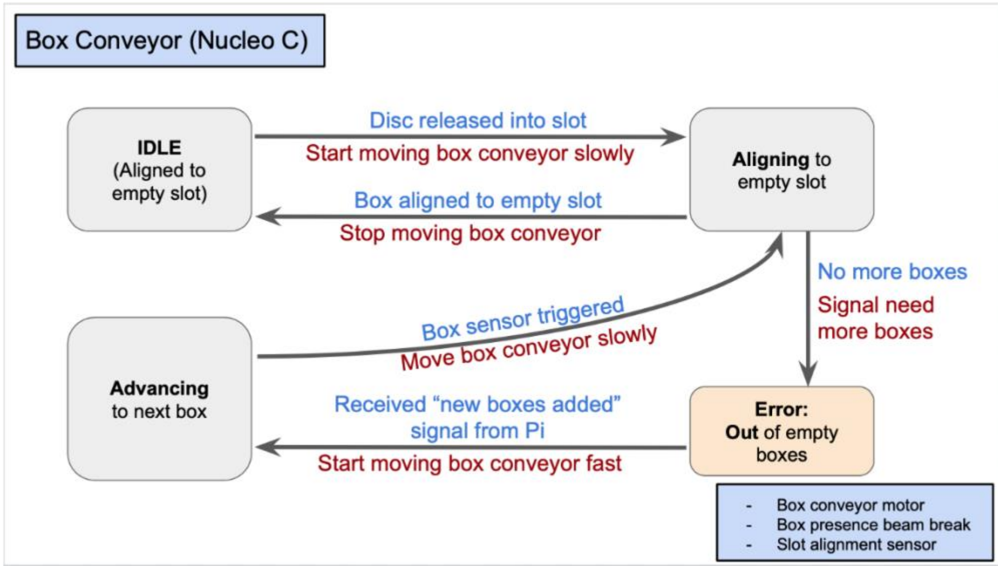


Figure 39. State diagram for the box conveyor assembly

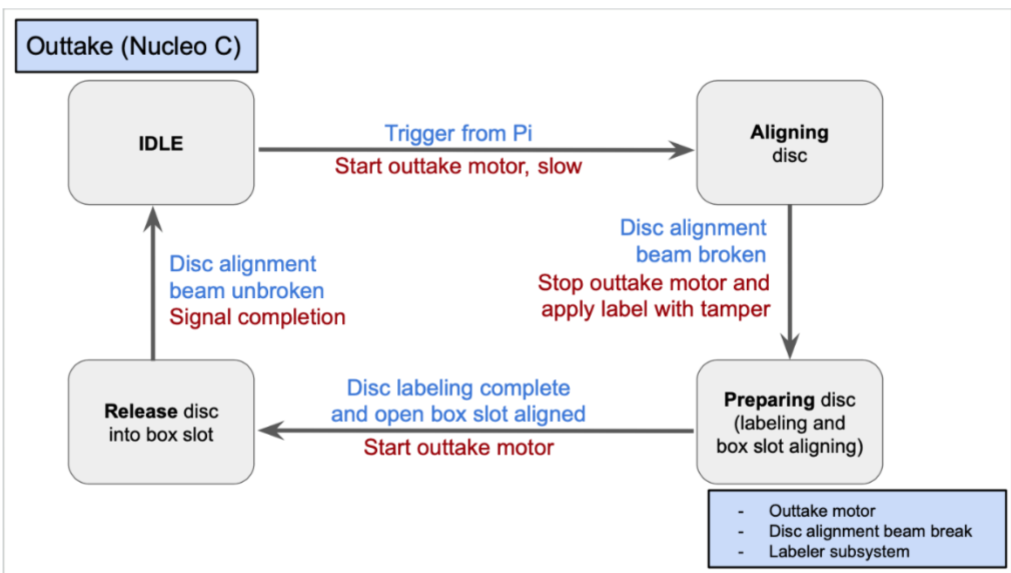


Figure 40. State diagram for the outtake ramp assembly

Unit Testing

To ensure proper mechanical functionality of the outtake ramp, user testing was conducted by manually guiding discs through the outtake ramp into a designated slot in a box positioned below. The test, consisting of 50 discs, yielded a 100% success rate, warranting further examination. Subsequent testing involved assessing electrical integration via the UI to ensure seamless communication between the Raspberry Pi and the Nucleo C microcontroller.

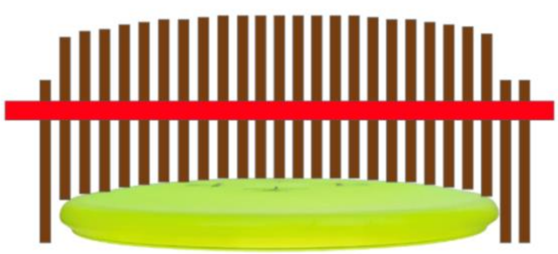
Continuing with the outtake system evaluation process, manual testing was performed on both the helical gears and the shaft and pulley driving mechanism. By manually rotating the hex shaft, multiple cycles revealed that the shaft and pulley design was inadequate, as the polyurethane belts consistently slipped from their drive wheels. Additionally, constant tension on the belts resulted in a shortened life cycle. Consequently, the team moved forward with the helical gear driving mechanism due to its smooth operation.

2.3.7 Researched and Developed Systems

Due to the large scope of this project, many systems were investigated and developed but unable to be fully integrated with completed systems, including systems to measure the edge profile and dome height of discs as well as a disc labeler system.

