Breakfast Sandwich Robot

A Major Qualifying Project for

Worcester Polytechnic Institute

submitted in partial fulfillment of the

Degree of Bachelor of Science

Submitted by:

Matthew Saludo Balquin (ECE, minor in RBE)

Trevor Faber (ME)

Samson Hodges (RBE)

Ethan Moynihan (CS, minor in RBE)

Advised by:

Prof. Fiona Levey (MME)

Prof. Pradeep Radhakrishnan (MME)

Prof. Bo Tang (ECE)

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Abstract

Current food automation efforts imitate industrial robots for manufacturing and have been too costly to implement at a large scale. Our team diverges from this approach by developing a novel strategy to autonomous food manipulation using an opposing gantry system. This system constrains the robot to operations within a two-dimensional plane, reducing the cost and complexity compared to traditional automation efforts. This innovation has allowed the team to create a robot capable of demonstrating this form of ingredient manipulation, something that has yet to be accomplished in industry. The opposing gantry automation approach is laying the groundwork for the industry to alleviate staffing demands and opening the door for accessible food options for all.

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Authorship

Section	Main Author	Editor 1	Editor 2
Abstract	Trevor	Ethan	
Acknowledgements	Trevor	Ethan	
Introduction	Ethan, Trevor	Trevor	
Literature Review	Ethan, Matt, Samson, Trevor	Trevor	Ethan
Food Safety	Matt, Trevor	Trevor	Ethan
Sensor Research	Matt, Samson, Ethan	Trevor	Ethan
Prior Food Robotics Innovations	Trevor	Ethan	Samson
Material Safety	Trevor	Ethan	
Project Goals, Constraints, Timeline, and Stakeholders	Samson	Trevor	Ethan
Robot Design	Trevor, Ethan, Samson, Matt		
Preliminary Food Testing	Ethan	Matt	Trevor
Gantry Design	Trevor	Ethan	Samson
Bread Distribution	Trevor	Samson	
Cheese Distribution	Trevor	Matt	
Egg Distribution	Trevor	Matt	Samson
Sausage Distribution	Samson, Trevor	Ethan	
Bread Slicing	Trevor	Samson	Matt
Egg Distribution	Trevor	Ethan	
End Effector Design	Trevor	Matt	
Work Surface Design	Trevor, Samson, Matt	Trevor	
System Cleaning	Trevor	Ethan	Matt
Camera Testing	Ethan	Matt	
Broader Impact	Trevor	Ethan	Matt, Samson
Robot Testing	Samson, Trevor	Trevor	
Camera Testing	Samson	Trevor	
Future Work	Samson, Ethan, Matt, Trevor		
Error Detection	Samson	Ethan	
Failure Detection	Samson	Trevor	Ethan
Conclusion	Trevor	Ethan	Matt
Reflections	Ethan, Samson, Trevor, Matt		

Table of Contents

List of Figures

List of Tables

1 Introduction

The use of robotics has incrementally improved the efficiency of the food processing industry since its first introduction in the 1990's by improving redundant pick and place routines (Caldwell 2013). Since then, robots have rapidly established themselves in the food industry worldwide. The introduction of robots has helped to alleviate disease, mishandling, and defects of food that commonly occurred because of human workers. On top of safety and quality concerns, robots have allowed workers to enjoy a more rewarding career in food processing plants, transitioning to jobs in ingredient inspecting and robot maintenance. Enhancements in robotics, material handling and artificial intelligence (AI) have allowed robots to make the jump from food processing and manufacturing to food preparation in recent years. Many restaurants have attempted to increase production and efficiency with the use of robotics, targeting everything from high end dining to the fast-food industry (Caldwell 2013).

This paper details the development of a Breakfast Sandwich Robot for the autonomous food service industry. Designed to make a breakfast sandwich autonomously, the Breakfast Sandwich Robot uses two opposing gantries to actuate spatulas to cook and assemble a traditional sausage, egg and cheese sandwich on an English muffin. As an enclosed system, the Breakfast Sandwich Robot is designed to handle all steps of cooking including the ingredient preparation, cooking, assembly and serving of the food.

The development of the Breakfast Sandwich Robot serves the purpose of demonstrating the opposing gantry technology and its ability to manipulate and prepare food in a more cost effective and efficient manner. The robot's design is centered around creating a breakfast sandwich, however the technology represented within the robot is not constrained to breakfast sandwiches. The team envisions the novel opposing gantry technology to be applicable to a large variety of sandwiches across the food industry.

The report is structured as follows:

Chapter 2: *Literature Review*, this section presents an analysis and synopsis of current robotic automation and limitations within the food industry.

Chapter 3: *Provisional Testing*, an overview of the testing conducted by the MQP team to establish design requirements and criteria for the subsequent design phase of the robot.

Chapter 4: *Robot Design,* this chapter intricately documents the design process undertaken by the team, highlighting major design decisions and challenges encountered.

Chapter 5: *Manufacturing and Assembly*, reviews the methodologies employed by the team in constructing the Breakfast Sandwich Robot.

Chapter 6: *Electronic Hardware,* provides an overview of the electronic hardware utilized in the project, along with key design decisions.

Chapter 7: *Software Controls,* this section offers an in-depth examination of the software controls governing the operation of the robot.

Chapter 8*: Robot Testing,* presents a comprehensive review of the testing procedures implemented to establish performance benchmarks and identify areas where the robot may fall short.

Chapter 9: *Broader* Impacts, examines the broader impact of the project's work and outlines the achievements of the MQP team.

Chapter 10: *Future Work,* suggests potential improvements to enhance the functionality of the system.

Chapter 11: *Conclusion,* reflects on the team's efforts throughout the MQP process and summarizes the overall project experience.

2 Literature Review

The Literature Review explores robotics innovation in the food industry, focusing on material handling, AI, and machine learning advancements. It discusses challenges in handling soft organic materials and highlights innovations in food handling tasks, including picking, placing, cutting, and gripping. Additionally, it addresses safety considerations, emphasizing the use of food-safe materials and cleaning systems. The review also examines sensing technologies for food quality and safety, such as thermocouples, computer vision, and strain gauges.

2.1 Prior Food Robotics Innovations

The future of robotics is often associated with large manufacturing plants, automotive assembly lines or large shipping operations. However, advancements in material handling, AI and machine learning have made robots a powerful asset to the food industry. Applications range from food processing to food preparation. In the future, industry 4.0 will extend to the food industry, transforming how food is manufactured (Hasnan, 218).

Considering current industrial robot implementations and ongoing research within the food industry, the pertinent question is not whether industrial robots will shape the future of food production. Rather it is when this transformation will reach its full potential. To meet customer demands, companies look to increase productivity, efficiency, and quality while reducing costs. Currently, the most effective way to do this is by automating. A survey conducted by Campden BRI in 2017 found 63% of food manufacturers intend to use automation to increase their product and market competitiveness. (Campden, 2017). However, many food manufactures are still not ready to take on the upfront cost of robots. They see their application as being too complicated for the implementation of robots (Bader & Rahimifard, 2018). Before industry sees a mass adoption of industrial robots, the envelope of research must be pushed further, and robots must be developed to be affordable.

There are many challenges that have caused robot implementation in the food industry to progress at a much slower rate. Faraf Bader and Shahin Rahimifard outlined these challenges in their report *Challenges for Industrial Robot Applications in Food Manufacturing*. The most significant challenge comes from the nature of handling soft organic materials. Robots must be capable of conforming to both slick and sticky surfaces of irregular shapes. Any handling errors can cause deformation and bruising, thus affecting the quality of products (Bader & Rahimifard, 2018). Because of these issues, much of the current robot innovation in the food industry is computer vision, AI, and end-effectors. In the case of the development of a breakfast sandwich robot, the end effector refers to the spatula which will be manipulating food.

2.1.1 Food Handling

Current industrial robotics applications in the food industry have been successful because of advancements in material handling. Specifically, material handling innovation is taking place in the robots themselves, end effectors, AI, and Machine Learning.

The IRB 360 Flexipicker from ABB robotics is a great example of innovation in the robots themselves. The IRB 360 Flexpicker has been specifically designed for picking and placing small objects (strawberries, blueberries, apples) as efficiently as possible, achieving 200 picks per minute (ABB Robotics Product Specification, 2018). This robot is an example of a departure from traditional robotic arms and uses a delta robot configuration to optimize speed and dexterity over strength. Fitted with the correct end-effector and paired with machine learning, this robot can be extremely effective in sorting through damaged or rotten berries.

With the deployment of the IRB 360 Flexipicker from ABB robotics, the missing piece in the picking berries example is an end effector that will interact with soft organic objects without bruising of deformation. Food is classified as a solid object under the umbrella of deformable objects. There are two main approaches to safely manipulate solid objects, force readout on each contact face or a prediction model of the deformation that will occur. Detecting forces on each contact surface is often referred to as “tactical servoing”. This process employs force sensors to read contact forces to optimize for pressure acting on the food surface (Sanchez et al., 2018).

To avoid the tactical servoing method, researchers have proposed the prediction model approach; this entailed generating the mesh of a deformable object and performing Finite Element Methods (FEM) to model a gripper's impact on deformable objects (Lin et al., 2015). For most food applications, this is difficult as it requires scanning each part before interacting with it.

Besides picking and placing, robots need to also cut food, a common operation in the meat processing sector. A group of researchers in 2014 were able to use a seven-axis industrial robot to separate beef muscle following a curve that would automatically update its trajectory when in contact with bone (Long et al., 2014). This work that was done in the robotic cutting of soft materials in the early 2010s is now being implemented in industry.

The meat processing sector, an industry with harsh working conditions and unfavorable pay, can greatly benefit from industrial robots. The company RoButcher is developing an autonomous meat factory cell, (a tight collection of robotic equipment that work in unison). The company is looking to develop cognitive thinking and AI tools that will direct an autonomous robot to interact with a carcass. RoButcher is an example of the movement from linear automation to cell-based automation in the food industry, utilizing ABB 6-axis industrial robotic arms (Takacs et al., 2022). Project Coordinator, Alex Mason, describes recent efforts leading to great advancements in custom tooling and cognitive reasoning. The team has developed custom end-effectors, which pair with algorithms to predict the specific incisions that need to be performed based on the changing parameters between each new pig (Robobutcher, 2022).

In the future, the RoButcher robotic cells will carry out all primary steps of pig-slaughtering with industrial robot arms. This includes the cutting of all four legs, the splitting of the carcass and the evisceration process (Alvseike et al., 2020). To accomplish this, the cell also consists of a "motorized carcass handling unit (CHU)" and intelligent cutting and gripping tools (Robobutcher, 2022).

Mark Seaton, from Scott Technology, has been researching robotic solutions in the meat industry over the last decade. He concluded that, "product consistency is the paramount advantage of the implementation of robotic solutions, but shelf life of meat, general food quality and workers' safety can improve as well." He followed up by citing, X-ray based cutting prediction and de-boning with industrial robotics as the future of the meat processing industry (Seaton, 2022).

Figure 1: Flippy (Miso Robotics 2023)

Flippy (seen in figure 1) from Miso Robotics is an example of a six-axis Industrial Robot arm being used in food preparation. Just like RoButcher, Flippy looks to replace a tedious and dangerous job, operating a fryer station. Flippy's contribution is expected to affect 500,000 jobs in the fast-food industry through a combination of improving safety and refining job responsibilities (Zimmer, 2023).

Any robot implemented in the food industry must be specifically designed to handle a kitchen environment. Flippy engineers stated the robotic arm went through many iterations to eliminate exposed wiring, joints, and actuators during development, boasting a custom sleeve that allows the entire robot to be wiped down to meet the NSF (National Sanitary Foundation) standards. Advancements in machine learning have enabled Flippy to make decisions to improve the frier operation, with the ability to optimize workflow and improve its cooking. Flippy leverages a closed feedback loop to teach the robot the perfect time to cook each ingredient in the fryer (Zimmer, 2023).

The adoption of robots in the food processing and preparation industry will play a crucial role in empowering food manufacturers by enhancing traceability and monitoring across all ingredients, processes, and products. These advancements will lead to a reduction in food product waste from supply chain errors, decreasing the price of food for consumers. The largest impact from the introduction of robots in the food industry is in their ability to automate tedious and redundant tasks. Advancements on robotics could not come at a better time, as labor shortages technology increase, automation will become the backbone of the quick service industry.

Preliminary research was central to the Break Fast Sandwich Robots design. The team identified the importance of tactical force feedback, lightweight agile systems and the necessary sanitation practices that needed to be followed.

2.2 Food Safety

With the growing implementation of robots in the food industry, regulations and standards must be updated to account for the changing industry. In the article Current Safety Legislation of Food Processing Smart Robot Systems, Takacs concludes “There is no technically comprehensive standard for agri-food robotics applications, that would cover all safety aspects, and no specific standard that would cover meat industry automation.” The current industry standard is to follow a “minimizing hazards principle,” with the most relevant standard being ISO 10218:2011 which is currently over 13 years old. Some robotic food handling companies find the best practice is to adopt safety standards from the medical industry. With no comprehensive food robot standards, understanding specific materials that are food safe can help ensure safe implementation of robots in the food industry (Takacs et al., 2022).

2.2.1 Food Safe Materials

A comprehensive understanding of materials that can be used within a food robotic system is necessary for the development of a breakfast sandwich robot. The three main material groups involved in the physical robot construction are metals, plastics, and lubricants.

The two most common metals used when autonomously interacting with food are stainless steel and aluminum. Chromium gives stainless steel its high corrosion resistance by forming a protective chromium oxide film on the surface. According to FDA regulations, food contact safe stainless steel must have at least 16% chromium content. Grades SAE 200, SAE 300 and SAE 400 have the correct amount of chromium, making them the FDA-approved choices for use in food preparation (Yorksaw). Stainless steel is the best option for any direct contact with food. Aluminum is often used for non-direct contact where robot manufacturers take advantage of its affordability and ease to fabricate. However, without being coated or anodized aluminum is not ideal for direct food contact. The exact effects of aluminum on human health are not fully understood but ingestion of aluminum can be attributed to the development of breast cancer and Alzheimer's dementia (Austrian Department of Health, 2014). In September 2013, the council of Europe passed a resolution for metals that contact food where specific release limits (SRLs) were detailed for aluminum. The SRL stated that the presence of aluminum contaminate could not exceed 5.00 mg/kg of food (Council of Europe, 2013). Levels of aluminum that approach the SRL limit are often attributed to aluminum additives in food and not food contact with aluminum (Stahl et al., 2017). The addition of heat in robotic systems increases the amount of contact contamination with aluminum. Research done on the use of aluminum foil in cooking can give insight into exposure risks of aluminum at higher temperatures. To reiterate, "Cooking temperature is more influential on aluminum leaching than cooking time, due to the changes of oxide layer from an amorphous to a crystalline structure” (Lamberti & Escher, 2007). A study from Turhan in 2006 revealed that when cooking food enclosed in aluminum foil at temperatures below 160°C, the release of aluminum is significantly slower compared to baking at temperatures exceeding 220°C. From these findings, we can conclude that aluminum is safe for food contact under relatively lower temperatures, but contact should be avoided, when possible, within high temperature environments.

With the absence of heat, plastics make a great food contact material, often being significantly cheaper than stainless steel and aluminum. NSF/ANSI 51-2023 is the standard for plastic materials in food applications. It is established that Acrylic, Acetal, HDPE, Silicon, Duratron, Delrin and Tygon are considered safe for most food applications (NSFApprovedPlasticMaterials, 2024). The accessibility and ease manufacturability of acrylic makes it ideal for our prototype. It is important to note that exposing acrylic to temperatures above 160°F (71°C) for sustained periods, where it can start to soften and potentially release chemicals will negate its food safe properties (Food and Drug Administration, 2023).

Within a robot system motion often requires the assistance of various lubricants. The NSF International certifies food-grade lubricants, maintaining a list of NSF registered lubricants on their website categorizing them as H1, H2 or H3 (sclubricants, 2017). H1 lubricants are designed for use in machinery and equipment where there might be incidental contact with food. They are intended to prevent contamination in case lubricants encounter food during food processing or handling. Within industry, H1 Lubricants are used for various food processing equipment, such as mixers, conveyors, and packaging machinery, to ensure food safety (sclubricants, 2017). NSF H1 certified Lubricants must adhere to strict toxicology parameters and may not contain trace elements of “Carcinogens, mutagens, teratogens, mineral acids or intentionally heavy metals such as antimony, arsenic, cadmium, lead, mercury or selenium” (sclubricants, 2017). H2 lubricants are not intended for direct contact with food. They are used in areas of food processing equipment where there is no possibility of contact with food. These lubricants are suitable for lubricating equipment parts that are inaccessible to food products, such as gears, bearings, and other machinery components (sclubricants, 2017). H3 lubricants are edible oils used for direct food application. They are often used to prevent the sticking of food products to cooking surfaces (NSF, 2021). H3 lubricants are inherently biodegradable and meet FDA 21 CFR 172.860 and 172.878 regulations (FDA, 2016).

2.2.2 Cleaning Systems

When developing automation solutions in food processing and packing, the introduction of contaminants into the food must be avoided. There are many cases where companies were fined, or even criminally charged by the CDC due to outbreaks caused by carelessness in their cleaning systems. There are two leading causes of bacteria entering a cooked food product: cross-contamination of ready-to-eat food from contact with uncooked food, and improper temperature control (ABB, 2014). Although these are the main contamination avenues, contamination can occur at any point. The Hazard Analysis and Critical Control Points (HACCP) is a systematic approach which can be used to reduce the risk of these (Herrera, 2004). Another way to mitigate contamination from “foreign bodies” is by replacing human operators with robots in food processing and packaging. There are many benefits to this approach: the tasks are very repetitive making it suitable for robots there is a lower risk of human injury, and there is a lower risk of contamination from foreign bodies.

Many automated systems use Clean-In-Place (CIP) systems, which allow for automatic cleaning without the disassembly of the machine. These cleaning systems rely on the principles of TACT – Time, Action, Chemical, and Temperature and was introduced by Herbert Sinner in 1959 (Ohlsson 2012). These considerations are essential for effective cleaning of any kind of system. Adequate time is needed to allow the cleaning method to effectively work. There must be an effective type of action often a movement from pressurized liquids or gases to remove contaminants. The cleaning must consist of suitable “chemicals” that account for appropriate pH level to avoid corrosion within the system, while effectively removing contaminants. Finally, the cleaning method must be at an adequate temperature to work without damaging the rest of the system, while still being hot enough to sterilize the system. Many systems adopt implementing Steam-In-Place (SIP) systems following CIP. The benefit of this is that it allows for additional sterilization as it kills any remaining microorganisms, making it suitable for pharmaceutical and food and beverage systems.

2.3 Sensor Feedback

This section reviews sensors (Thermocouple, Computer Vision, Stain Gauge) that were critical to the robot design, responsible for providing close loop feedback to the robot.

2.3.1 Thermocouples

Measuring temperature is critically important in the food industry to avoid the spread of food borne illness. According to the Food Safety and Inspection Service (FSIS), eggs and ground meats should reach a minimum internal temperature of 160°F (71.1°C) to prevent foodborne illness (FSIS, 2020). To ensure that our sausage and eggs are cooked properly, thermocouples are used to regulate the worksurface temperature. There are eight thermocouple categories, each has distinct temperature ranges and accuracies as shown in appendix B.

2.3.2 Computer Vision

Alignment of the ingredients is instrumental to consistently assembling a breakfast sandwich by reducing variation in ingredients center positions during sandwich stacking. Computer vision is commonly implemented to properly align parts in assembly environments. In a recent study, Chi Zhang demonstrates the use of a monocular vision system to align parts via the center-point of the desired placement location (Zhang, 2019). Assembly of the breakfast sandwich ingredients will use a similar approach. The robot uses computer vision and linear actuation along the z axis to align ingredient center points.

2.3.3 Strain Gauge

A sensor to measure weight can confirm that the spatula successfully picked up an ingredient. The team came up with two different approaches, a strain gauge and a flex sensor. Flex sensors were ruled out as it was necessary to place them directly on the spatula with potential exposure to heat. Instead, a strain gauge is placed on the spatula shaft, reducing heat exposure. Several types of strain gauges exist, with resistive strain gauges being the most common in robotics. These gauges change resistance as they deform, a phenomenon quantified using the gauge factor. Strain gauges operate by converting the change in length due to the strain to a resistance at a factor known as the gauge factor. The gauge factor is characterized by the formula:

$$K = \frac{\frac{\Delta R}{R}}{\frac{\Delta L}{L}}$$

where R is the resistance of the strain gauge, and L is the length of the strain gauge. To interface with a microcontroller, one can use a Wheatstone bridge to convert the changes in resistance into usable voltages read by an analog to digital converter (ADC). In turn, the HX711 ADC converts voltages to binary, communicating with the ESP-32 microcontroller which reads the binary output and converts the strain to a weight in kg.

In conclusion, this chapter has provided an in-depth exploration of prior innovations in food robotics, highlighting the transformative potential of robotics in the food industry. From advancements in material handling to the integration of AI and machine learning, robots are reshaping food processing and preparation tasks. However, challenges such as handling soft organic materials and ensuring food safety remain significant considerations. Moving forward, the following chapter will delve into the significance and objectives of the project.

3 Project Significance and Objective

Labor is the largest expense for the quick service industry, an expense that is growing as labor shortages drive up wages. There were “800,000 less workers in October 2021 than there were in February 2020” in the quick service industry (US Department of Labor). This is a trend that has continued outside the covid bubble, with Bloomberg reporting, “three years after Covid hit the US, the $900 billion US foodservice industry still can’t recruit enough employees (Patten 2023).”

Automation may serve as the solution to the increase in staffing shortages that continue to plague the industry. Implementation of automation at a cost and complexity that can be accessible to the industry is currently limiting the implementation of robots throughout the food industry. This project's purpose was to pursue automation with reduced complexity to provide technology that can be used in the quick service food industry.

Project Goal:

The goal of the Breakfast Sandwich Robot is to explore an opposing gantry approach to food automation through the development of a robotic protype that autonomously prepares breakfast sandwiches.

Project Constraints:

Adhere to Code of Federal Regulations and the FDA's official guidance documents below
FDA Title 21 CFR Part 110 (Good Manufacturing Practices) FDA Title 21 CFR Part 120 outlines HACCP (requirements for certain types of food processing). FDA Title 21 CFR Part 1, Subpart O (sanitary transportation) Title 21 of the Code of Federal Regulations (CFR) Part 174-186 (food contact substances).
Financials
Stay within the $1,500 budget for prototyping breakfast sandwich automation technology. Adhere to an estimated $81,000 commercial development price per unit under scaled manufacturing. (See Appendix C)

Project Stakeholders:

This project adheres to many stakeholders, for instance potential investors, especially from the fast-food and quick-service industry. It is also being evaluated by Major Qualifying Project (MQP) judges. In addition, potential buyers of the robot and customers interested in the sandwiches it produces are significant stakeholders shaping its development and adoption. Collaboration among these parties is essential for the project's success (as described in table 1).

Table 1: Project Stakeholders

Breakfast Robot project team	Pradeep Radhakrishnan, Fiona Levey, and Bo Tang
WPI	MQP judges
Potential investors	Potential purchasers of the robot
Fast Food / Quick Service Industry	Potential customers of the sandwich

High Level Project Requirements:

- Autonomously Prepare Breakfast Sandwich in 6 min.
- Abide by all FDA food standards.
- Cost Effective Solution

Project Timeline Breakdown:

The Breakfat Sandwich Robot project can be split into three phases.

- preliminary testing and design
- construction and fabrication
- Robot Testing and Demonstration

The Breakfast Sandwich Robot MQP project spanned over four 7-week terms, distinguished as A, B, C and C. A term was reserved for early preliminary testing and robot design, the team developed the initial high level conceptual design of the robot. During this period the gantry and frame of the robot was also fully designed. B and C terms were a mix of fabrication, design and redesign. To ensure all members were able to work as effectively as possible, an effort was made to construct the gantry system as early as possible, creating a physical testing apparatus for the software and electronic components of the project. The first major milestone was the end of term B where the team demonstrated a gantry moving and receiving a sausage from the sausage distribution system. Throughout this period, the team followed a process of design, analyzing, build, test and rebuild. D term consisted of more design and fabrication as well as significant testing and trouble shooting.

4 Preliminary Food Testing

During the team's research, it was found that there was a lack of data on the exact food preparation, cooking, and assembly methods that the team sought to employ. Due to this, the team ran tests on the specific ingredients and their interactions with materials that would be imperative to the breakfast sandwich robot. The team caried out the following tests to:

- Determine the force required to slice through cheese
- Determine the force required to slice through English muffins
- Observe crumb creation during bread slicing
- Observe food interaction with stainless steel surfaces
- Understand spatula interactions with ingredients
- Observe egg cooking methods
- Observe sausage cooking methods
- Observe bread toasting methods

All these tests helped formulate the design criteria of the subsystems and account for potential failure modes.

4.1.1 Testing the force required to slice through cheese:

The design process of the cheese slicing method was initially narrowed down to a wire cutting system that is commonly used by cheese cutting boards as it is the easiest to maintain, clean and fixture to an apparatus. The use of a knife or grated cheese were the two other designs that were considered but were ultimately not pursued due to their difficulty cleaning and maintenance issues. The only maintenance the wire required would be a replacement in the event it snaps. The team tested the use of a standard cheese slicing wire of 24-gauge stainless-steel wire to slice through a block of cheese with a width of 2.5 inches to validate that the wire would work with the required cheese block size.

The procedure consisted of:

1. Removing the cheddar cheese directly from the refrigerator and placing it on a scale.
2. Passing the wire through the cheese while maintaining constant tension in the wire.
3. Measuring the reactionary force on the scale.

The required Materials:

- Chedder Block with a 7.62cm cross sectional width

- 24-gauge stainless-steel wire
- Food Scale
- Fridge

The resulting force from our test was 25.48831 N. This experiment pictured in figure 2 proved that it is possible and effective to cut cheese with stainless-steel wire. The cheese distribution system was then designed around the use of steel wire to slice the cheese as seen in the section Robot Design under the subsection cheese distribution.

Figure 2: (left) Cheese Slicing with Stainless Steel Wire (right) Pre-Experiment Configuration

4.1.2 Testing the crumbs created from an English muffin versus that of a bagel

Bread was a challenging ingredient for manipulation in a proposed system. If using a pre sliced English muffin or a bagel, the distribution becomes more complicated, and the bread can become damaged as you try to separate the two halves. A main complication when distributing pre-sliced bread would be jamming. When using unsliced bread, more crumbs are introduced into the system which requires a more thorough cleaning system to remove the debris. Initially, the team worried that introducing too many crumbs to the system would become a large issue and would increase the difficulty of cleaning the worksurface. To combat this, the team visually tested the number of crumbs that slicing either an English muffin or a bagel would create.

The procedure consisted of:

1. Placing an uncut English muffin on a white plate
2. Slicing with a knife

3. Separating the two halves
4. Repeating with an uncut bagel

The required materials:

- 1 uncut English muffin
- 1 uncut bagel
- Kitchen knife
- 2 white plates

Figure 3: Qualitative Crumb Distribution Test

After a visual analysis of the two plates shown in Figure 3 (English muffin on the left and bagel on the right), it was found that both ingredients produced a reduced quantity of crumbs than what was envisioned after being sliced. The team factored this into the design of system cleaning, but the test was not particularly helpful in the choice between English muffins and bagels as the ingredient of choice (as discussed in subsection 5.6 Bread (English Muffin) Distribution and Slicing). Further testing as described in subsection XX helped the team determine which of the two options to use.

4.1.3 Testing the food interaction with stainless steel surfaces and spatula ingredient interaction testing

The food safety findings (as discussed in section 2.2) lead the team to choose stainless steel as the work surface of the robot. It was necessary to perform tests to see how each ingredient interacted with the spatulas and work surface when being manipulated. These tests were run to better understand how the ingredients moved as they were manipulated by the spatulas.

The procedure consisted of two stages: Preparation and Conducting tests.

The sequence of steps involved during the Preparation phase were:

1. Slice and toast interior of the bagel
2. Slice and toast interior of the toast English Muffin
3. Cook sausage
4. Set T square perpendicular to table side, attach stainless steel spatula surface to T square
5. Set up camera to record top view

Three tests were conducted and are explained below.

Test 1:

1. Place each ingredient on the test rig
2. Begin recording
3. Move spatula 40cm (about 1.31 ft)
4. Visually measure ingredient center deflection from center line.
5. Repeat for all ingredients

Test 2:

1. Tape the second stainless-steel spatula on centerline, 10cm from the starting position of the initial spatula.
2. Manually actuate the test rig until the ingredient has been placed onto spatula
3. Take qualitative note of the interaction between the ingredient and the spatula
4. Repeat steps 11-12 but raise the spatula at a 5-degree angle.
5. Take qualitative note of the interaction between the ingredient and the spatula
6. Repeat for all ingredients

Test 3:

1. Tape spatula to food scale
2. Place food scale on its side
3. Clamp ingredient with enough clamping force to hold it in position
4. Slowly let up clamping force until ingredient falls.
5. Note the final load on the ingredient before it drops.
6. Repeat steps 19-21 for each ingredient.

The required Materials:

- 1 sausage patty
- 1 bagel
- 1 English muffin
- Two stainless steel spatulas
- Tape
- Spatula wedge

- T square
- Marker
- Tape measure
- Camera

In test one set up as pictured in figure 5, the team did not notice significant final change on center orientation due to the ingredient oscillation throughout its travel. However, a visual analysis of how the ingredients moved as the spatula actuated them was observed. The bagel had the firmest exterior with the most deformities, which caused it to drift more than that of the sausage or the English muffin. In test two set up as pictured in figure 4, the English muffin was able to be easily slid onto the spatula on both its face and exterior without binding. The bagel could easily slide onto the spatula on its exterior with minimal deviation, but when slid on its cut face it would often experience binding on the lip of the spatula causing irregular springing motion, sending the bagel off center. The sausage was easily able to slide onto the spatula. The 5-degree angle of elevation positively impacted how the ingredients slide onto the spatula. When working with the bagel on its cut face the irregular motion was nearly eliminated but still experienced deviations of the center axis. Test three was unable to be conducted while properly measuring the force exerted on the spatulas. The results from these tests were crucial for understanding the internal mechanics of food manipulation inside of the robot, leading the team to choose an English muffin as the bread of choice for the breakfast sandwich robot.

Figure 4: Spatula Interaction with Food Test Set Up

Figure 5: Spatula Food Interaction Testing

4.1.4 Bread Toasting Methods

The team tested various cooking methods to understand their relative efficiencies quantitatively and qualitatively, observing how the flavor and texture affected the product. The methods that the team sought to employ to test cooking the bread with were broiling, 'air frying' in a convection oven, and toasting in a pan using direct heat.

The procedures consisted of:

Test 1: Broiling
1. Preheat toaster oven on broil setting
2. Place English muffin slice side up 2 inches from the broiler
3. Record amount of time required for a golden-brown toast

Test 2: Air frying
1. Place English muffin in air fryer
2. Bring to 400°F
3. Record amount of time required for a golden-brown toast

Test 3: Frying pan
1. Preheat skillet to a high surface temperature
2. Place English muffin face side down on the skillet
3. Intermittently flip to check for golden-brown toast
4. Record amount of time required for a golden-brown toast

The required Materials:
- 3 English muffins
- 1 air fryer
- 1 skillet
- 1 kitchen stove
- 1 Toaster oven with broil setting
- 1 Timer

Toasting under the broiler took 4 minutes and 44 seconds and resulted in a crunchy exterior with a warm soft interior. Toasting in the air fryer took 2 minutes and 8 seconds and had similar results to the broiler, with the only noticeable difference being that the bottom also achieved a pleasant crunch. Toasting in the skillet took 2 minutes and 23 seconds, resulting in the cut part being crunchy and golden brown however lacking uniform temperature throughout.

4.1.5 Testing egg cooking in silicone baking molds

A variety of tests were run to both qualitatively and quantitatively test different egg cooking methods. The team explored the use of whole or pre-scrambled eggs under different cooking methods. Original tests were run using silicone baking molds to contain the eggs.

The procedures consisted of:

Test 1: Silicone

1. Line the center two slots of the silicon baking mold with canola oil, the far-right slots with olive oil and the far-left slots stay unlubricated.
2. Crack one whole egg into the font silicon slot with canola spray.
3. Crack one whole egg into the front slot without spray.
4. Crack one whole egg into the slot with olive oil.
5. Repeat steps 2-4 with the scrambled eggs and the back slots.
6. Place in oven at preheated 190.556°C toaster oven on broil until internal temperature of 73.8889°C
7. Record time and remove from oven
8. Flip to remove eggs from silicone baking mat
9. Check to see if egg came out in one piece and a uniform shape
10. Qualitatively test taste and texture

Test 2: Poaching

1. Bring a pot of water to a just below a boil (82.2222-87.7778°C)
2. Place scrambled eggs into singular silicone baking mold
3. Lower eggs into water slowly and begin timer
4. Remove once internal temperature reaches 73.8889°C
5. Record time
6. Qualitatively test taste and texture

Test 3: Air fryer

1. Scramble eggs and place them in a baking mold
2. Place baking mold into an air fryer heated to 204.444°C
3. Cook until internal temperature reaches 73.8889°C
4. Remove and measure internal temperature
5. Qualitatively test taste and texture

Test 4: Pan Frying

1. Scramble eggs and place them in a small stainless-steel pan
2. Placed on electric griddle at 176.667°C
3. Cook until internal temperature reaches 73.8889°C
4. Remove and measure internal temperature
5. Qualitatively test taste and texture

The required Materials:

- 8 whole eggs
- Olive oil
- Canola oil cooking spray
- 1 toaster oven
- Silicone baking mold with 3-inch diameters
- Pot with heating source
- Water
- 1 air fryer

Cooking the eggs on the silicone baking mat as shown in figure 6 under the broiler took 11 minutes and 27 seconds for the whole egg and 9 minutes and 56 seconds for the scrambled egg. The texture of the scrambled egg was fluffy and flavorful, the whole egg had a tacky texture, and was deemed to taste subjectively worse. Removal test caused the whole egg to crumble and stick to the silicone during removal from the baking mold as pictured in figure 7. The scrambled egg removed in one piece and did not leave anything in the baking mold. With how poorly the whole egg cooked and its inability to stay in one-piece, scrambled eggs were chosen as the type of egg going forward in testing. From there, the egg was tested in a similar routine in a silicon poaching cup as pictured in figure 8. The egg could be cooked in 4 minutes and 32 seconds, making it the most time-effective method yet. The egg produced had a denser texture than that cooked in the broiler, with a wet tacky exterior texture. The egg cooked in the air fryer took 8 minutes and 42 seconds to cook. The texture that was produced was like that of the egg cooked under the broiler, but also took less time. Cooking the scrambled egg on a pan placed on a griddle with a cover provided the best overall results as pictured in figure 9. With a 3:20 cooking time for a subjectively “tasty” egg, the panfried egg was picked as the final method.

Figure 6: Egg Cooking Test Before Oven

Figure 7: Egg Cooking Removal Results

Figure 8: Egg Poaching Test

Figure 9: Pan Fry Scrambled Egg

4.1.6 Testing sausage cooking methods

The team chose pre-cooked sausage patties from Jimmy Dean as the preferred choice of sausage, recognizing raw meat to be outside the scope of the project. The sausage was tested on similar metrics of the above egg test. The team was specifically observing the Maillard reaction that occurs when cooking meat (browning) in a high heat environment, increasing the flavor (Tamanna and Mahmood, 2015).

The procedures consisted of Broiling, Pan frying, Air Frying and are detailed below:

Test 1: Broiling

1. Preheat a toaster oven to 190.556 °C on the broil setting
2. Place refrigerated sausage patties on a baking sheet
3. Place the baking sheet 2 inches from the broiler
4. Time until 165°F internal temperature and remove
5. Visually inspect for browning and test taste

Test 2: Pan frying

1. Preheat a skillet to medium high heat ~204.444°C
2. Cook sausage, flipping intermittently
3. Time until 165°F internal temperature and remove
4. Visually inspect for browning and test taste

Test 3: Air frying

1. Place refrigerated sausage in an air fryer basket
2. Place basket in air fryer and heat to 204.444°C
3. Time until 73.8889°C internal temperature and remove
4. Visually inspect for browning and test taste

The required Materials:

- 3 sausage patties
- 1 toaster oven
- 1 baking sheet
- 1 stainless steel skillet and heating source
- 1 air fryer
- Electric griddle

When cooked under the broiler, the sausage took 7 minutes and 14 seconds. The side facing the broiler achieved a nice brown coloration while the underside remained pale, a ring of grease was left around where the sausage sat. When cooked in the skillet the sausage took 2 minutes and 21 seconds. Both sides of the sausage were able to achieve a good brown coloration, but there were lots of residue left on the pan which was subsequently difficult to remove. When cooked in the air fryer the sausage took 6 minutes and 30 seconds. Like the broiler, the top was able to achieve a nice brown coloration and crisp texture while the bottom was mostly pale leaving behind a ring of grease. Cooking the sausage in the pan left the most difficult mess to clean up, but regardless a cleaning procedure will need to be implemented to remove the grease buildup from the system regardless of the method of sausage cooking. To help combat this, the sausage dispensing unit was designed to be easily disassembled by hand and cleaned, while the worksurface will be easily wiped down by hand.