Edge Profile and Height Measurement System

The inherited system used a series of rakes to measure the full profile of discs, which could then represent the upper half of the edge profile as well as the dome height of discs (Figure 41). In the space where the current flexibility module is placed, a series of ⅛-inch laser cut acrylic pieces would rest on the surface of the disc and a camera would take a picture of the profile generated by the rakes. The image would be processed through a computer vision pipeline to generate an approximate profile of the disc (Figure 42).



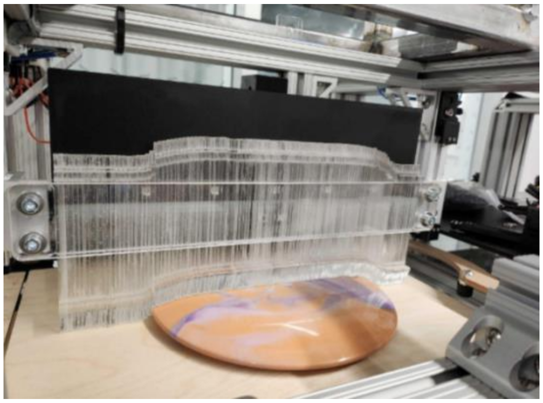


Figure 41. Inherited profile measurement system diagram (left) and implementation (right)

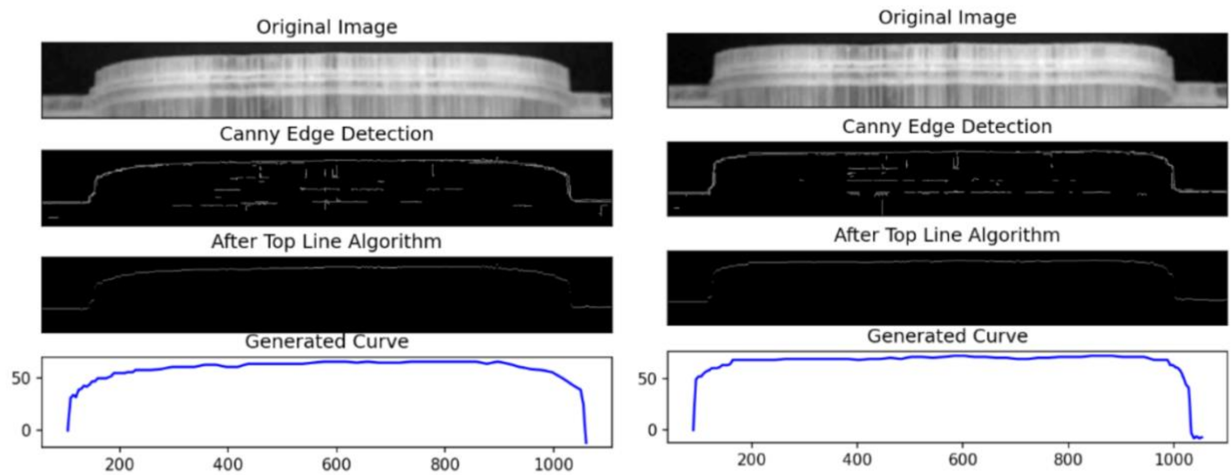


Figure 42. Images of different discs using profile module (top), Canny Edge Detection processing on captured profile image (second from top), graph using custom algorithm to isolate topmost pixels of Canny Edge (third), and final generated curve (bottom)

The profile generated by this system could not accurately or precisely represent the edge profile or the dome height of discs, and the client emphasized a need for greater precision when capturing these measurements. To replace the rake system, we tested laser rangefinders because they could easily measure and graphically represent a curved profile and they could capture the profile more precisely. One rangefinder would be mounted below the conveyor and one above. As the disc was pushed by the conveyor, the rangefinders would measure the top and bottom profiles, capturing the full edge profile and the dome height. We first attempted with an Adafruit VL6180X laser time-of-flight sensor due to its high resolution, purported repeatability metrics, and relatively low price. However, prototyping and testing revealed that laser rangefinders within our budget cannot accurately measure discs with reflective or holographic coatings, or translucent discs, due to the laser either reflecting off the surface of discs or beaming through the entirety of them. More advanced laser range finders, such as laser specular reflection time-of-flight sensors, could perform the profile measurement on reflective, holographic or translucent discs, but these options proved to be beyond budget limitations. In conversation with our sponsor, we concluded that it would be resource-efficient to investigate measuring dome height individually, instead of the full or edge profile of discs.

To measure the dome height of discs, the height and flexibility modules were to be integrated together into one system. The height could be calculated based on the motor encoders, lead screw dimensions, and a series of limit switches. A limit switch was integrated into one of the

3D printed “thumbs” that applies the center force to the disc. As a disc is contacted by the “thumbs” on the lower carriage assembly, the limit switch would be placed such that it contacts the center of the disc underside. Once the limit switch is triggered, the height of the initial point of contact is recorded by the module. Next, the disc is raised vertically upward until it contacts the two load cells, and another height measurement is recorded. Afterwards, the module uses the initial position of the disc and its final deflection height to determine the full height of the disc. However, this method would not measure the precise dome height of a disc, as the load cells only contact the edges of the disc rather than the center of the dome on the top of the disc. Therefore, we did not pursue this method further.