4.1.7 Testing the force required to slice through English Muffins

After deciding to use English muffins (as discussed in section 4.1.3) as the bread for the sandwich, tests on slicing methods were performed to develop design requirements for the bread slicing device. After the success of slicing cheese with steel wire, the team wanted to test the possibility to use it to slice the bread. Additionally, the use of a straight edge knife was tested. The team decided against testing the use of a serrated knife as the reciprocating motion would add to the complexity of the bread slicing apparatus.

Test 1: Steel wire

1. Vertically place English muffin on the scale and stabilize as pictured in figure 10
2. Calibrate the scale
3. Run wire through the English muffin vertically from the top towards the scale
4. Record maximum force registered on the scale

Test 2: Knife

1. Vertically place English muffin on the scale and stabilize as pictured in figure 11
2. Calibrate the scale
3. Run knife through the English muffin vertically from the top towards the scale
4. Record maximum force registered on the scale

The required Materials:

- 2 English muffins
- 24-gauge stainless-steel wire
- Sharp kitchen knife
- Kitchen scale

The resulting force of using the wire to cut the English muffin was 10.764696 N and the resulting force of using the knife to cut the English muffin was 12.721914 N. This test showed the feasibility of using a wire slicer which will be easier to fabricate and mount than a knife.

Figure 10: English Muffin Slicing with Wire

Figure 11: English Muffin Slicing with Knife

5 Robot Design:

The design chapter follows the team's progress of designing the opposing gantry and distribution technology with the goal of preparing a breakfast sandwich.

5.1 Gantry Design

Current approaches to automating food preparation have fallen into two categories, food preparation with industrial robotic arms and assembly line food preparation systems. Companies such as miso robotics are developing robotic arms that can emulate human workers, for the most part these arms are operating grills and fryer stations. Assembly line systems consist of large conveyor belt strategies and are designed to make pizzas, salads, and burgers.

Industrial robotic arms in food preparation have inherent flaws. Attempting to emulate human employees through industrial robotic arms means building a robot for an environment initially designed for humans. Fast food restaurants have spent millions of dollars in research and development of optimized kitchen environments. These environments have been specifically designed for human workers. Now robotic companies are working to develop robots to work in these spaces instead of developing optimal workspaces for robots.

The other approach of "assembly line" robotic food preparation has been applicable to only a few food categories, held back by its low versatility and large upfront expense. Mimicking a traditional Rube Golberg machine these robots have many complex parts that are expensive to manufacture at scale and maintain. An example of these "assembly line" Robots can be seen in figure 12 below, where creator, formerly Momentum Machines, has developed a conveyor system that prepares burgers.

Figure 12: Burger Robot from Creator

The industry needs a third approach to food automation technology with all the versatility of robotic arms without the cost and complexity. By leveraging gantry technology that has been developed for 3D printers and CNC routers our robot is developed with the versatility of Industrial Robot arms at a lower price and complexity. The preparation environment has been redesigned specifically for robots rather than humans. Opposing two gantries increases the robot's control, employing separate end effector interaction techniques, enabling the robot to manipulate food items with high levels of dexterity. This creates a large advantage over companies such as Creator who rely on gravity fed systems coupled with an arrangement of conveyor belts and distribution systems.

The following gantry Requirements have been outlined to prepare a breakfast sandwich within 6 minutes chosen based on the cook times of each ingredient found in preliminary testing, a time that drops drastically with assumptions of precooked ingredients and preparing multiple sandwiches at the same time.

- Assert 20 N of force in the x direction.
- Assert 20 N of force in the y direction.
- Achieve a max acceleration of 0.3m/s^2.
- Achieve a max velocity of 0.5 m/s.

The requirements were chosen based on spatula manipulation testing described earlier as well as the time requirements. With the gantry functional requirements and criteria outlined, a decision matrix was used to evaluate different gantry design approaches (see table 2). Rigidity was weighted at an importance of 20% due to the lack of external vibrations and loads within the system. Affordability was rated at 80% due to budget constraints. Complexity was weighted at 50% as chances of failure as well as manufacturing complexity increase. Speed was weighted at 40% as the size of the gantries are under 1m in all directions. Accuracy and precision were weighted at 70% for the precision pick and place actions. Contamination risk was weighted at 50% as the FDA food safety requirements were an overall requirement of all subsystems. The reasoning for each score is described in table 3 and is on the scale from 1 being unfavorable to 10 being favorable.

The Core x-y belt with idle pulley design uses a coupling of two motors to drive a gantry. A ball Screw method involves three motors driving screws to linearly actuate the gantry in two dimensions. A traditional belt drive would be configured similarly to a ball screw approach but use belts instead. A Hybrid system would be a combination of belts and ball screws. Other approaches that were disregarded due to implementation concerns would be a rack and pinion approach or some combination of rack and pinion with other design approaches.

Table 2: Gantry Design Matrix

Belt Drive		Design Ideas			
Design Criteria	Weight (Importance 0%-100%)	Core x-y	Ball Screw	Traditional Belt Drive	Hybrid system
Rigidity	20%	3	10	4	7
Affordability	80%	9	3	5	4
Complexity	50%	7	7	7	6
Speed	40%	8	2	8	4
Accuracy & Precision	70%	6	9	6	4
Contamination Risk	50%	8	2	6	4
TOTAL		22.7	16	18.7	14

Table 3: Gantry Design Matrix Reasoning

Design Matrix Reasoning					
Design Criteria	Weight (Importance 0%-100%)	Core x-y	Ball Screw	Traditional Belt Drive	Hybrid system
Rigidity	Rigidity is not highly important; the robot will experience small external loads and vibrations.	Belt drive systems have poor rigidity, core x-y also have longer continued belts.	Ball Screws have high rigidity.	Belt drive systems have poor rigidity.	There will be poor rigidity in a singular axis.
Affordability	The development of this technology is for commercial viability. Cost must be accounted for.	Core XY requires one less motor than other systems and overall cheaper manufacturing and implementation.	Ball screws have high manufacturing and material costs.	Requires additional motors of each gantry.	Requires additional motors of each gantry.
Complexity	Complexity drives up cost, Manufacturing time and modes of failure.	Complexity was quantified by the number of parts and their manufacturability.	Complexity was quantified by the number of parts and their manufacturability.	Complexity was quantified by the number of parts and their manufacturability.	Complexity was quantified by the number of parts and their manufacturability.
Speed	The speed of the gantry will dictate the time to cook a breakfast sandwich.	Belt Drives provide faster actuation.	Lead Screws are slow to actuate.	Belt Drives provide faster actuation.	Lead Screws are slow to actuate.
Accuracy & Precision	Accuracy is important, but not within more than +/- .5mm	Belt Driven systems use Kevlar backing to comeback stretching, improving precision.	Ball Screws experience play is extremely accurate.	Belt Driven systems use Kevlar backing to comeback stretching,	Hybrid system will only have the accuracy of both systems.

				improving precision.	
Contamination Risk	With any robotic food preparation, contamination must be accounted for.	Belt Drive requires no lubricants.	Lead Screws require lubricants that could potentially contaminat e food.	Belt Drive requires less lubricants.	Hybrid system will still require some lubricants

5.1.1 Gantry Motor Sizing

The appropriate specifications for the motors and belts to drive the gantry were extracted from the functional requirements previously outlined. A MATLAB simulation was developed to calculate the tension force within the belts and motor torque necessary to meet the functional requirements given specific gantry travel paths, acceleration, and final velocity (See Appendix A for calculation code). The following basic equations are used to govern the physics of gantry motion.

Newtons Second Law (F = Force, m = Mass, a = Acceleration)

$$F = m * a$$

Coefficient of Friction (f = Friction Force, μ = Coefficient of Friction, N = Normal Force)

$$f = \mu N$$

Vector formulation for Torque (τ = Torque, r = radius, F = Force)

$$\tau = r\ x\ F$$

These calculations found a necessary operating torque of 0.17Nm at 530rpm based on a predetermined position, acceleration and velocity shown below in figures 13, 14, 15, and 16.

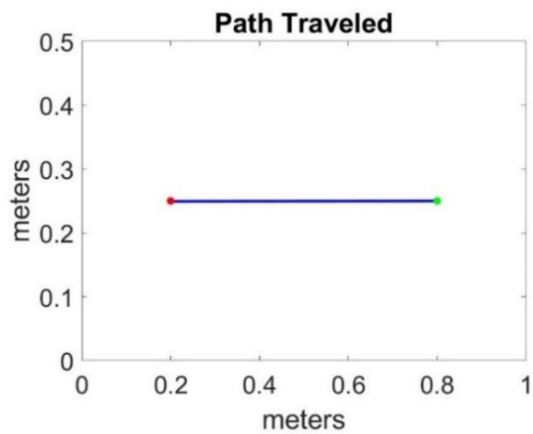


Figure 13: Path Travel Input MATLAB Sim

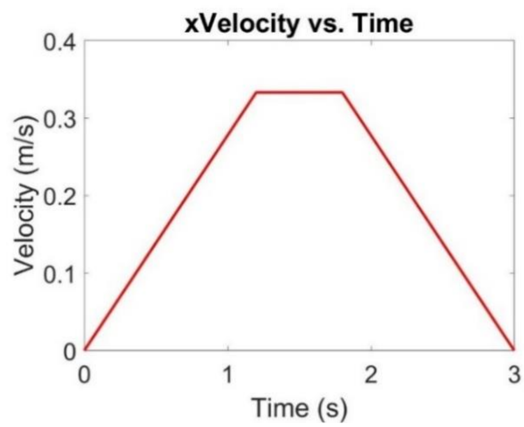


Figure 14: Velocity Profile Input MATLAB Sim

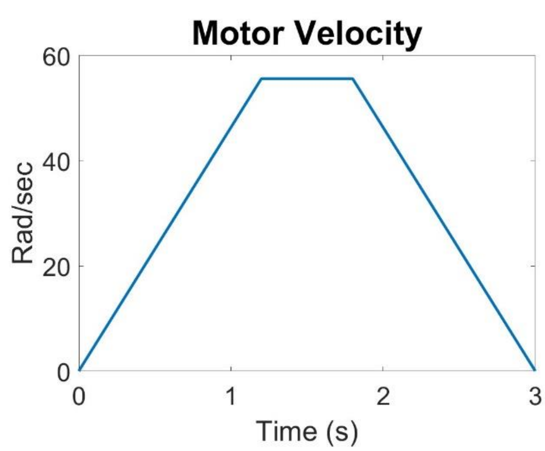


Figure 15: Required Individual Motor Velocity Output MATLAB Sim

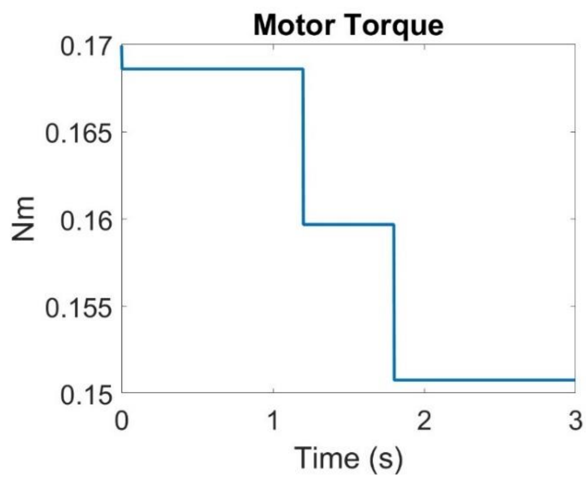


Figure 16: Required Individual Motor Torque Output MATLAB Sim

When these results were compared to a stepper motor torque-speed curve, it was found that the Gantry required a 2phase 2Amp 57mm NEMA 23 stepper motor to adequately meet the torque and speed specifications that abided the functional requirements of the gantry design.

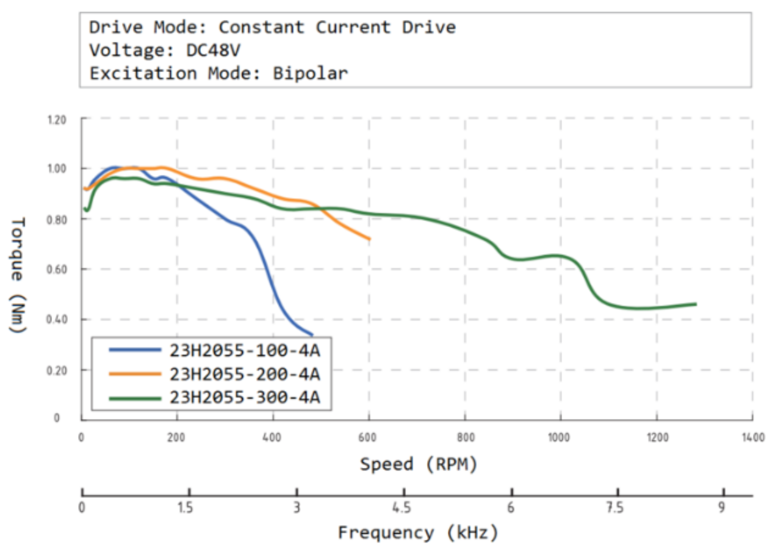


Figure 17: 2phase 2Amp 57mm NEMA 23 stepper motor torque-speed curve (NEMA 23 2phase 2Amp 57mm — DINGS' Motion USA)

5.1.2 Gantry Frame and Linear Motion

The design process prioritized utilizing existing materials, opting for 8020 aluminum extrusion due to its ease of manufacturing, assembly, and widespread availability. Its design has extrusion extending past the end of both the largest sides to mount the gantries which is pictured in figure 18. This choice facilitated modular integration of each subsystem into the frame with an approximate open 0.3x1m of total space, streamlining both the design and assembly processes. Moreover, it offered flexibility for future iterations and modifications to the robot design.

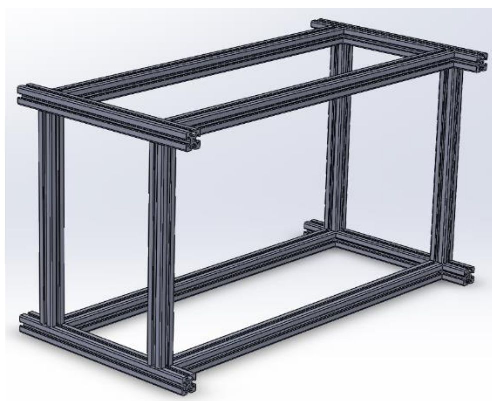


Figure 18: Robot Frame From 8020 Extrusion

Two approaches were examined for gantry linear motion: linear rail, and linear motion shafts. Linear rails were found to be outside the project budget so linear shafts were chosen. However linear rails would be considered a commercial protype due to their increased rigidity. The gantry design using linear motion shafts is pictured in figure 19.

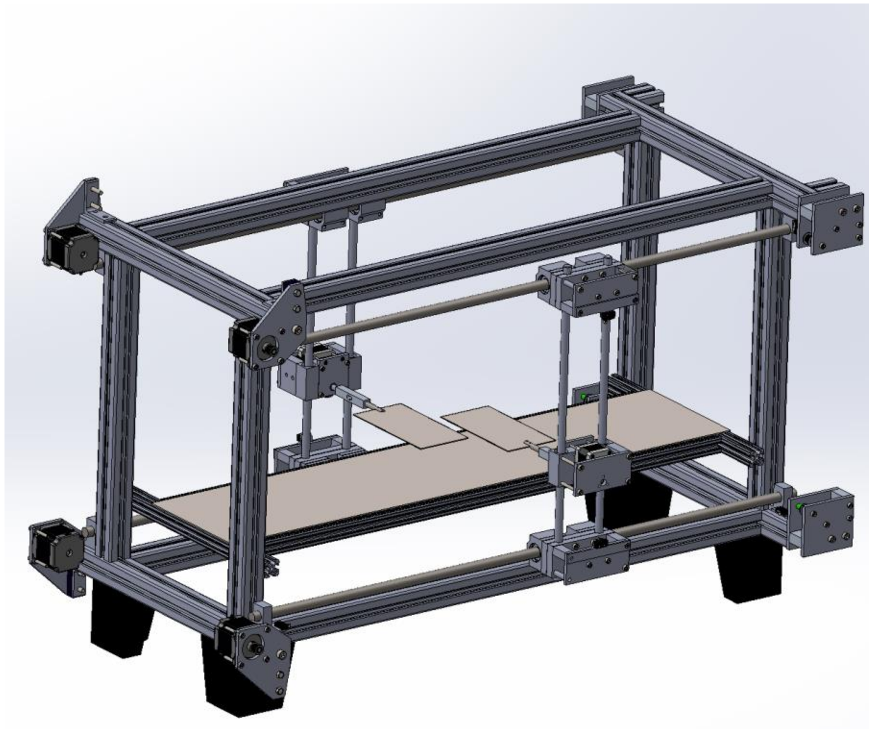


Figure 19: CAD Rendering of Gantry Design

NEMA 23 Motor mount plates were designed to be laser cut from 1/4in acrylic sheet, accept a vibration dampening TPU spacer and then be bolted to the frame as shown in figure 20. This would be replaced by an aluminum bracket within a commercial application.

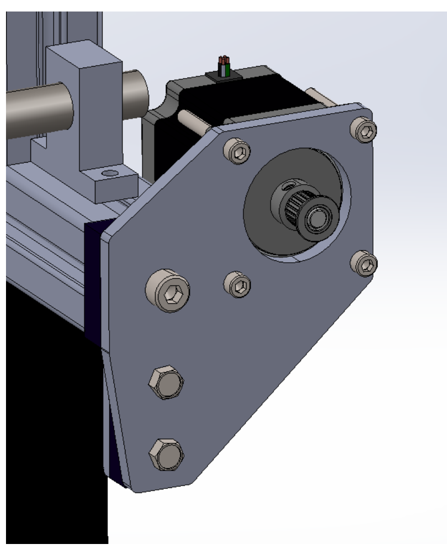


Figure 20: NEMA 23 Motor Mount CAD Rendering

The corner pulley brackets were also designed and constructed from 3D printed spacers and acrylic sheets, however within a commercial application they would be supported by aluminum brackets. The bracket housing served the purpose of supporting the pulley axel from both sides, ensuring pulley alignment across the gantry. The pulley axel is a number 10 machine screw, which creates a tight screw clearance fit on the 5mm ID of the pulley bearings reducing slop on the rotational axes. Plastic spacers of 1mm and 10mm in thickness were used to hold the pulley aligned with the belt on the system shown in figure 21. This design facilitated easy adjustments of belt tension to a predefined level. By loosening the top two mounting screws, applying a 70N on load, and then retightening the screws, uniform belt tension is achieved. This method ensures consistent belt tension and is particularly suitable for 10mm GT2 timing belt configurations.