Labeler System

The client expressed their desire for a system to label discs processed by the machine with a barcode that corresponds to the collected data of that disc. Discs would then be inventoried based on barcode information and could be easily identified if one were to be misplaced or removed from its allotted box slot. To autonomously label discs after data collection, a separate label module would need to be created, featuring a motorized tamper arm to securely stick labels to each disc.
We explored the possibility of integrating such a module into the system, however, extensive research revealed that existing industrial solutions were too expensive. Following discussions with a sales representative regarding their labeler tamper module, we received a quote of $8,500, which, despite being the most economical option available, still exceeded our budget.

The proposed system design incorporates an industrial-grade label printer and a linear actuated tamper for applying the label to the disc. The Zebra ZT231 TT Printer emerged as the preferred choice due to its high-volume capacity of over 1,000 prints per day, integrated liner take-up feature, and 203 dots per inch resolution, allowing for a large number of discs to be processed and labeled at a time. To facilitate label application, a prototype of the label tamper arm was developed. The tamper uses a suction box to securely grip the non-adhesive side of the label, ensuring smooth transfer from the printer to the disc. The linear actuator, powered by a DC motor, controls the rack and pinion mechanism for precise movement (Figure 43).

Figure 43. Labeler tamper prototype which features a rack and pinion linear actuator and a suction box to grab the label

Chapter 3: Broader Impacts

To understand the broader impacts of this project, we analyzed the ethical, technological, economic, societal, global and environmental aspects of this project. To ensure that our project was ethical and technologically sound, we strictly followed the ASME Code of Ethics as well followed the Professional Disc Golf Association standards of disc measurement. To ensure that this project was viable, we performed economic analysis of the return on investment for Maple Hill. Finally, to evaluate the impact producing this machine could have societally, globally, and environmentally, we analyzed automation in the workforce and potential energy consumption.

3.1 Engineering Ethics

This MQP project works closely with a private client, Maple Hill Disc Golf. Throughout the course of this project, our team has employed one of the fundamental principles of the ASME Code of Ethics: “being honest and impartial, and serving with fidelity their clients (including their employers) and the public” (*American Society of Mechanical Engineers Code of Ethics*, 2021). At the beginning of this project, our team was instructed not to publicly, or openly, discuss that Maple Hill was our client, as they wanted to keep the discussions of the inner workings of this project contained. The primary reasoning behind this was due to Maple Hill’s desire not to give their competitors any ideas about implementing a similar autonomous machine to improve their online stores. With this being the case, our team continuously upheld our promise to Maple Hill with continued fidelity.

3.2 Codes and Standards

As stated previously in the background section of Chapter 1, our team used the PDGA Technical Standards for this project. This set of technical standards offers manufacturers of discs a set of guidelines such that their products can be approved by the PDGA. Every disc that is manufactured is tested by the PDGA Technical Standards Working Group so that all equipment used in the sport of disc golf meets the basic specifications laid out by the PDGA. Our team used these technical standards as a guideline for our measurement modules, so that our machine could provide the measurement data to the correct precision and accuracy. In addition to this, our team used these standards so that our measurement modules would be able to handle the varying sizes and configurations of discs. For example, our scale module needed to be precise to one-hundredth (0.01) of a gram while also being able to handle the maximum sized disc of 200 grams of weight per the PDGA specifications.

Furthermore, our team used the testing procedures from the technical standards in order to determine how the PDGA finds the specific characteristics and dimensions of a disc. The tests performed by the PDGA are a guideline and there are variations in the ways that the dimensions can be measured. Some of the specific tests, like the one for the outer diameter for example, were achieved utilizing cameras rather than manually measuring the diameter via calipers. These tests were remodeled or changed sl3ightly based upon PDGA technical standards in order for our team to make them fully autonomous and repeatable.

3.3 Economic Factors

This machine saves time and money for the stakeholder. It allows workers to autonomously measure disc attributes rather than manually. The cost of the manual measurement compared to the cost of the autonomous machine shows the bigger picture of what this project achieves for the client.

Manual	Cost
Measurement Time (minutes/disc)	5
Wage for measuring operator $/hr	$18
Hours time for 100 discs	8.33
Wages paid for 100 disc	$150

Figure 44. Assumptions and costs for manual measurement

Manual measurement of discs takes approximately 5 minutes per disc, and the wage for the employee is assumed to be $18 per hour. Using these assumptions, it can be calculated that it will take 8.33 hours to measure 100 discs, which will cost the stakeholder $150 in wages (Figure 44).

Automatic	Cost
Upfront Costs	$11,750
Wage for measuring operator $/hr	$18
Time needed for 100 discs (minutes)	5
Measurement Time (minutes/disc)	0.5
Hours time for 100 discs	0.83
Wages paid for 100 disc	$1.50

Figure 45. Assumptions and costs for autonomous measurement

Although autonomous measurement incurs a significant upfront cost, it has a much lower operating cost. Autonomous measurement of discs takes approximately 30 seconds per disc, and the wage for the operator is $18. However, the operator is only paid for the 5 minutes of work they contribute to the operation of the machine per 100 discs, the time needed to load 100 discs and press start. Using these assumptions, it can be calculated that operating costs are only $1.50 in wages per 100 discs. Additionally, it can be calculated that it will only take 0.83 hours, or 50 minutes, to measure 100 discs (Figure 45).

Comparing the manual and automatic results, automatic measuring is 10x shorter in total measuring time, and 100x less in the wages paid per disc. This increase in speed achieves the goal of faster throughput for a much lower operating cost.