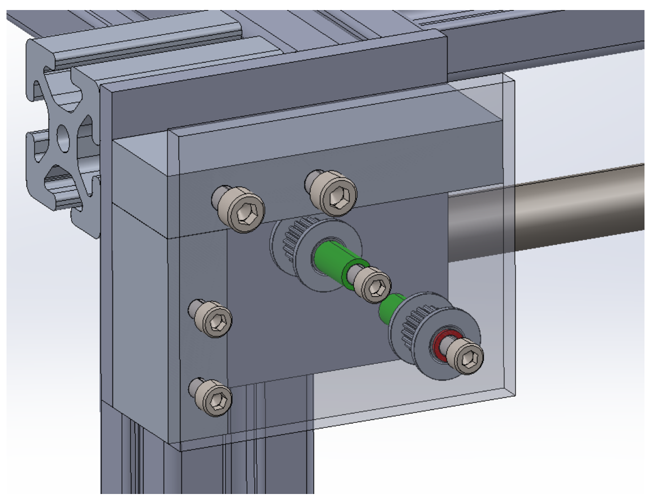


Figure 21: Corner Pulley Brackets CAD Rendering

The Y-axis alignment mount shown below in figure 22 is designed to align and clamp the Y-axis shafts perpendicular to the x-axis while coupling them to the motion of the X-axis by sandwiching the shafts with two machined aluminum blocks. 3D printed spacers and acrylic plates are then used on the back of the alignment mount to support the belt pulleys in the same manner as the corner pulley brackets. A limit switch is mounted to the bottom of the Y-axis alignment to act as the homing feedback in the y direction.

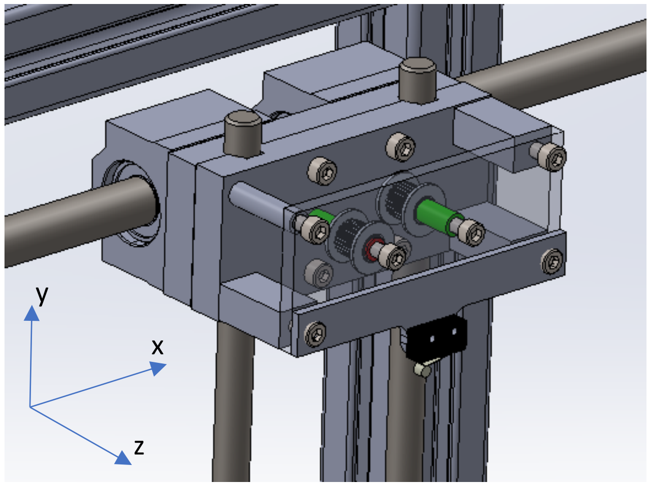


Figure 22: Y Axis Alignment Mounts CAD Rendering

5.2 End Effector Design

The robots utilized two gantries to manipulate food using spatula end effectors. Throughout the development process, the team explored various approaches to enhance system versatility. Initially, we aimed to implement a tool change mechanism at one gantry's end to enable autonomous attachment of cups for cooking eggs and other cleaning attachments. However, after evaluating numerous design options, it became apparent that this feature exceeded the scope of the current project. Consequently, the decision was made to handle egg cooking separately from gantry motion.

Instead, the team focused on a key modification between the two gantry end effectors: integrating a load cell into one of them. This load cell served dual purposes. First, it enabled the robot to detect the presence and identity of items on the spatula by mapping their weight. Second, it provided force feedback during item clamping with the two spatulas. This feedback mechanism, essential for tasks such as picking up and flipping items, involved the spatulas exerting pressure on each other until the load cell registered a predetermined value.

In the subsequent section, we will delve into the challenges encountered during the spatula change process before examining the design decision-making process behind the current spatula end effectors utilized by the robot.

5.2.1 Utensil Change

The following Functional requirements were developed to govern the development of an end effector (utensil) changing apparatus:

- Change utensils in under 10 seconds.
- Utensils experience less than 3 degrees of deflection under max load.
- Transfer rotational motion through utensil changing mechanisms.
- Materials in accordance with FDA and USDA standards (non-contact food safe).

The following three design approaches were considered in the development of the utensil changer.

CNC automated tool changer using a Bridgeport taper (BT) tool shank found in the manufacturing industry pictured in figure 23. In this design the utensil would change using pneumatics as a clamping force on the utensil shaft.

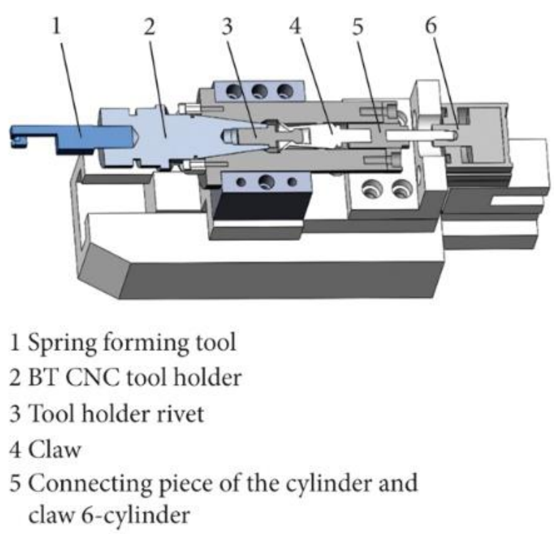


Figure 23: CNC Automatic Tool Changer Mechanism (Wang & Cheng, 2020)

The Locking Mechanism Design is pictured in figure 24 below. The prongs on the shaft of the changing unit would slide into groves on a utensil, the servo would actuate to a set distance, the spatula stepper would rotate a determined distance, and the servo would return to its original position. With the tension from the internal spring, the utensil would remain locked in place.

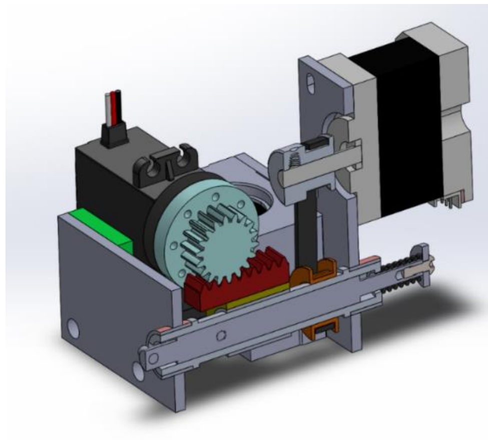


Figure 24:Utensil Change Locking Mechanism CAD Render

The Vacuum Locking Mechanism design is pictured in figure 25 below. This design would use a vacuum to hold the utensil in place, repressurizing the vacuum would release the utensil.

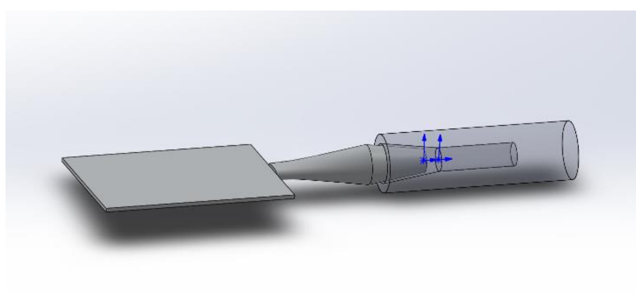


Figure 25: Utensil Change Vacuum System CAD Render

A decision matrix shown in table 4 was used to select the best design solution to investigate and each category was weighted for the following reasons. Complexity was given a weight of 40% was assigned to factor the amount of possible failure points in each. Cost was given a weight of 80% due to budget constraints. Rigidity was given a weight of 70% as a non-rigid utensil does not reach our accuracy goals. Time efficiency was given a weight of 20% as there would seldom be a need for a utensil change. Compactness was given a weight of 50% due spatial constraints within the gantry. The reasonings for each score are listed below in table 5 on a scale of 1 to 10 where 1 was unfavorable and 10 was favorable.

The Locking Mechanism was found to be most favorable, with low cost, simplicity and compactness being the driving factors. Tables 4 and 5 provide more details.

Table 4: Utensil Change Design Matrix

		Design Ideas		
Design Criteria	Weight (Importance 0%-100%)	Locking Mechanism	CNC Mill Mechanism	Vacuum Mechanism
Complexity	40%	5	2	6
Cost	80%	8	1	3
Rigidity	70%	3	8	6
Time Efficiency	20%	4	8	9
compactness	50%	8	2	4
TOTAL		15.3	9.8	12.8

Table 5: Utensil Change Design Matrix Reasoning

Design Matrix Reasoning				
Design Criteria	Weight (Importance 0%-100%)	Locking Mechanism	CNC Mill Mechanism	Vacuum Mechanism
Complexity	Increased complexity will increase points of failure within the system.	The locking mechanism has many moving parts	The CNC Mill Mechanism has the most complex design	The Vacuum Mechanism has the least number of parts.
Cost	Because of our Budget Cost Is important.	The locking mechanism will be cheapest to implement	Requires expensive vacuum pump	Requires expensive vacuum pump
Rigidity	Rigidity will be important when maintaining locational precision under loads.	The locking Mechanism will rely on a spring to counter utensil load, losing rigidity.	CNC Mill Mechanism is designed to experience large impact loads with precision, making it very rigid.	Vacuum Mechanism will stay rigid until the seal is broken, losing its hold on the tool.

Time Efficiency	Time to change utensils is important but small differences in time will not greatly affect overall preparation time.	The locking mechanism will take the longest to actuate.	CNC Mill will be the fastest	The vacuum will be fast if there are no sealing issues.
Compactness	The utensil changer will need to be positioned within a small space.	Most compact Mechanism	Largest Mechanism, not very compact.	Must deal with vacuum tubing.

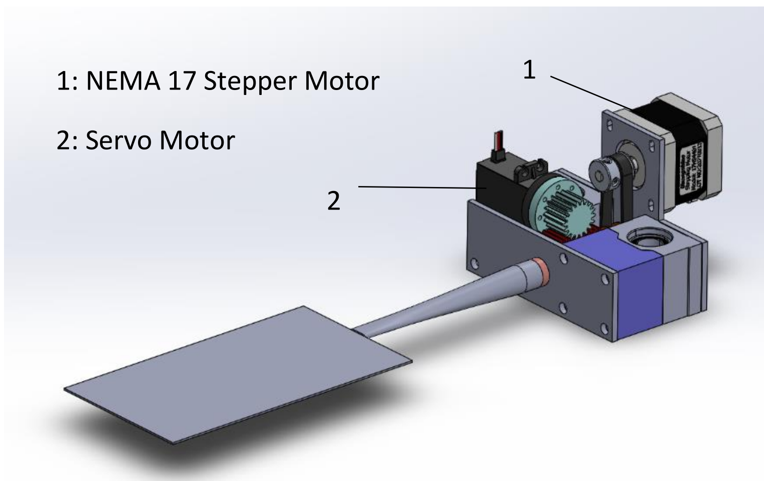


Figure 26: Utensil Change Full View CAD Rendering

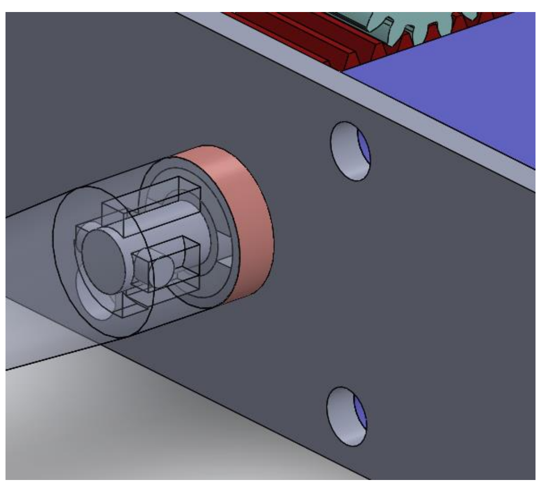


Figure 27: Utensil Change Locking Mechanism

The locking mechanism employs an inserting shaft and pin to interface with the spatula, facilitating the transmission of rotational motion through the mechanism to the end effector. This rotational motion is actuated by a NEMA 17 stepper motor, as depicted in Figure 26. Concurrently, the locking shaft is inserted by a servo motor, which converts its rotational motion to linear motion using a rack and pinion design. The inserting motion is augmented by a spring, which alleviates the load from the servo when the mechanism is in a resting position as pictured in Figure 27.

In the process of prototyping and refining this design, it became apparent that its implementation would be overly intricate and prohibitively expensive due to the precise tolerances required. Consequently, a decision was reached to abandon the spatula change concept and instead pursue egg cooking and cleaning through alternative means.

5.2.2 Fixed Spatula Design

The following Functional requirements were developed to govern the development of an end effector (spatula) design that would not switch between utensils:

- Complete at least 180 degrees of rotation about the spatula centerline.
- Utensils experience less than 3 degrees of deflection under max load.
- 1 degree of backlash about the spatula centerline.
- Materials in accordance with the FDA Code of Federal Regulations (CFR), Title 21

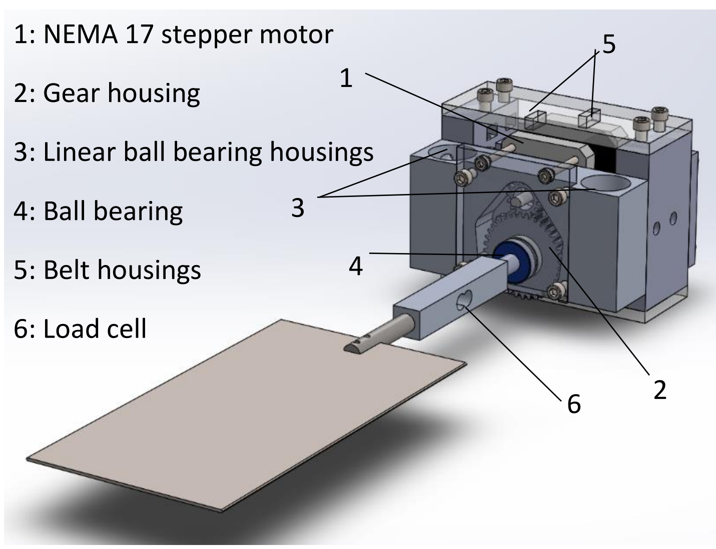


Figure 28: End effector CAD Render

The end effector design relies on a machined housing from aluminum 6061 that encases the press fit Uxcell LM8UU Linear Ball bearings and rear press fit spatula rotary shaft bearing. A bore is machined from the housing to hold the spatula gearing, which is enclosed by a 9mm thick laser cut acrylic sheet with a reamed hole to accept the front spatula bearing. The source of rotation is a NEMA 17 42mm stepper motor that drives a spur gear at a 3:1 ratio. The gears were oriented from “ABS-like resin” and accepted a 5mm ID and 8mm ID collet.

The axel loaded bearings that were used to support the spatula shaft had significant play. To eliminate play the design incorporated two thrust washers to preload the system and eliminate axel play. A square box surrounds the exterior of the NEMA 17 to anchor the gantry belts, which propel the spatula within the machine. An important modification made to the design was the addition of slotted acrylic plates on the top and bottom of the spatula housing. These plates ensured that the belts remained parallel to each other, maintaining constant belt tension throughout the robot's range of motion.

The spatula itself was constructed from 16-gauge AISI 304 stainless steel, driven by an 8mm AISI 304 stainless steel shaft. Additionally, an aluminum load cell was incorporated into one of the end effectors, enabling a control algorithm to detect system failures (as discussed in section 11.4). Two holes were machined into the load cell to accommodate press-fit connections on both ends of the shaft. To wire the load cell to the rest of the machine, another hole was bored into the main axle to route wires through. At the end of this shaft, a rotary wire coupler was used to maintain electrical contact while the spatula was rotating without twisting wires.

Throughout the manufacturing and implementation of the spatulas, several challenges were encountered. Minimizing play and deflection in the system was crucial to ensuring accurate manipulation. On the first spatula holder, the team faced issues with cheap, low-quality linear bearings that exhibited noticeable play on the 12mm linear shaft. To address this, a tight interference fit was employed to the second housing to reduce play. However, this solution increased friction in the system. Additionally, the sliding fit between the bearing inner diameter and the spatula shaft contributed to play that was not fully eliminated. For commercial applications, tensioned angular contact bearings and higher quality linear bearings could be utilized to further mitigate play.

5.3 Bread (English Muffin) Distribution and Slicing

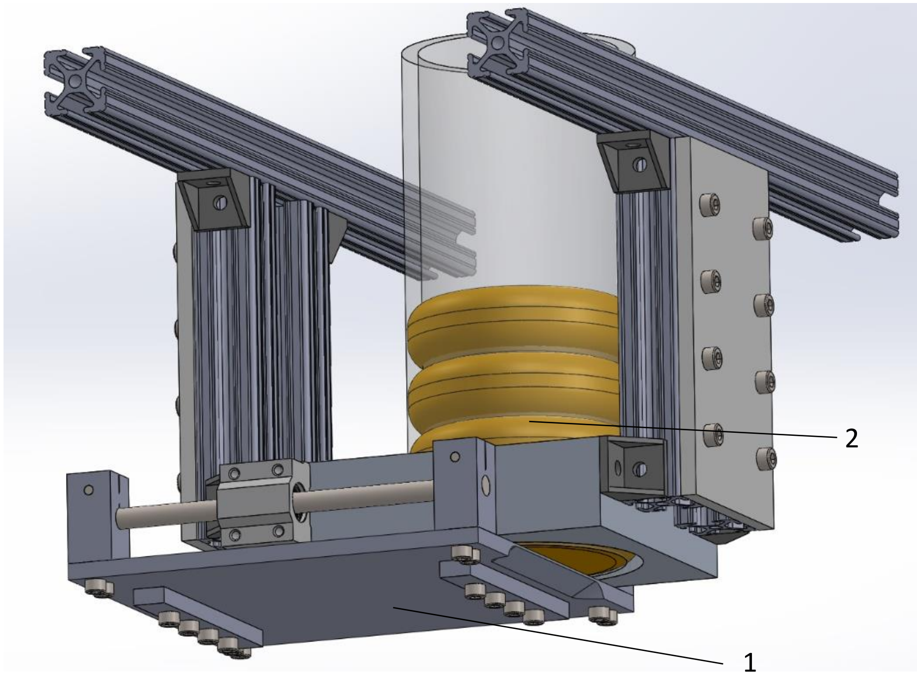
The Bread Distribution Requirements are as follows:

- All present materials abide by FDA Standards.
- Distribute English Muffin in under 8 seconds.
- Bread is consistently sliced at the same height.
- Accessible for cleaning crumbs from system.

There were two design approaches taken when evaluating the optimal method of distributing and slicing bread.

5.3.1 Bread Distribution and Slicing Design Approach One

Pictured in figure 29, approach one was designed to eliminate added complexity, distributing bread in an under actuated manner. Motion within this system was coupled with spatula movement to open and close a trap door. The apparatus would then rely on gravity to lower bread into the system. Utilizing both spatulas, the door is slid open by spatula one while the second spatula follows it. One English muffin can fall onto the second spatula, before the first spatula closes the door again.



1: Door mechanism

2: Gravity fed storage unit

Figure 29: Bread distribution CAD Design

The main frame construction of the bread distribution System was made from Aluminum 8020 extrusion and food safe acrylic. Acrylic parts are easier to manufacture than stainless steel while meeting the same NSF sanitary requirements and the design requirements for this system (see material safety section).

Bread distribution and Slicing Approach One requires a slicing mechanism outside of the bread distribution subsystem. This would require actuating the distribution system and receiving the English muffin before moving on to a second step. This step requires a separate apparatus to slice the bread. From the teams' testing results, the following functional requirements were identified for a bread slicing mechanism:

- Slice English a muffin in one cut under 5 seconds.
- Apply an actuation force of 25 Newtons.
- All present materials abide by FDA Standards.

A decision Matrix was constructed to evaluate slicing strategies as shown below in table 6. Required Actuation force was given a weight of 80% to avoid mechanical damage. Cost was given a weight of 80% due to budget constraints. Complexity was given a weight of 50% due to manufacturing time constraints. Reliability was given a weight of 70% due to the repeatability of the action without failures importance to a proper product. These are further discussed in table 7 and are on a scale of 1 to 10 with 1 as unfavorable and 10 as favorable.

Table 6: Bread Slicing Design Matrix

		Design Ideas		
Design Criteria	Weight (Importance 0%-100%)	Slice Bread with Wire	Slice Bread Straight Knife	Oscillating Bread knife
Required Actuation Force	60%	8	7	9
Cost	80%	9	5	4
Complexity	50%	7	7	3
Reliability	70%	5	7	5
TOTAL		19	16.6	13.6

Table 7: Bread Slicing Matrix Reasoning

Design Matrix Reasoning				
Design Criteria	Weight (Importance 0%-100%)	Slice Bread with Wire	Slice Bread Straight Knife	Oscillating Bread knife
Required Actuation Force	Larger required forces mean larger motors must be used. Increases likelihood of system breaking.	10.7647 N	12.72191 N	~0 N
Cost	A constrained prototype budget makes cost a significant factor	$10-15 spool stainless steel wire	$20-30	$100-110
Complexity	Complexity drives up cost, manufacturing time, and likelihood of failure.	Easy to cut to correct length and implement into system	It is harder to mount a knife as it's much larger than wire. More dangerous as knives are sharp	Same process as straight knife, but requires extra degree of actuation
Reliability	Reliability is necessary to prevent system from jamming or deforming the English muffins	Wire is susceptible to snapping	Knives are durable, but susceptible to being dulled	Extra parts and complexity mean more places to fail

Like the bread distribution system, the proposed bread slicer couples its motion with the gantry, saving on the cost and complexity of the machine. As discovered in our bread slicing testing (as discussed in section 4.1.7), the English muffins that will be sliced come partially separated, which allows a wire to cut through the bread with less then 15 newtons of actuating force. Our approach to bread slicing has many benefits over a traditional approach of oscillating serrated knives, as our system does not require an extra motor and mechanism to operate and does not create a large spread of crumbs.

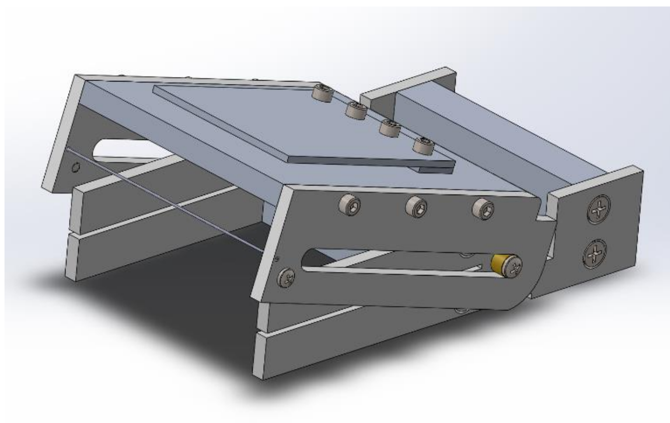


Figure 30: Bread Slicer CAD Rendering

5.3.2 Bread Distribution and Slicing Desing Approach Two

The under actuation and reliance on the gantries for motion presented significant concerns for reliability and repeatability. Although the designs of approach one was physically more simplistic, they required a more complex level of gantry controls to operate. In the development of the Bread Distribution and Slicing Approach Two, the team opted for a dependable design that operates independently from the gantry's movements. This design integrates both slicing and distribution into a single motion, streamlining the process for efficiency and effectiveness.

The design incorporates a rotary disc (refer to figure 31 & 32 below) to transfer an English muffin from the stack to the distribution hole. Along this trajectory, a tensioned wire consistently slices the bread in half at a uniform height with each repetition. Any crumbs generated during this process can then pass through a perforated plate into a containment system. The rotary disk is powered by a NEMA 23 motor at an 8:45 gear ratio, resulting in a rotary disc torque of 13.5 Nm and a cutting force of 192.86 N. These specifications far exceed the initial force requirement. The implementation of these design decisions are shown in the full CAD design and assembled system. This is shown in figures 33 and 34 respectively.

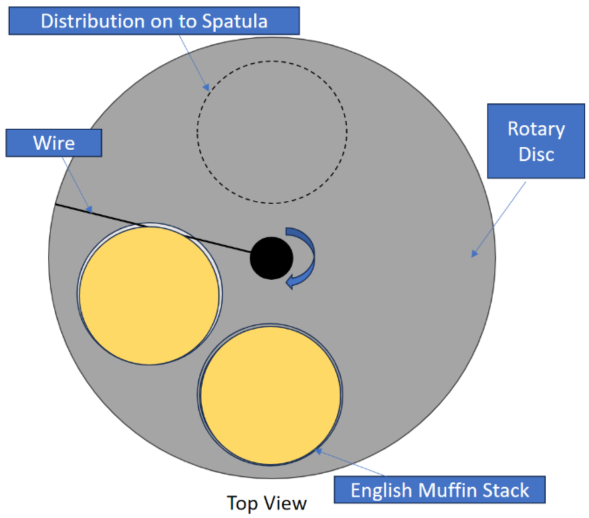


Figure 31: Top View Diagram of bread distribution system.

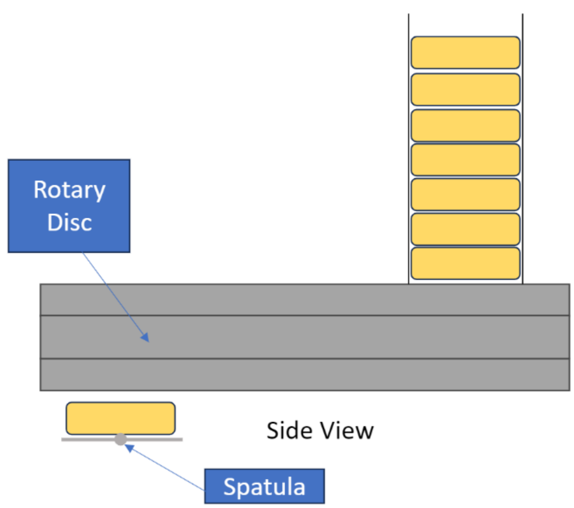


Figure 32: Side View Diagram of bread distribution system.

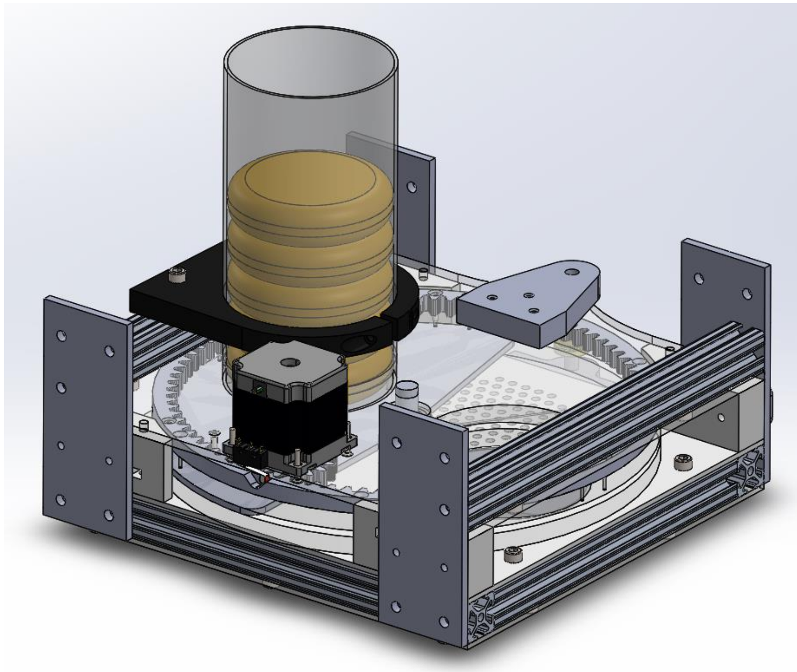


Figure 33: CAD model of bread distribution system.

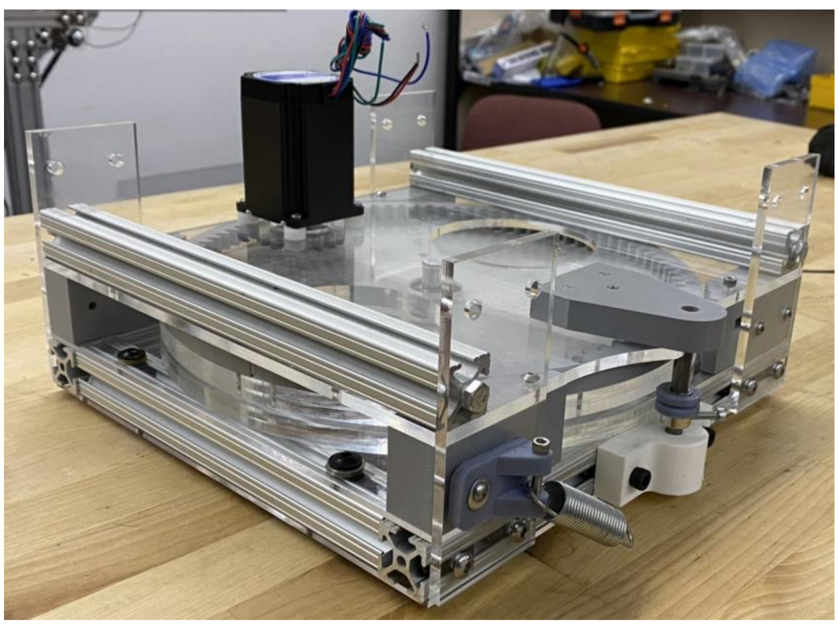


Figure 34: Finished bread distribution system.

5.4 Cheese Distribution

Research and testing have allowed the team to develop the following functional requirements for the cheese distribution system:

- Actuate the wire with 30 N of force.
- Physically distribute cheese in under 5 seconds.
- Clean contact surface every distribution cycle eliminating all visual residue of crumbs and cheese residue.
- Ability to wipe down contact surfaces with disinfectant.
- Abide by FDA Standards.
- 250mm x 250mm width, depth constraint.

The cheese distribution system was designed to distribute sliced cheese rather than shredded cheese. Starting with a solid cheddar cheese block, the block is fed with a silicone conveyor system into the cutting mechanism. A rack and pinion actuated slicing sled feeds a stainless-steel wire through the block of cheese, cutting it to the desired width. The conveyor system was designed to be driven with stepper motors (see figure 35) giving precise control over cheese slice width. The slicing sled is then driven by geared DC motors, with homing switches for positional feedback.

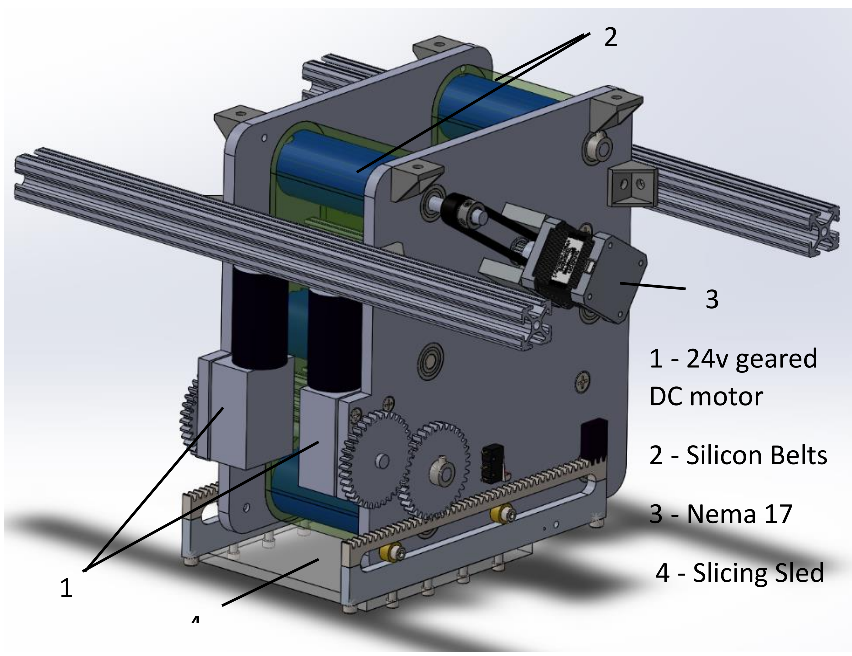
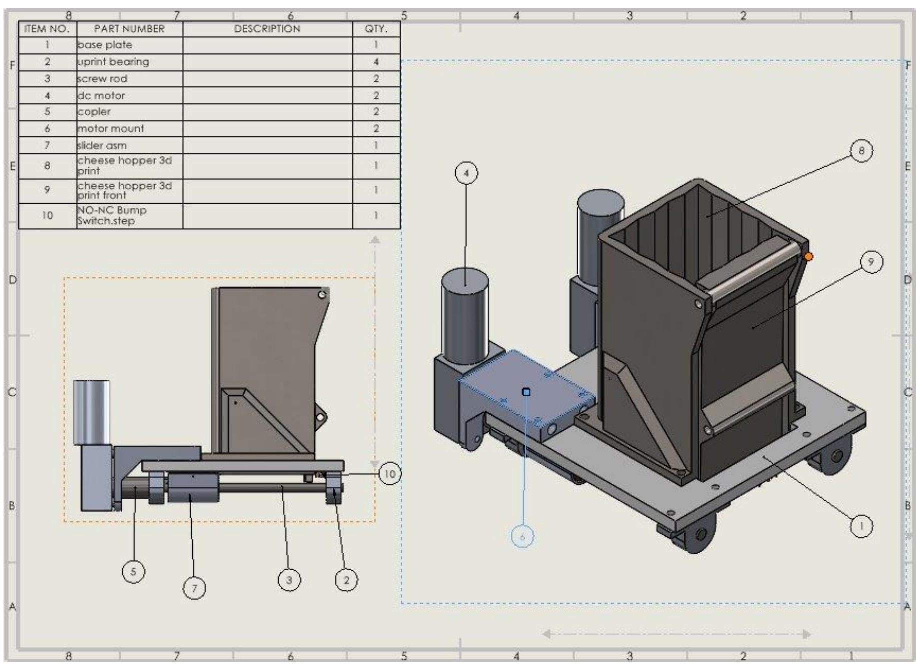


Figure 35: Cheese Distribution and Slicing System CAD render

5.4.1 Work of the ME 4320 Team

Students in ME 4320 course during D-2024 were tasked with the redesign, manufacturing, assembly, and testing of the cheese distribution system. Redesign of the cheese distribution system saw the removal of the silicon belts, opting for a gravity fed system. Slicing of the cheese was performed by stainless steel wire. Two DC motors were used to drive the linear motion of the bottom plate with lead screws. With this design, lowering of the cheese and slicing was accomplished with the same linear actuation, greatly reducing the complexity of the design. This system clamped the cheese using spring tension and lowered it by releasing this tension, allowing the cheese to lower to the sliding plate. Manufacturing of the cheese distribution was accomplished using additive manufacturing for the body of the unit. Factory parts were used for fastening and the lead screws. Assembly of the distribution system was completed by the ME 4320 team. Testing of the completed product was conducted by driving the DC motors at a constant speed to produce a slice of cheese. Figure 36 shows the CAD assembly that the ME4320 team developed including a BOM.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	base plate		1
2	uprint bearing		4
3	screw rod		2
4	dc motor		2
5	copler		2
6	motor mount		2
7	slider asm		1
8	cheese hopper 3d print		1
9	cheese hopper 3d print front		1
10	NO-NC Bump Switch.step		1

Figure 36: Cheese Distribution BOM

Figure 37 below shows the construction progress of the cheese distribution as of 4/19/2024. The main plate has been laser cut from 0.375in acrylic while the rest of the structural components were 3D printed and covered with an epoxy coating.

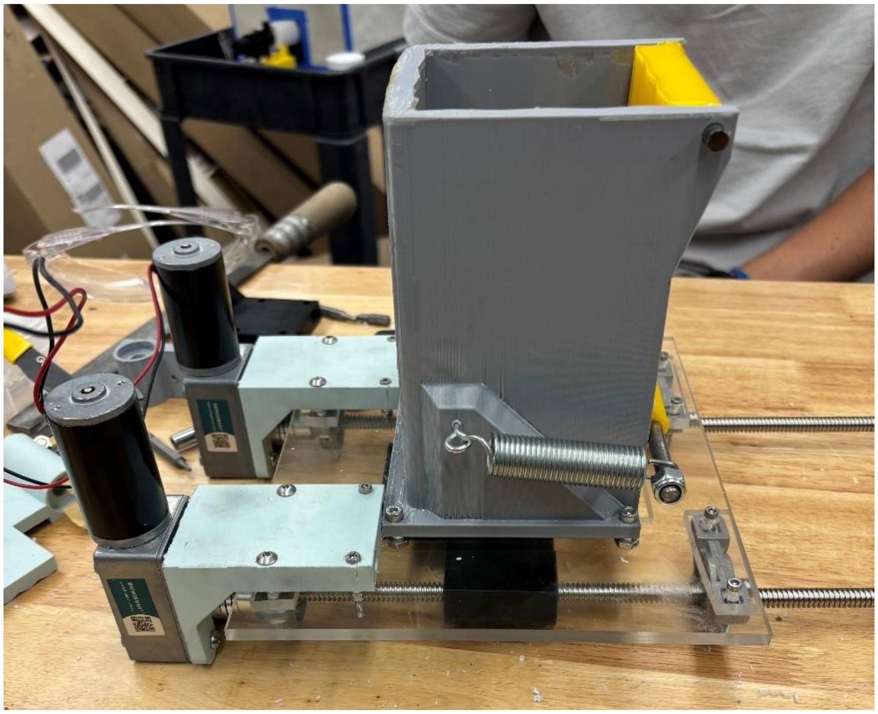


Figure 37: Cheese Distribution Prototype

From more information on the design, fabrication and assembly of the cheese distribution system see Appendix I.