Analysis	Cost-Benefit
Upfront Cost Difference	-$11,750
Recurring Cost Difference (Benefit per 100 discs)	$148.50
Number of Discs Until Break Even	7912
Hours saved per 100 Discs	7.50

Figure 46. Assumptions and calculations for net benefit

The recurring benefit can be extrapolated to determine how quickly the initial investment is paid off. Compared to the manual measuring system, the autonomous measuring system has a $11,750 higher upfront cost. Additionally, the recurring operating benefit of using the autonomous machine over manual measurements is $148.50 per 100 discs (Figure 46). Using these calculated assumptions, the number of discs that must be measured can be calculated using the formula $Discs\ to\ Breakeven = upfront\ cost\ benefit\ per\ disc$. The stakeholder must measure ~8000 discs automatically to break even on the upfront investment of $11,750. The global disc golf market size as of 2022 is USD 205.7 million, and is estimated to quadruple in the next ten years (Business Research Insights, 2024), currently in the hundreds of millions, disc golf industry produces 100,000's discs a year globally, and with a flourishing online store our sponsor will be able to recoup their investment within a reasonable timeline.

In the cost-benefit analysis, all measurements are in terms of 100 discs measured rather than in terms of time because the number of discs measured over time will vary heavily based on the demand of the website. Evaluating the cost in terms of the number of discs measured is a much more accurate way to represent the real costs and benefits of the system. Additionally, the time period of return is assumed to be less than one year, so interest rates were not used to discount future cash flows to present value.

Autonomous data collection has clear benefits over manual data collection. Time saved, reliability of information, and cost are the three most valuable variables to the stakeholder. Using the machine is 10x faster than manual measurements, so it will free up workers to work on other tasks for the company. Additionally, having reliable information for customers on the website will put them out in front of their online competition. Finally, using the machine is 100x more cost efficient than manual measurements, and will recoup initial investment after measurement of ~8000 discs. Autonomous data collection is more time efficient, provides more reliable data, and is cheaper in terms of operating cost.

3.4 Societal and Global Impacts

The creation of this machine poses the opportunity for other disc golf courses and manufacturers to use an autonomous system such as this to accurately and efficiently obtain the measurements of discs and inventory them. The machine created in this MQP has the potential to directly impact the disc golf industry. Disc golf courses and manufacturers could see increases in profits and brand likeability as consumers are offered more accurate measurements of discs in a quick, seamless manner. Likewise, such a machine could revolutionize the ways in which disc golfers typically shop. With more automated machines in the industry, increases in precision and additions of new measurement modules within machines could allow disc golfers the ease of being able to shop online for their discs rather than travel to stores. These measurements also offer a standardized and quantifiable way to rate disc golf discs on a numeric scale for a range of characteristics. Current manufacturers offer numeric scales for characteristics such as the disc's stability or speed, which are typically based upon the dimensions and measurements of a disc. One of the issues in the current market is that every manufacturer has a different numeric scale and different parameters for their ratings. With a standardized machine, the industry could see greater consistency for rating and measuring these discs, which would benefit the average disc golfer.

While the potential benefits for a machine like this are immense, there are unintended consequences as well. Although the current iteration of the machine requires an operator to load discs and remove boxes, future prototypes could see the need for a human operator become obsolete. With the growth in automated technology and artificial intelligence (AI), future iterations of such a machine could see an increase and spread of technological unemployment, or loss of jobs due to technological changes and advancements. While the disc golf industry is relatively small, widespread use of this machine could mean that many individuals are left unemployed. In addition to this, job automation may not stop at machine operators. Other positions within the disc golf industry and within disc golf companies could also be in jeopardy, especially with the recent advancements in AI.

3.5 Environmental Impact

One of the largest environmental impacts of this project is the energy consumption from the machine. Currently the machine can be powered off of a 24-volt power supply. If the application of this machine were to increase across the disc golf industry and/or the machine was to increase in size, potential alternatives to power the machine may need to be investigated. Unfortunately, as of 2022, the current per capita electrical generation from fossil fuels in the United States is roughly 60% (Figure 47). With this data, the current electricity generation for our machine is from fossil fuels.

There are steady improvements in the increasing use of renewable energy sources. As of the first quarter in 2022, the United States has reached an all-time high, with 24% of electricity generation coming from renewable sources (Figure 47). This suggests that by the time these autonomous machines are fully adopted within the disc golf industry, the likelihood that they are powered by renewable energy sources is high. In the short-term, however, there is the potential for a negative contribution to pollution levels as our project draws power from fossil fuel generated energy.

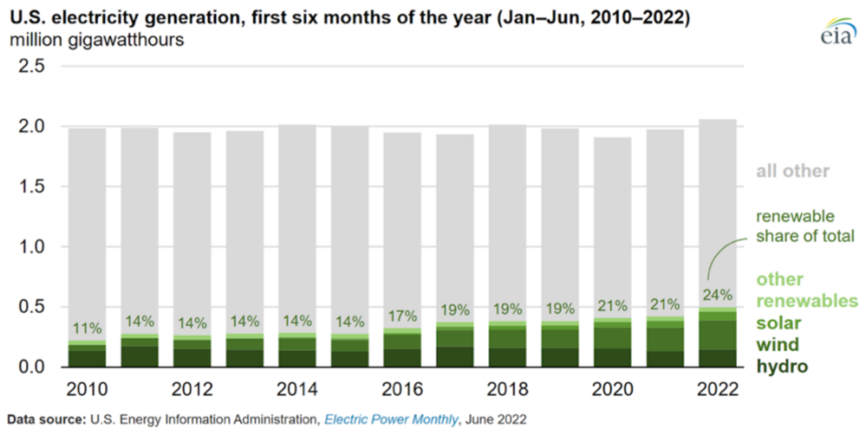


Figure 47. U.S. electricity generation, first six months of the year for 2010-2022 via U.S. Energy Information Administration (EIA) [(Fasching, 2022)]

Chapter 4: Discussion and Recommendations

4.1 System Testing

System testing was conducted through a comprehensive demonstration involving the client. This consisted of running the machine with the buttons that were implemented on the GUI. Through this demonstration, the client gained insight into the system's operational dynamics. Concurrently, our team identified and documented various bugs and issues, tagging them for resolution in future iterations.

The demonstration highlighted the machine’s capability to effectively guide a disc through all three conveyors, aligning with the team's predefined objectives. However, while measurements from the remaining modules were functional, they exhibited a lack of integration with the broader system. Although communication via ROS was established across all modules, there is still a need for refinement in timing and integration to optimize system performance.

4.2 Discussion of Solution

The current iteration of this capstone project has produced a semi-autonomous machine that is able to transport a disc fully through the machine with each measurement and motion module talking to one another via ROS. Each measurement module has been integrated and is able to be operated via the Raspberry Pi powered touchscreen on the front of the machine. Discs are able to be dropped, advanced, and measured in each measurement module through the UI via a series of buttons. Along with this operation, the UI ROS node, which offers a simple GUI for the operator, can receive data in real time and update the display screen as new data is received from each measurement module.

4.3 Recommendations

With a working solution in place, there are a few recommendations that we believe can further improve the automated machine. This includes adding modules for added measurements beyond the standard, improving the UI, and exploring a way to export data straight to an online store.

In order to expand the coverage of the data provided by Maple Hill, additional measurement modules can be added due to the system’s modular design. The addition of new modules will ensure that Maple Hill has data beyond the core measurements needed to purchase a disc. An example of an added module would be a sensor that can measure the profile of the disc. Small sensors were tested during the team's design process. However, due to the lack of quality in the budget sensors, the profile was unable to be attained. With an added system such as this, the client would be able to provide all the measurements of the disc while providing the customer with an insight into the actual shape of the disc as well.

The UI incorporated in the machine allows for the necessary components to properly run the machine. However, a more user-friendly interface would make it easier for the client to ensure the proper measurements are being collected while also being able to easily run the machine through the tap of a button.

The last recommendation that the team would like to provide is the ability to export the collected measurements and photos directly to the online store. Storing the data in a separate CV file for further upload to the online store works but lessens the automation of the machine. Being able to upload all the data directly to the online store would create a much more time efficient process and completely automate the machine.

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Appendices

Appendix A: GitHub Repository

https://github.com/WPI-Disc-Golf-MQP

Appendix B: Design Process

Axiomatic design was created to decrease the amount of prototyping that is necessary during the engineering process. Functional Requirements (FR's) of the design must be identified and compared to potential solutions known as Design Parameters (DP's). FR's are the primary tasks of the design, and the DP's are how the design is able to complete those tasks. Critically analyzing how the FR's and the DP's relate can remove issues in the design before prototypes are created, thus decreasing the number of prototypes.

	DP1: Chain, Sprocket, Push Bar System	DP2: Sensor and State Control System	DP3: Machine Control System Implimentation
FR1: Syncronyze motion between modules	x		
FR2: Sense where discs are and measuring attributes		x	
FR3: Minimize time spent to cycle a new disc to each module		x	x

Figure 48. Coupling matrix

This coupling matrix shows the order in which prototyping should occur (Figure 48). The sensor and state control system (DP2) should be finalized before designing the machine control system implementation (DP3), so that FR2 and FR3 can be satisfied before fine tuning FR3 with DP3. This makes intuitive sense because the module is built independent of a control system first, and is then integrated into the system architecture software after the module has been completed. Looking at the interactions between FRs and DPs in this way was critical to determining prototyping focus, and eliminating wasted prototypes and engineering time.

FR0: Provide mechanically repeatable way to move discs to each module

1. Synchronize motion between modules (to one motor)
   1.1. Direct X direction motion
   1.2. Direct all disc motion with a single drive system
   1.3. Provide mechanical support equipment
2. Sense where discs are and measuring disc attributes
   2.1. Determine where sensors are required
   2.2. Locate discs in the system using sensors (or Install sensors to locate the disc)
3. Minimize time spent moving discs between measuring modules
   3.1. Control timing of the conveyor states
   3.2. Control timing of the previous motion (intake) and the current motion (conveyor)

DP0: Conveyor System

1. Chain, Sprocket, Push Bar System
   1.1. DC brushless motor
   1.2. Synchronize left and right chain via idler
   1.3. Install multiple single-disc push bars
   1.4. Tensioner, Idler, Gear System
2. Sensor and State Control System
   2.1. State Machine Control System
   2.2. Centering Beam Break Sensor
   2.3. Backup Beam Break Sensor
3. Machine Control System Implementation
   3.1. ROS communication System
   3.2. Design Graphical User Interface (GUI)

Figure 49. FR and DP hierarchy

FR's and DP's are hierarchical, meaning that each can be broken down in order to fully analyze the project. For the main conveyor system, the main FR of the system is to provide a mechanically repeatable way to move discs to each module (FR0). To achieve that goal, the main conveyor system (DP0) was created. Figure 49 shows the hierarchy of the FR's and the DP's that fall under this system. In order to create a main conveyor system, a chain sprocket and push bar system (DP1), sensor and state system (DP2), and machine control system implementation (DP3) must be designed and prototyped. Similarly, providing a mechanically repeatable way to move discs to each module (FR0) requires synchronizing motion between modules (FR1), sensing where discs are and measuring disc attributes (FR2), and minimizing time spent moving discs between measuring modules (FR3). Hierarchical decomposition enabled the team to break down the main conveyor system into an achievable set of goals to efficiently prototype the design.