5.5 Egg Distribution

Egg Distribution Requirements:

- All present materials abide by FDA Standards.
- Pump Egg In under 20 seconds.
- Egg is not frothy.
- Move cup/pan up and down at 20mm/s in Y direction.
- Flip egg within .5 seconds.

The Egg Distribution System was designed to distribute liquid eggs. Using liquid eggs avoids the need to manipulate and autonomously crack eggs. A peristaltic pump design was utilized to move the liquid eggs from a storage container into a mini frying pan. To meet the egg distribution requirements the peristaltic pump (see figure 38) was sourced to run on 12V/24V DC with a Flow rate of 10 - 452 mL/min. This design allows the eggs to have no contact with the pump as they are introduced to the system, making it easier to clean. Having no moving components directly in contact with the egg distribution system is ideal for implementing a flushing protocol to clean out egg renaissance.

Figure 38: Peristaltic Pump

The frying pan would then be lowered onto an electric griddle where the egg would be cooked. The eggs had to be pumped out in a timely manner, avoiding froth. To quantify this, the team ran the pump at different RPMs to see which RPM gave us the best results. Based on the results shown in table 8 and figure 39, we found that 80-140 RPM gave us the best results (Carey et.al, 2023).

Table 8: Speed of the pump, in RPMs, recorded time required to pump 1/3 cup of liquid egg, in seconds, and the required voltage from the power source to run the system.

Speed (rpm)	Time to pump 1/3 cup of eggs (s)	Volts (V)
20	105	12
40	50	13
50	40	15
60	32	15
80	23	17
100	15	19
120	15	21
140	12	22
160	11	25.5
180	9	27
200	8	28.5

250	6	31.6
300	4.75	31.6

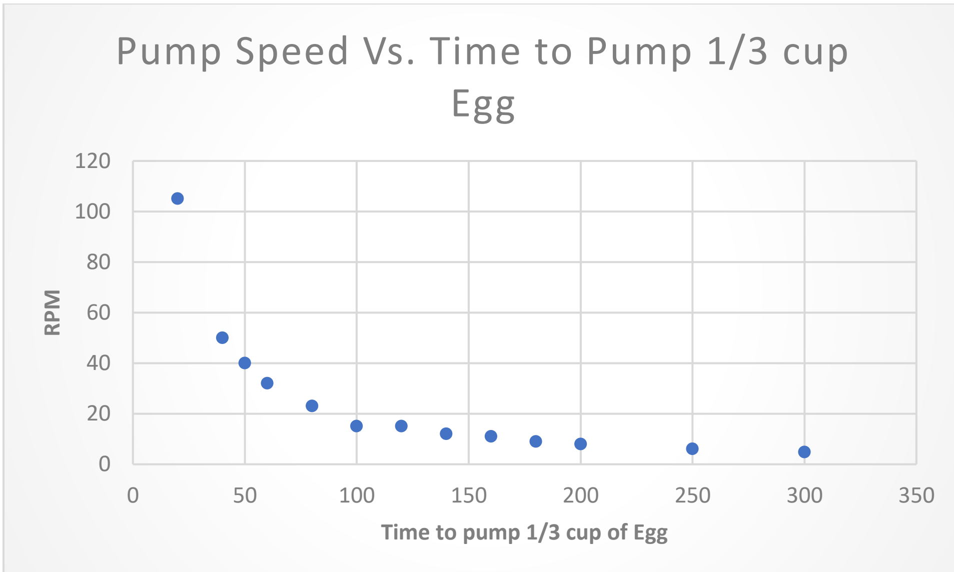


Figure 39: Graph of pump speed, in RPMs, versus the time it takes for the pump to transport 1/3 cup of liquid egg, in seconds.

Once the team decided on distributing the egg through a peristaltic pump, we explored two options to cook the egg. The first being poaching (see figure 40) and the second being frying. From the testing done in the preliminary testing section it was found that both methods had similar cooking times. The first approach was to poach the egg, where the team 3d printed a nylon poaching cup that would be inlayed by a silicon cup.

Figure 40: Egg Poaching Cup

The team deemed implementing a water boiling system too complicated within the current scope of the project and transitioned to frying the egg in a miniature frypan. For both egg cooking approaches, the cup/pan needed to be lifted and lowered in the Y direction as well as rotated to flip the cooked egg out of the cup/pan.

5.5.1 Egg Cooking Approach One

Approach one (see figure 41) used a HGH15CA linear rail and bearing to constrain motion in the Y direction with a lead screw driving the cup/pan up and down. The rotation would then be driven by a 6mm gt2 timing belt. The main issues with this design were the availability of the HGH15CA linear rail and bearing and containing the cup/pan perpendicular to the Y axis.

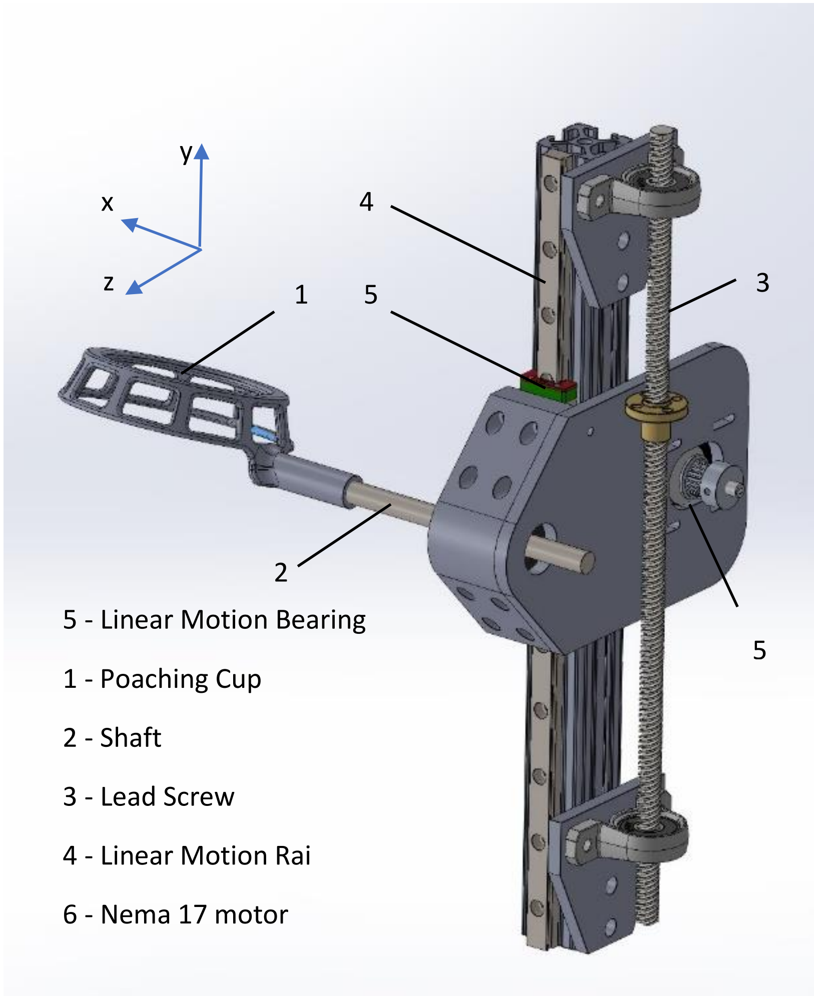


Figure 41: Egg Cooking Apparatus Approach One

5.5.2 Egg Cooking Approach Two

The second approach took lessons learned from the first, incorporating linear motion supports on both side of the cup/pan shaft (see figure 43). The motion in Y was constrained by 4 Uxcell 8mm linear bearings and 2 8mm Shafts. Like approach one the motion was driven by a NEMA 17 stepper attached to a lead screw through a 6mm gt2 timing belt, translating rotational motion to linear motion. The belt pulley ratio created a 1:1.5 gear up for the NEMA 17, creating a max holding torque of 0.35 Nm acting on the lead screw. The required torque for the lead screw can be calculated from the following parameters in Table 9.

Table 9: Lead Screw Variable Values

F = Load	**14.7 N**
L = Lead (Pitch)	0.002 M
E = Efficiency	0.5 (Standard Value)
M = Friction Coefficient on thread interface	0.19 (The Engineering Toolbox)

$$Torque = \frac{F * L}{2 * M * E} = 0.15\ Nm$$

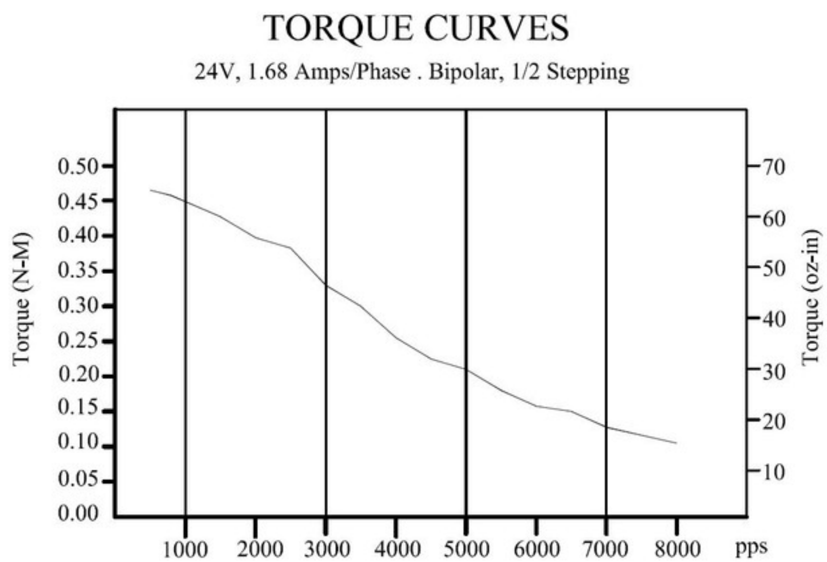


Figure 42: NEMA 17 Torque - Speed Curve (open builds part store)

From the provided torque-speed curve (figure 42) we can predict an operating speed of 6000 pps (pulse per second) which translates to 900 rpm (revolutions per minute) assuming a resolution of 400 steps per revolution. Linear velocity in the Y direction can then be calculated to be 30mm/s. This meets the design requirement of 20mm/s velocity in the Y direction.

To relay position control to the computer, a limit switch homed the zero position in Y while an optical encoder was used for rotational position control on the cup/pan shaft.

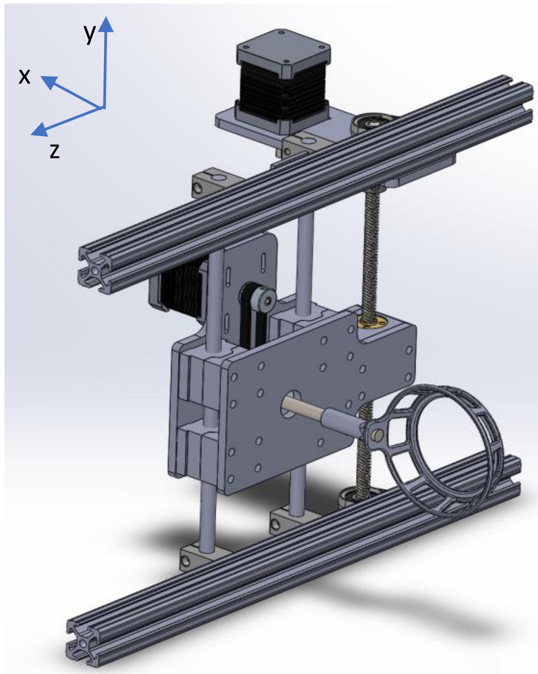


Figure 43: Egg Cooking Apparatus Approach Two

5.6 Sausage Distribution

The purpose of the Sausage Distribution System was to dispense store bought sausage patties onto the spatula. Through research and testing conducted by the MQP team and the B-term 2023 ME4320 team, the following requirements were established:

- Must be able to move individual sausage patties from storage tube to an actuator
- That actuator then dispenses the sausage patty onto the spatula
- Storage tube must hold six sausage patties
- Confined to 300 x 300 mm area
- Abide by all FDA Standards

After the design requirements were put in place a design matrix was constructed to investigate proposed design approaches.

WEIGHTED
Decision Matrix

Design Criteria	Weightage	Rationale	Prototype A RATING	Prototype A TOTAL	Prototype B RATING	Prototype B TOTAL	OPTION C RATING	OPTION C TOTAL	OPTION D RATING	OPTION D TOTAL
Required Force (can transport patty)	16%	System must be able to hold the required number of patties	5	16.00%	5	16.00%	3	12.00%	4	16.00%
Patty Damage	15%	Important that the design does not do any damage to the patty	4	12.00%	4	12.00%				
Material Cost	6%	Cost of material is important to keep in mind, but not most important factor	3	3.60%	2	2.40%	2	3.00%	4	6.00%
Labor Cost	5%	Required labor for assembly is a factor, not as important as others	2	2.00%	3	3.00%	2	2.50%	1	1.25%
Maintenance Frequency	7%	Ideal design can run for long periods of time without needing maintenance	2	2.80%	3	4.20%				
Efficiency of Cycle	20%	Cycle must have ability to run efficienctly, otherwise design will not work	3	12.00%	4	16.00%	2	10.00%		0.00%
Ability to Clean and Repair	15%	Ability to take design apart and clean is very important	1	3.00%	3	9.00%		0.00%		0.00%
Manufacturability	16%	Design must be able to be built and manufactured	2	6.40%	3	9.60%	3	12.00%	2	8.00%
	max			TOTAL Prototype A		TOTAL Prototype B		TOTAL OPTION C		TOTAL OPTION D
	100%			57.80%		72.20%		39.50%		31.25%

Scale:	5 = highest rating; meets criteria
	1 = lowest rating; does not meet criteria

Figure 44: Design matrix for sausage distribution

The ME 4320 team quickly narrowed the sausage distribution down to two approaches, one provided by the MQP team and one developed by the ME 4320 team. The testing and prototyping for each approach were carried out by the ME4320 team and outlined in the following section.

5.6.1 Sausage Distribution Approach 1

The first approach relied on gravity to dispense sausage patties as pictured in figure 45. First, the sausage patties were loaded into an acrylic tube. At the bottom of the tube the stack of sausages rest on a platform. A push plate was then used to push individual sausage patties through a slot in the storage tube. The sausage patties then fell gently on the spatula. The push plate could then be retracted, allowing for another sausage patty to fall onto the platform. To actuate the push plate a lead screw was used powered by a 12V DC motor.

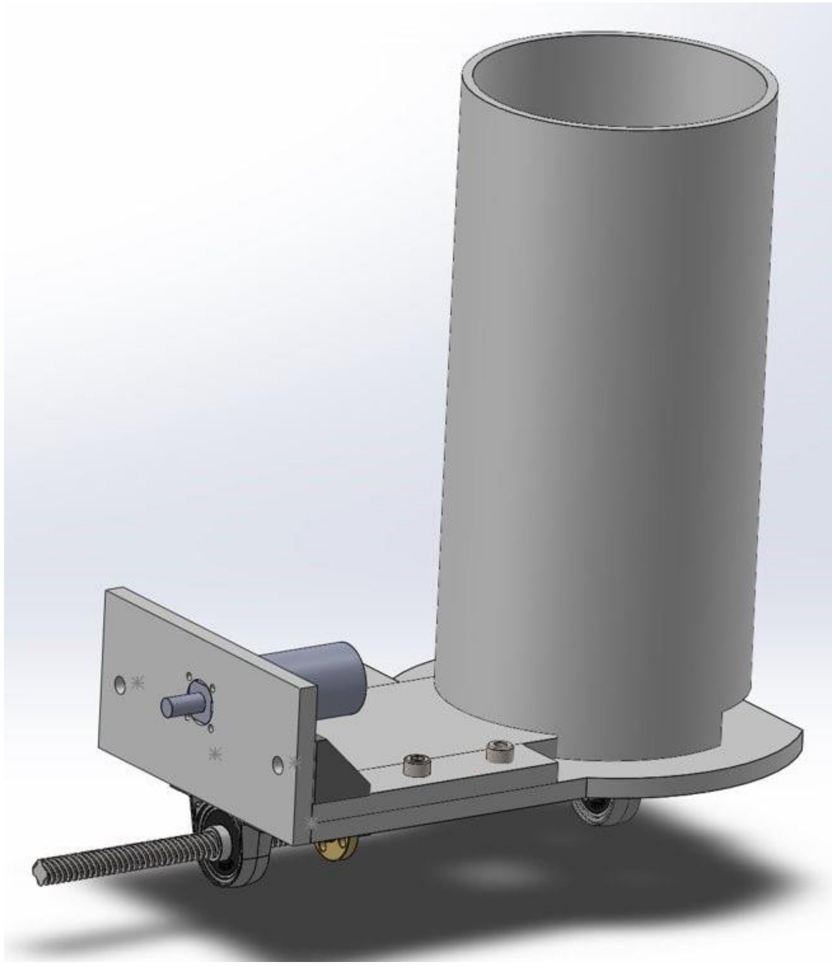


Figure 45: CAD model for sausage distribution approach 1

5.6.2 Sausage Distribution Approach 2

The second approach to sausage distribution relied on using a multilayer rotational system as pictured in figure 46. Sausage patties were loaded into an acrylic storage tube and landed on a rotating disk. This disk had three circular holes in it, allowing sausage patties to fall through, resting on the static disk. This allowed for three sausages to be dispensed every time the rotating disk completed one revolution. The static disk was attached to the bottom of the rotating disk and had one hole for dispensing the sausage patties. As the rotating disk rotated, it pushed individual patties that fell through its slots towards the dispensing slot. The sausage patties then fell through the dispensing hole onto the spatula. The system was powered by a NEMA 17 motor, which drove an external spur gear to turn the rotating disk.