		DP1: Chain, Sprocket, Push Bar System	DP1.1: DC Brushless Motor with Gear Ratio	DP1.2: Syncronized Left and Right Chain via Idler	DP1.3: Install multiple single-disc push bars	DP1.4: Tensioner, Idler, Gear System	DP2: Sensor and State System	DP2.1 State Machine Control System	DP2.2: Centering Beam Break Sensor	DP2.3: Backup Beam Break Sensor	DP3: Raspberry Pi Computer	DP3.1: ROS Communication System	DP3.2: Design Graphical User Interface (GUI)
FR1: Syncronyze motion between modules		x											
	FR 1.1: Direct X direction motion		x	x									
	FR 1.2: Direct all disc motion with a single drive system				x								
	FR 1.3: Provide mechanical support equipment					x							
FR2: Sense where discs are within the system							x						
	FR2.1: Determine where sensors are required							x					
	FR2.1: Locate discs in the system using sensors								x	x			
FR3: Minimize time spent to cycle a new disc to each module							x				x		
	FR3.1: Control timing of the conveyor states							x					
	FR3.2: Control timing of the previous motion (intake) and the current motion (conveyor)											x	
	FR3.3: Run a cycle at the press of a button												x

Figure 50. Comparison of project requirements to implemented design solutions

Figure 50 compares the requirements of the project to the different designs implemented into the solution. Analyzing the matrix, the main conveyor module must be first developed mechanically and electrically as a module, then implemented into the main communications and control system. This will allow the module to work independently of the communications and control system.

Appendix C: Wiring Diagrams

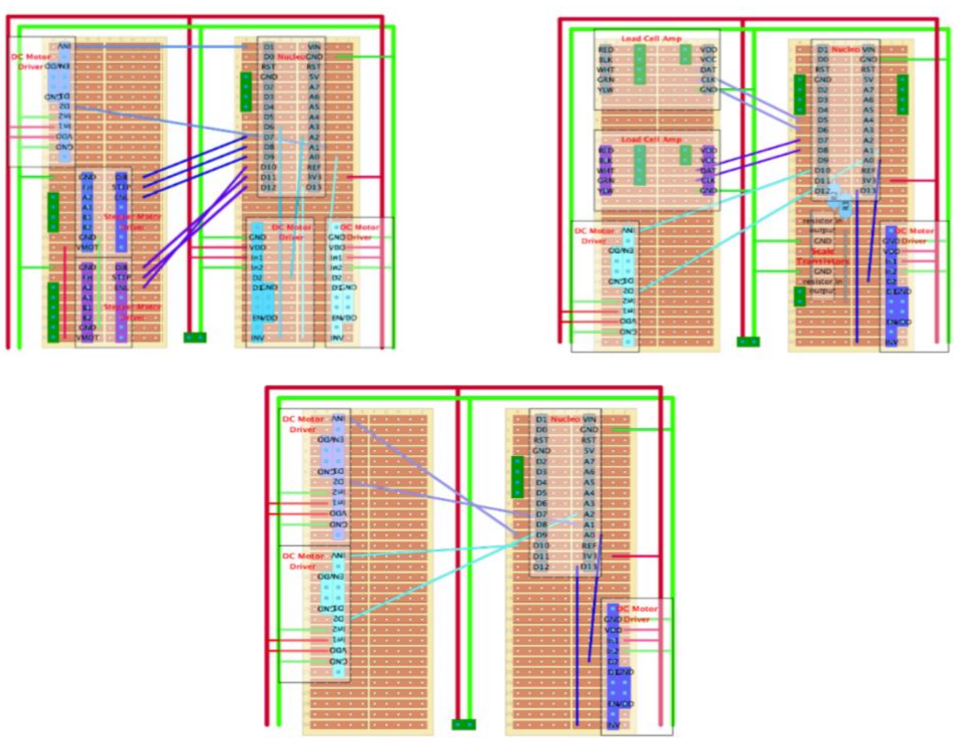

Figure 51. Wire diagrams for Nucleo A (first), B (second), and C (third) from left to right

Appendix D: Full Electrical System Diagram

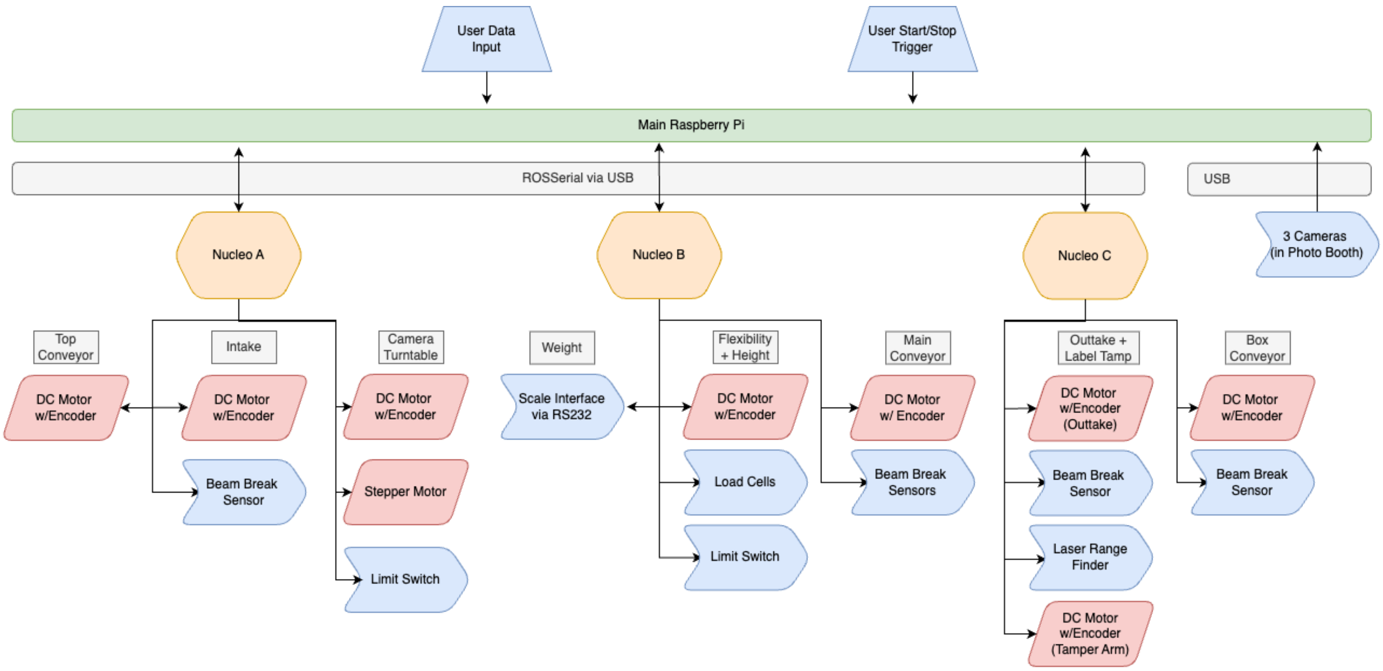

Figure 52. Full electrical system diagram

Appendix E: Main Conveyor Friction and Motor Calculations

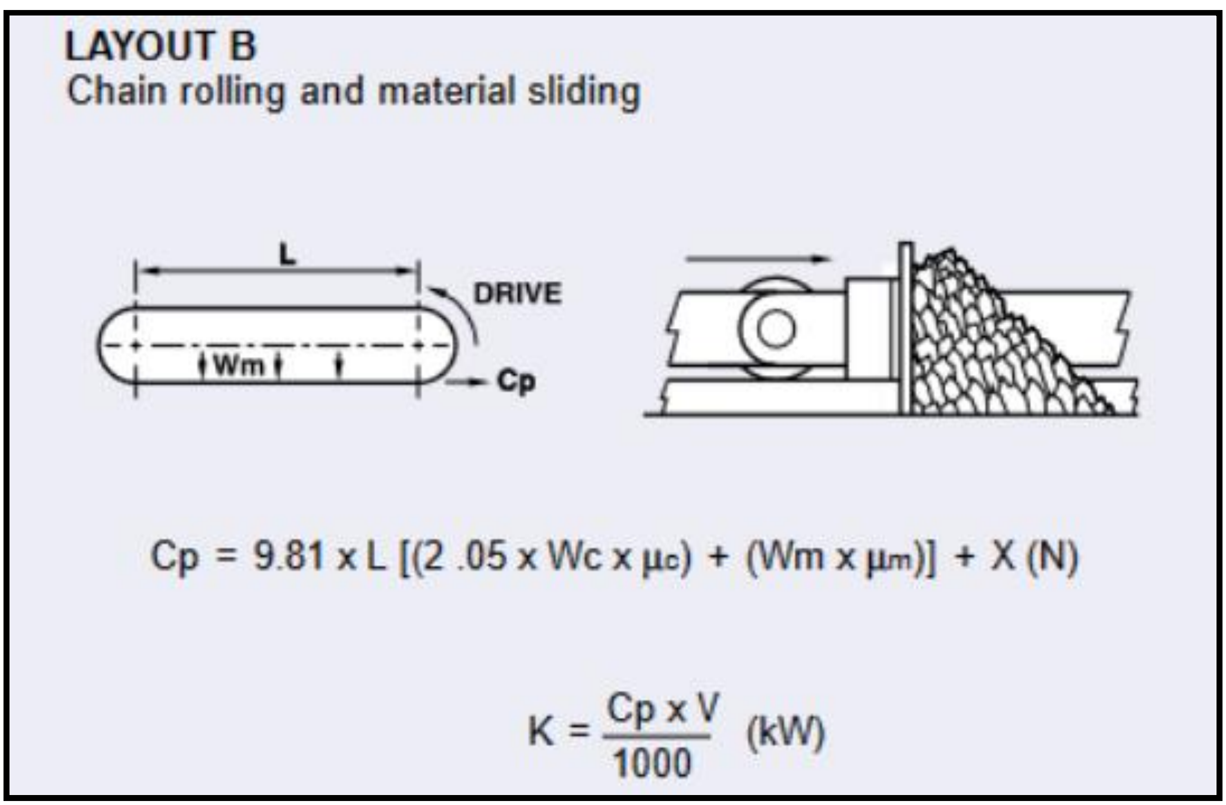

Figure 53. Equation for Chain Pull (Renold, n.d.)