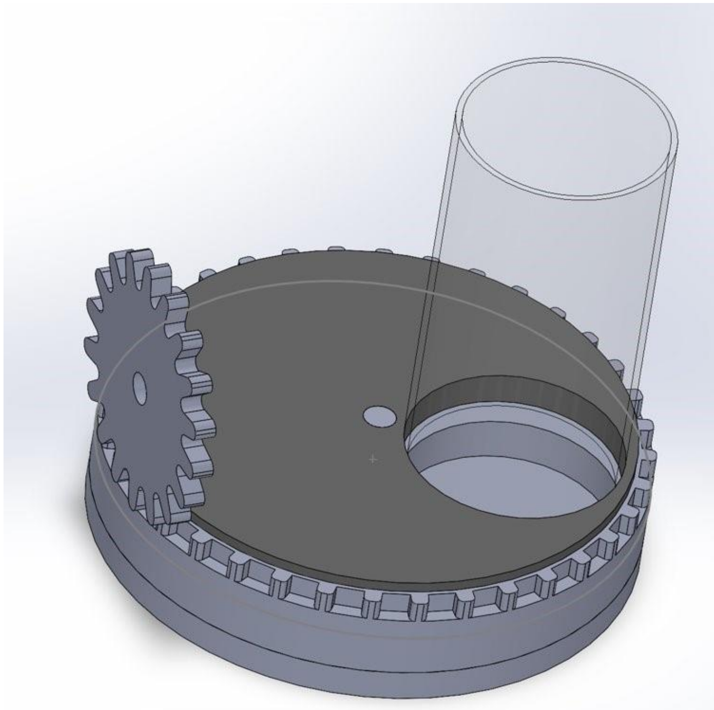


Figure 46: CAD of sausage distribution system approach 2, 1st iteration

5.6.3 Sausage Distribution Final Design

To choose which approach worked best, the ME4320 team tested both designs for: sausage damage, grease left in the system, and reliability. Sausages that were thawed for five minutes and sausages at room temperature were run through the system for testing. Through their testing they found that the second approach would work best for our application. However, there were necessary modifications to meet the given requirements.

The first modification was reducing the number of slots in the rotating disk from three to one. The ME4320 team ran into jamming issues during testing with the original design, so the extra two slots were eliminated to prevent this.

The second modification was embedding the external spur gear attached to the motor into the system. To make this modification possible, a second spur gear was attached to the top of the rotating disk. This decreased the risk of damage to the system, and made it more compact as the gears were now concealed in the system.

The final modification was attaching two 9mm clamps to the bottom and top plates. This allowed the ME4320 team to attach aluminum t-slotted rails to the system to hold it in together. This also served as a place to attach the system to the robot's frame. Figure 47 below shows the CAD model of the team's final design. Figure 48 shows the sausage distribution system mounted to the robot. Followed by figure 49, which shows the sausage distribution system distributing sausage patties.

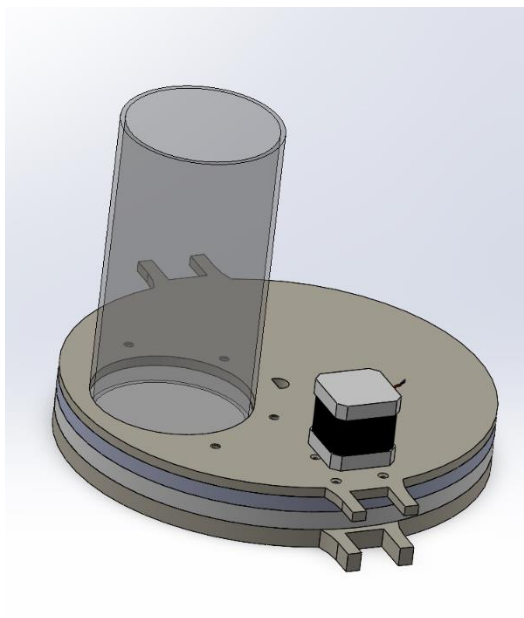


Figure 47: CAD of Final Design (2nd iteration of 2nd approach)

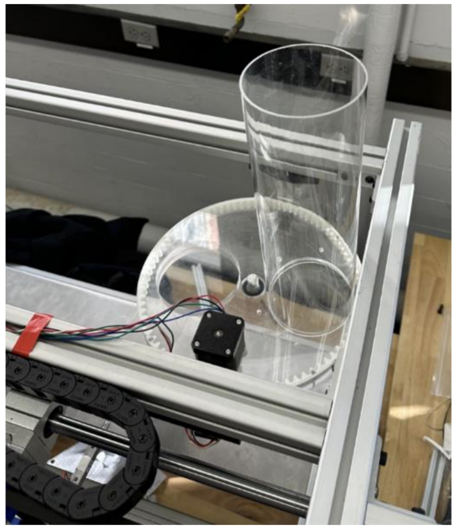


Figure 48: Sausage Distribution System installed on the robot

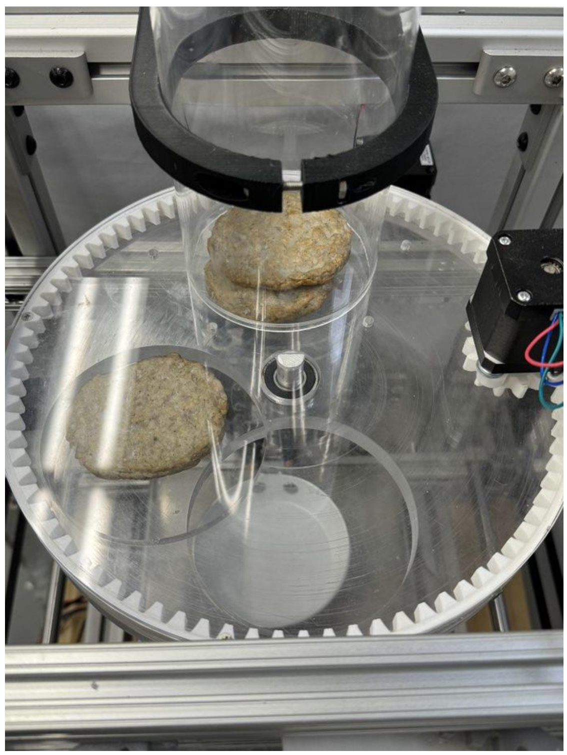


Figure 49: Sausage Distribution System in Action

5.7 Work Surface and Griddle

Manipulation, cooking and assembly of ingredients required griddle like surface. The Work Surface Requirements were as follows:

- All present materials abide by FDA Standards.

- Measured flatness with less than 2mm deviation from a reference surface.
- Contain ridged surface
- Ease of Cleaning.
- Withstand temperatures up to 300°C.
- Must produce a thermal gradient of 230°C that dissipates down to ambient temperature.
- Contains thermal monitoring and failure detection.
- Has closed loop thermal control.

The worksurface features an 8020-aluminum extrusion frame with a 16 gauge AISI 304 stainless steel worksurface (meets FDA requirements) as pictured in figures 50 and 51. An electric heat source was then designed to be pressed against the bottom of the stainless steel to transfer heat through conduction. To insulate the stainless steel, a layer of ceramic insulation was utilized to separate the thermal gradient acting on the work surface from dissipating through the 8020-aluminum extrusion. Finally, the 8020 runners on each end of the work surface are used to attach the surface to the robot frame.

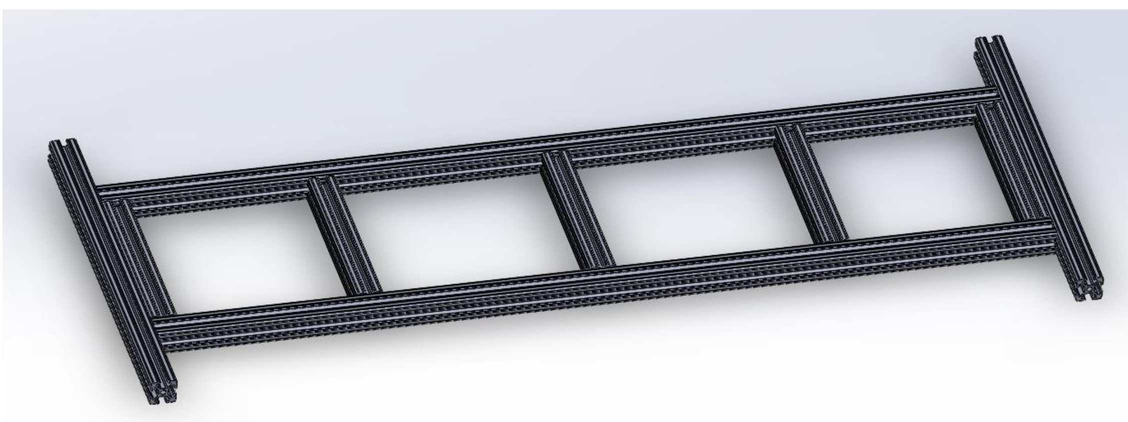


Figure 50: Worksurface 8020 Frame CAD Render

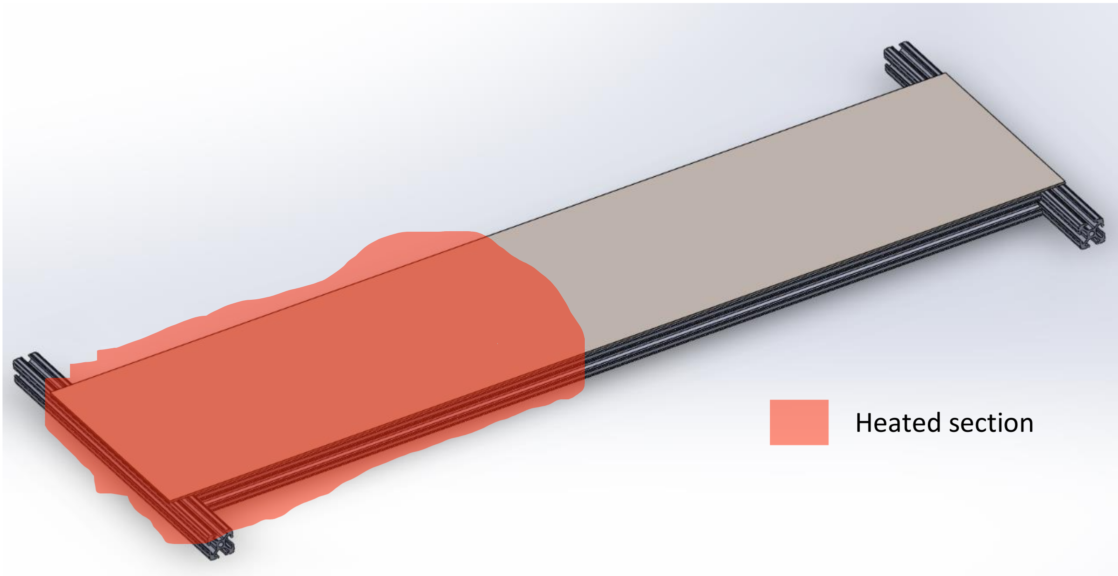


Figure 51: Worksurface CAD Render

5.7.1 Griddle Heat Source

An electric griddle was used to cook the egg and sausage, toast the bread, and melt the cheese. The griddle relied on a heat source from a Black and Decker GD2011B electric griddle. The griddle needed to achieve different temperatures across the worksurface to facilitate cooking, toasting, melting and warming all at the same time. To attain this, the worksurface needed to exhibit a thermal profile. Based on ideal cooking temperatures and test done in the preliminary testing section, boundary conditions of 230°C on the left side of the griddle and ambient temperature at right were chosen at steady state conditions. The free convection over the work surface was roughly modeled to have a convection coefficient of 9.3 W/m^2*K under the assumptions of a mean uniform temperature, Steady state, Laminar flow, Negligible radiation and simple flat geometry. The convection coefficient was estimated using the following equations (Lienhard 2024).

$$\text{Prandtl number} = \text{Pr} = \frac{\mu * C}{k}$$

μ - fluid viscosity
C - fluid specific heat
k - fluid thermal conductivity

$$Grashof\ number = \ Gr = \frac{L^3 \rho^2 g * dT * \beta}{\mu^2}$$

ρ - fluid density
g - gravitational acceleration
β - fluid thermal expansion coefficient
ΔT = Temperature difference
L = characteristic length

$$Rayleigh\ number = \ Ra = Gr * Pr$$

$$Nusselt\ number = NU = L * \frac{h}{k}$$

(This Nusselt number correlation with the convection coefficient is valid because of the assumption specified above.)

From these conditions, a SolidWorks simulation was run to find the 1500-watt heat source to be ideal to meet the desired thermal gradient. The results of this simulation can be seen in figure 52.

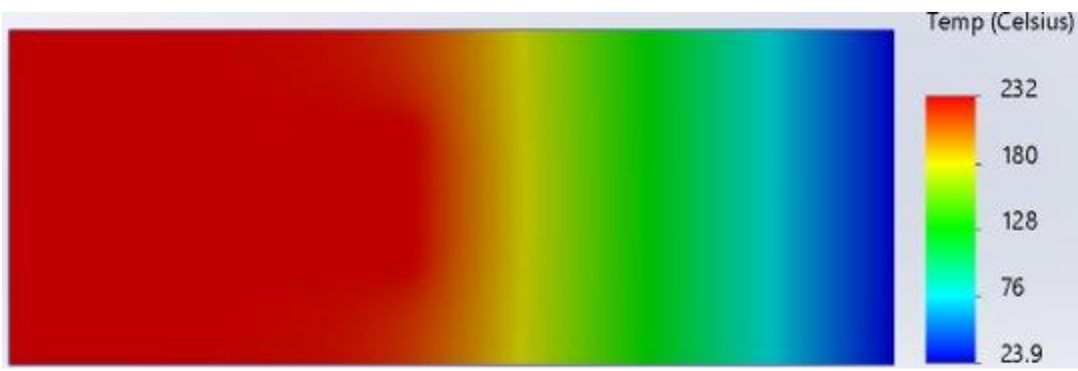


Figure 52: Work Surface Thermal Profile

5.8 System Cleaning

The cleaning system is responsible for removing all crumbs and grease from within the system. Designing and implementing this was found to be outside the current project scope. However, the team theorized that a grease and crumb trap facilitated by an automated scraper and pressurized air system would be effective in cleaning the work surface. At its current stage, the team envisions a routine cleaning procedure performed by a human. This procedure would be performed routinely based on a combination of sandwiches prepared and time elapsed.

6 Sensor Design

Sensor design decisions for the thermocouple and camera system are detailed in this section. While not fully integrated within the machine, plans for implementation into the system can be seen in chapter 12.

6.1 Implementation of Thermocouple

To measure the temperature of the griddle, we used TEMPCO Type J air probe thermocouples. These thermocouples had a temperature sensing range of 0-760°C and had an accuracy within ± 2.2°C within that range. Table 10 below describes our reasoning for choosing this type of thermocouple with the following design criteria. Cost with a weight of 80% due to the budget constraints of this project. Temperature range with a weight of 70% as the ideal ranges need to span the full range of the heating capacity of the machine. Accuracy with a weight of 50% as small difference in the temperature will not have a large effect on the ingredients cooking process. The reasoning for each weight is given in table 11 and is on a scale of 1 being unfavorable to 10 being favorable.

Table 10: Thermocouple Design Matrix

Thermocouple		Design Ideas			
Design Criteria	Weight (Importance 0%-100%)	Omega ROHS Type J	TEMPCO Type J	Dayton Type K	Omega "Stick On" Thermistor
Cost	80%	7	8	5	2
Temperature Range	70%	9	10	9	0
Accuracy	50%	9	9	9	10
TOTAL		16.4	17.9	14.8	6.6

Table 11: Thermocouple Design Matrix Reasoning

Design Criteria	Weight (Importance 0%-100%)	Omega ROHS Type J	TEMPCO Type J	Dayton Type K	Omega "Stick On" Thermistor
Cost	Budget will play a key role in thermocouple selection.	$69.78 for 5	$18.52 for 1	$31 for 1	$73.33 for 1
Temperature Range	Thermocouple must be able to measure up to 260 deg C	0-260 °C	0-760 °C	0-260 °C	-80-120 °C
Accuracy	Accuracy of at least +- 3 C is important to maintaining consistent cooking temperature.	± 2.2 °C	± 2.2 °C	± 2.2 °C	± 0.2 °C

Two MAX6677 analog to digital converters (ADC) were used to convert the voltage signals generated by each thermocouple into useable temperature readings. The temperature readings obtained from these signals were then averaged together to get the actual temperature. This approach was taken to mitigate discrepancies between the two thermocouples, and to increase precision.

Each thermocouple will be ceramically insulated on one side and pressed against the bottom of the worksurface at equally spaced locations. This will allow the team to dynamically control the thermal profile on the worksurface and act as a failsafe. The failsafe system is composed of Schmitt trigger with hysteresis, as seen in the figure below. Both thermocouples are attached to a Wheatstone bridge as denoted by RT. Once the voltage goes past the threshold, the op-amp U1 switches off, thus turning off the system (the system is represented as the diode D1) as shown in figure 53 shown below.

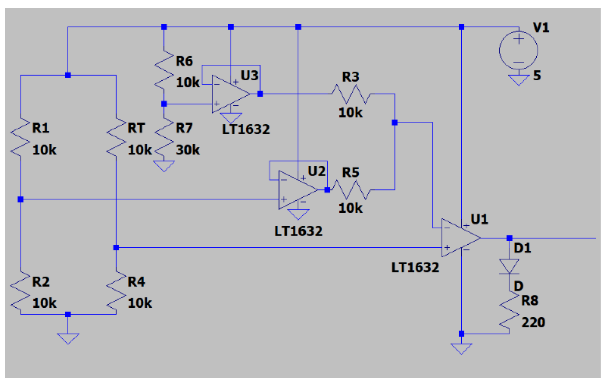


Figure 53: Oven Fail Safe Circuit Design

6.2 Thermocouple Calibration

Two calibration tests were conducted on the thermocouples to ensure they were producing accurate results. In the first test, we grabbed the thermocouples with our hands for ten seconds and then let go of them. Our goal was to see how close the thermocouples would read to body temperature. The thermocouples measured the temperature of our hands at 36°C. However, the thermocouples were slow to respond as it took them 1.5 minutes to give an accurate hand temperature reading. It also took an additional 3.5 minutes for the thermocouples to read room temperature again. This test was conducted at the low end of the thermocouple's temperature sensing range, which means that the thermocouples are less sensitive to change in temperature according to TEMPCO.

In the second calibration test, we used thermocouples to measure the boiling point of water. We placed the thermocouples in a pot of room temperature water and heated that water up to a rolling boil. Once the water boiled, the thermocouples read 94°C. However, it took one additional minute after the water boiled for the thermocouples to accurately read the temperature of the boiling water at 100°C. During this calibration, we learned that once the thermocouples read 100°C, they became much more sensitive to temperature change. We were able to touch the thermocouples to the side of the pot and saw an immediate increase in temperature. We then took the thermocouples out of the boiling water and saw the temperature reading immediately drop back down to room temperature. Through this calibration, we learned that our thermocouple readings were accurate, and the lack of sensitivity in the thermocouples was eliminated for temperatures greater than or equal to 100°C.

6.3 Camera Vision System Design

The camera system was crucial in detecting errors within the machine. A decision matrix for the choice of camera is detailed in table 12 below. Built in processing had a weight of 80% as it alleviated compute resources on the machine's computer. Cost had a weight of 50% as budget constraints were important. Color detection had a weight of 40% as it was a useful built in feature. The pixel count had a weight of 20% as most modern cameras have a high resolution. The reason for each score is detailed in table 13 below and is on a score of 1 being unfavorable and 10 being favorable.