<u>Nomenclature:</u>

L = length of machine from sprocket to sprocket [m]

W_c = weight of conveyor chains per unit length [kg/m]

W_m = weight of the load per unit length [kg/m]

μ_c = coefficient of friction between the sprockets and chain

μ_m = coefficient of friction between the disc and wood

C_p = total chain pull [N]

R_{out} = outer radius [m]

R_{in} = inner radius [m]

F_{out} = output force

$Torque_{out}$ = output torque

$Torque_{in}$ = input torque

<u>Total Chain Pull Calculation:</u>

$L = 1.5$ m

$W_c = 0.18$ kg/m

$W_m = weight\ of\ dics \times \frac{4\ discs}{L} = \frac{0.8}{1.5\ m}$ = 0.533 kg/m

$\mu_c = 0.2$

$\mu_m = 0.4$

$C_p = g \times L\ [(2.05 \times W_c \times\ \mu_c) + (W_m \times \mu_m)]\ N = 9.81 \times 1.5\ [(2.05 \times 0.18 \times\ 0.2) +$
$(0.533 \times 0.4)] = \mathbf{4.22\ N}$

<u>Torque Calculation:</u>

$$R_{out} = 0.0698\,m \qquad R_{in} = 0.0381\,m \qquad F_{out} = 8.44\,N$$

$$Gear\ Ratio = \frac{R_{out}}{R_{in}} = \frac{0.0698\,m}{0.0381\,m} = 1.83$$

$$Torque_{out} = (R_{out})(F_{out}) = (0.0698\,m)(8.44\,N) = 0.56\,N \cdot m$$

$$Torque_{in} = \frac{Torque_{out}}{Gear\ Ratio} = \frac{0.56\,N \cdot m}{1.83} = \mathbf{0.306\,N \cdot m}$$

Appendix F: Camera Turntable Motor Calculations

Nomenclature:

$\mu_{frict} = coefficient\ of\ friction$

Calculation:

$$Screw\ Lead = 0.2\,cm \qquad Thrust = 0.498\,kg \qquad Efficiency = 0.2 \qquad \mu_{frict} = 0.19$$

$$Torque = \frac{(Thrust)(Screw\ Lead)}{2(Efficiency)(\mu_{frict})} = \frac{(0.498\,kg)(0.2\,cm)}{2(0.2)(0.19)} = \mathbf{1.31\,kg \cdot cm}$$

Appendix G: Load Cell Calibration and Test Data

Nomenclature:

$y =$ output voltage reading from load cells

$m =$ slope of calibration curve linear trendline

$x =$ applied force [g]

$b =$ y-intercept of calibration curve

Equation:

$$y = mx + b \rightarrow x = \frac{(y - b)}{m}$$

Calibration Data:

Precision Weight [grams]	Weight on Load Cell [grams]	Load Cell 1 Reading [voltage]	Load Cell 2 Reading [voltage]
500.310	500.310	8.911	2.837
200.127	700.437	10.888	6.328
131.033	834.420	13.752	9.278
128.550	965.453	14.792	12.017
130.593	1095.953	15.975	14.689
130.500	1226.547	15.686	17.485
129.027	1355.097	17.970	20.124
129.710	1484.807	20.958	20.517
133.983	1613.833	23.527	21.763

Hand Testing Data:

Disc 1 –

Load Cell 1 Output Voltage [V]	Load Cell 2 Output Voltage [V]	Actual Load Cell 1 Reading Disc 1 [grams]	Actual Load Cell 2 Reading Disc 1 [grams]	Actual Load Cell 1 Reading [kilograms]	Actual Load Cell 2 Reading [kilograms]	Average Force Reading of Both Load Cells [kilograms]
5.14	4.03	200.298	-89.172	0.200	-0.0892	0.056
20.03	30.97	1430.876	1407.494	1.431	1.4075	1.419
35.41	46.92	2701.950	2293.606	2.702	2.2936	2.498
56.71	75.95	4462.281	3906.383	4.462	3.9064	4.184
71.10	89.73	5651.537	4671.939	5.652	4.6719	5.162
73.55	94.82	5854.017	4954.717	5.854	4.9547	5.404
77.78	100.30	6203.603	5259.161	6.204	5.2592	5.731

Note: Actual Load Cell Reading [grams] is equivalent to the x value in linear slope equation.

Disc 2 -

Note: Actual Load Cell Reading [grams] is equivalent to the x value in linear slope equation.

Load Cell 1 Output Voltage [V]	**Load Cell 2 Output Voltage [V]**	**Actual Load Cell 1 Reading Disc 2 [grams]**	**Actual Load Cell 2 Reading Disc 2 [grams]**	**Actual Load Cell 1 Reading [kilograms]**	**Actual Load Cell 2 Reading [kilograms]**	**Average Force Reading of Both Load Cells [kilograms]**
1.57	2.70	-94.744	-163.061	-0.095	-0.163	-0.129
15.01	17.48	1016.000	658.050	1.016	0.658	0.837
46.59	54.38	3625.917	2708.050	3.626	2.708	3.167
55.40	54.61	4354.017	2720.828	4.354	2.721	3.537
61.75	60.96	4878.810	3073.606	4.879	3.074	3.976
64.27	64.40	5087.074	3264.717	5.087	3.265	4.176

Note: Actual Load Cell Reading [grams] is equivalent to the x value in linear slope equation.