Table 12: Camera Design Matrix

		Design Ideas		
Design Criteria	Weight (Importance 0%-100%)	HuskeyLens	OpenMV	Generic Webcam
Built in processing	70%	8	8	1
Cost	50%	4	3	6
Color Detection	40%	7	7	0
Pixel Count	20%	7	4	5
TOTAL		11.8	10.7	4.7

Table 13: Camera Design Matrix Reasoning

Design Matrix Reasoning				
Design Criteria	Weight (Importance 0%-100%)	HuskeyLens	OpenMV	Generic Webcam
Built in processing	Built in processing of the image is important when trying to conserve computing resources and limit the use of additional microcontrollers.	Processes image and can detect patterns, color segments, and pixel thresholds.	Processes image and can detect patterns, color blobs, and pixel thresholds.	Returns an image
Cost	Due to the constrained budget, our team must heavily weigh the costs of each piece of equipment.	$55-64	$85	$20-30
Color Detection	The camera's first use is to detect ingredients and center them, with the plan to use color detection to achieve this.	Detects colors and can find center point	Detects color blobs and can find center point	Needs external processing
Pixel Count	The pixel density of the camera affects the resolution of the end image.	2 megapixels	.3 megapixels	1-2 megapixels within price range

The OpenMV camera may have been the second-best camera system researched, but it was available to the team to borrow so it was chosen for the ingredient alignment system. It also came with its own integrated development environment (IDE). This allowed the team access to OpenMV’s prewritten image processing algorithms.

To find the ideal algorithms for detecting food misalignments on the spatula, different image processing algorithms were tested. The first method tested was using a blob detection algorithm (OpenMV, 2024). This algorithm relied on finding clusters of pixels that were similar in color. A box was then drawn around a pixel cluster with a cross in the center. This indicated the location of a found food item. After testing, this method was not chosen as the size of individual food items were not consistent. Inconsistent lighting also caused food items to not be consistent in color either. Figure 54 below provides an example of the blob detection algorithm detection for finding a bun. The was used as a quality control benchmark for this algorithm.

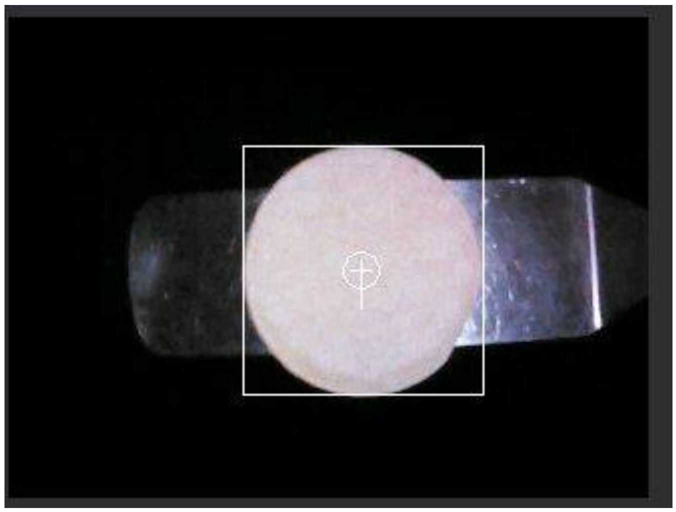


Figure 54: Blob Detection on Bread

The second method tested was canny edge detection (OpenMV, 2024). This method was used to detect food items by outlining their edges. Blob detection was then used to determine the location of said food item. This method was not chosen as background noise could not be filtered out effectively. Our food items were not perfectly smooth, so the algorithm picked up variations in the edges of the ingredients. Figure 55 below demonstrates these algorithms being used to detect a pencil on a desk. This detection was used as a quality control benchmark for these algorithms.

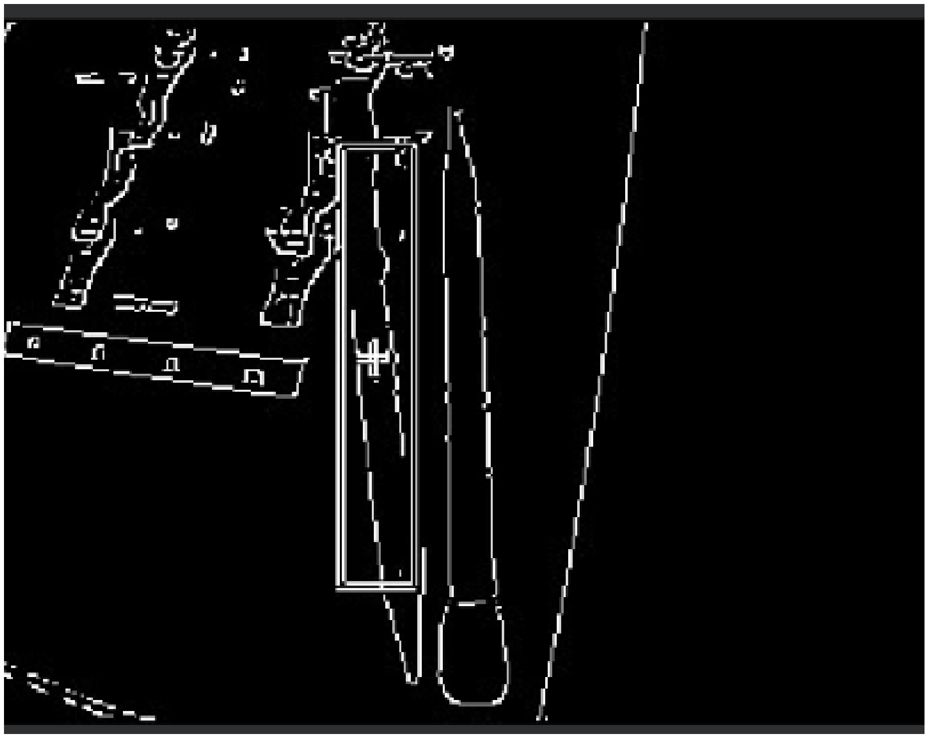


Figure 55: Canny Edge Detection & Blob Detection on a Pencil

The third method tested was a circular detection algorithm (OpenMV, 2024). This algorithm used the Circle Hough Transform (CHT) to find circles of a given radius. The center of the circle was then marked with a cross to denote its location. This method was not selected as background noise could not be effectively filtered out. Since our food items were not perfectly round or smooth, the algorithm struggled to consistently find the food items. Figure 56 below shows the algorithm detecting a copper weight. This weight was used as a quality control benchmark for this algorithm.

Figure 56: Circle Detection on a Copper Weight

The chosen method was a combination of an image differencing algorithm and blob detection. A stored image of an empty spatula was compared to images the camera took of the spatula while the robot was running. By using these comparisons, a black mask was created so that only food items remained visible. Blob detection was then used to find the food item's location on the spatula. Figure 57 shows the algorithms running together to perfectly detect a sausage patty.

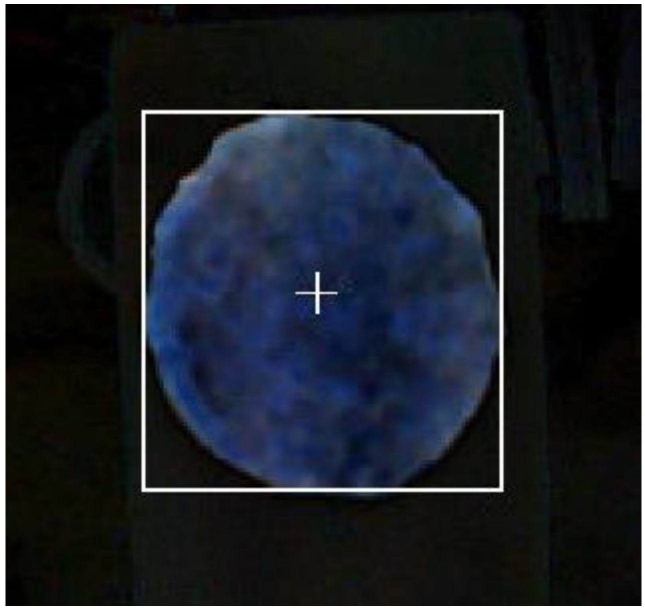


Figure 57: Camera Position Testing using Image Differencing and Blob Detection

To determine if a misalignment occurred, distance thresholding was implemented. The distance in pixels was calculated from the center of the food item to the center of the spatula. If that distance was greater than 25 pixels in X or 45 pixels in Y, a misalignment occurred.

7 Manufacturing and Assembly

This section overviews the manufacturing and assembly process of the Breakfast Sandwich Robot frame as well as its subsystems.

7.1 Full Breakfast Sandwich Robot Assembly

The full assembly of the robot can be seen in figure 58. This includes the sausage and bread distribution systems, egg manipulation system, and both gantries.

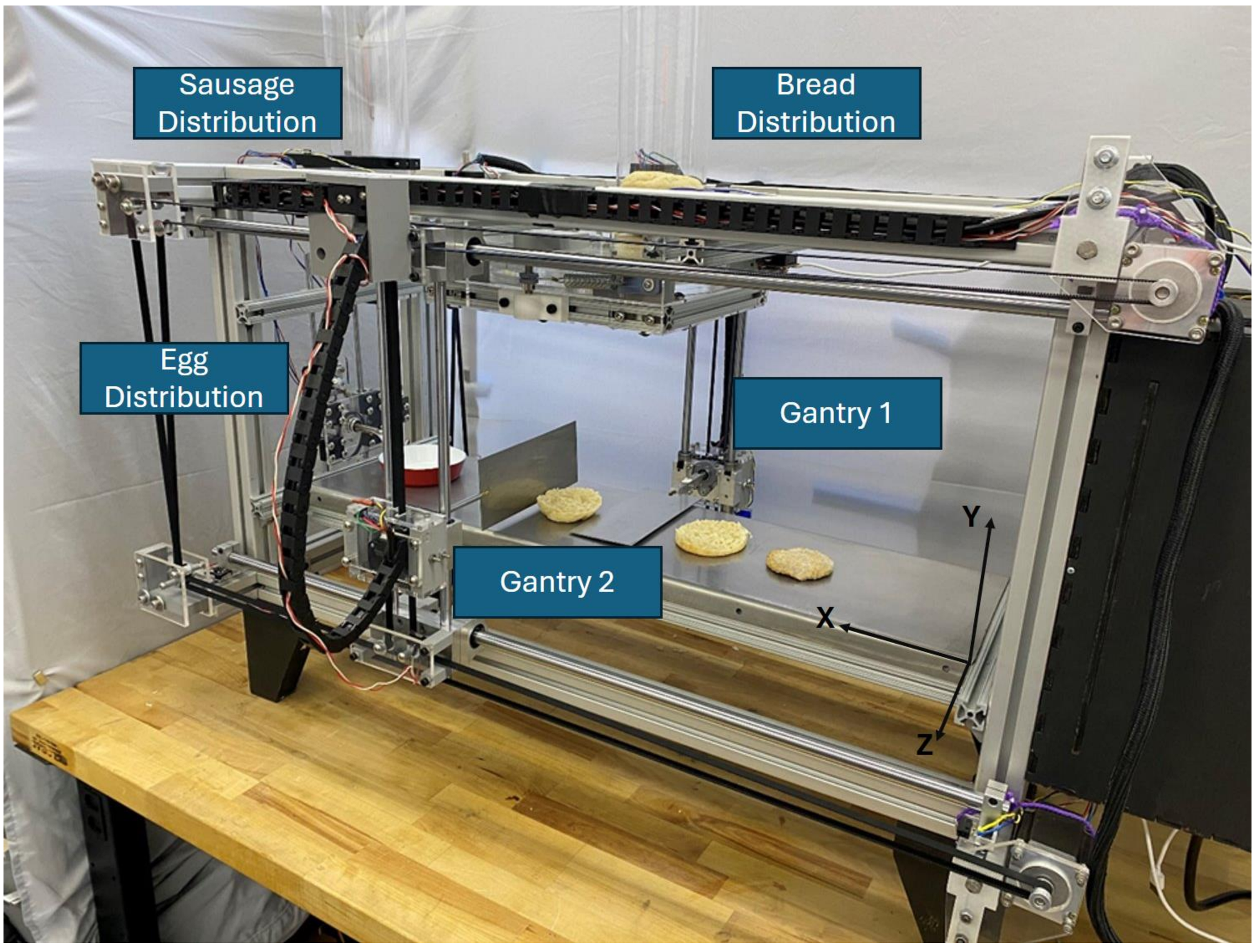


Figure 58: Full Breakfast Sandwich Robot Assembly

7.2 Frame Manufacturing and Assembly

The decision was made to separate the manufacturing and assembly sections from the preliminary testing and design sections of this paper. This does not necessarily follow the chronological order of the project, with prototyping being a large part of the iterative design process. However, this allows the team to organize all the design decisions made throughout the project in one section without going in depth into manufacturing in assembly.

The first step in the manufacturing and prototyping stage of the Breakfast Sandwich Robot was the construction of the frame as pictured in figure 59 below. The 8020 6061 aluminum extrusion frame sections were carefully measured and cut to size on a horizontal band saw and then thoroughly washed. Aluminum elbow brackets were used to fix the aluminum frame in place. The frame itself would be used as a reference for the fixturing of the X axis linear guide rods. To ensure alignment, the 8020 aluminum extrusion was grouped by dimensions before being cut to size. The offset of the extrusions 1 and 2 could then be referenced to the butt of extrusion 3 (see figure 60).

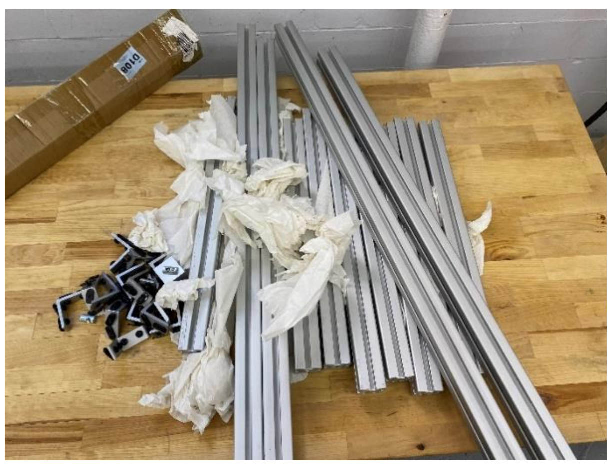


Figure 59: Washed 40 Series 8020 for Frame Construction

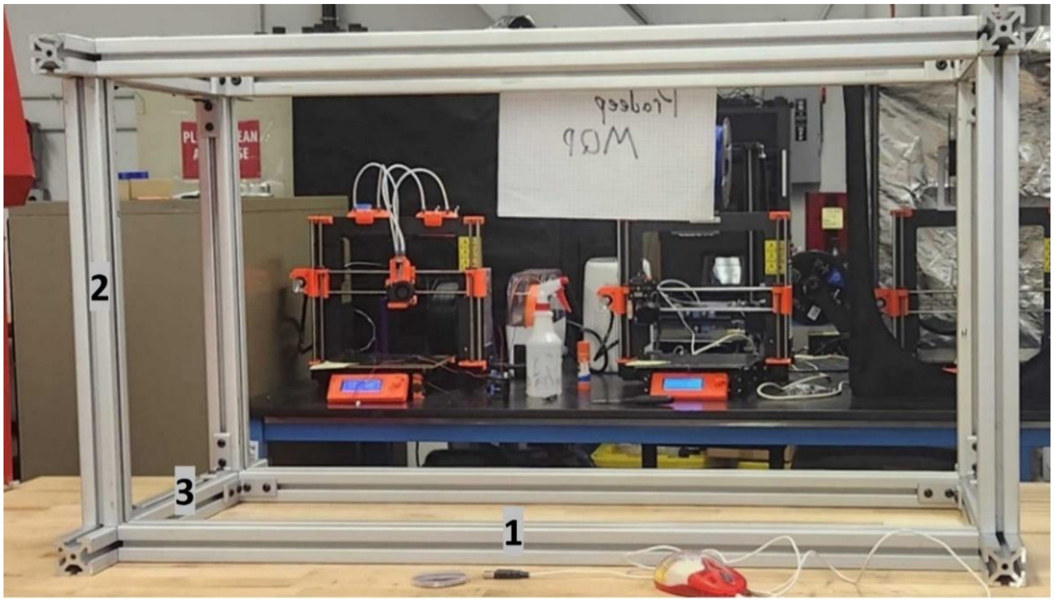


Figure 60: Assembled Robot Frame

7.3 Gantry and End effector Manufacturing and Assembly

Each Gantry consisted of four sub-assemblies, NEMA 23 motor mounts, Corner pulley brackets, spatula housing and the y axis alignment mounts. For the purpose of simplicity, this section refers to the assembly and manufacturing process of gantry 1 as it follows the same process as gantry 2. The figures below display each sub-assembly installed and assembled within the gantry system.

The figure 61 below depicts the y axis alignment mount with the linear guide shaft alignment plates sandwiching the y axis linear rails. The alignment mounts were machined on a super mini mill in the WPI machine Shop. The 3D printed ABS blocks, and a laser cut acrylic sheet were then fixed to the aluminum alignment plates. The pulleys and 3D printed spacers could then be held in place as the number 10 machine screws secured them.

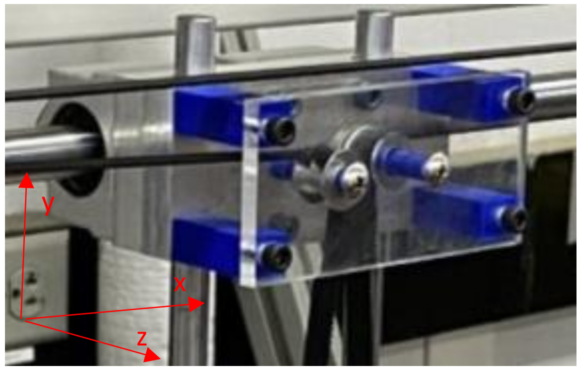


Figure 61: Y axis alignment mount

The Corner pulley brackets were constructed from ABS 3D printed spacers and laser cut 5.2mm acrylic sheet, shown below in figure 62. M6 bolts were then used to secure the bracket to the frame while number machine 10 screws held the pulleys and spacers, like the y axis alignment sub assembly.

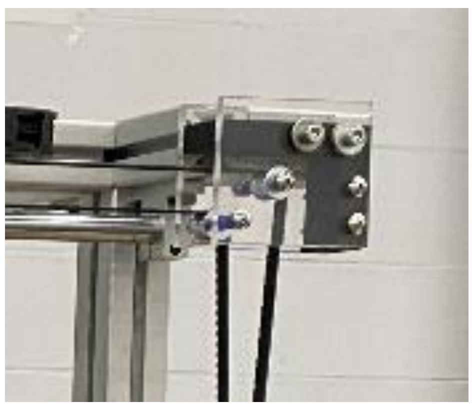
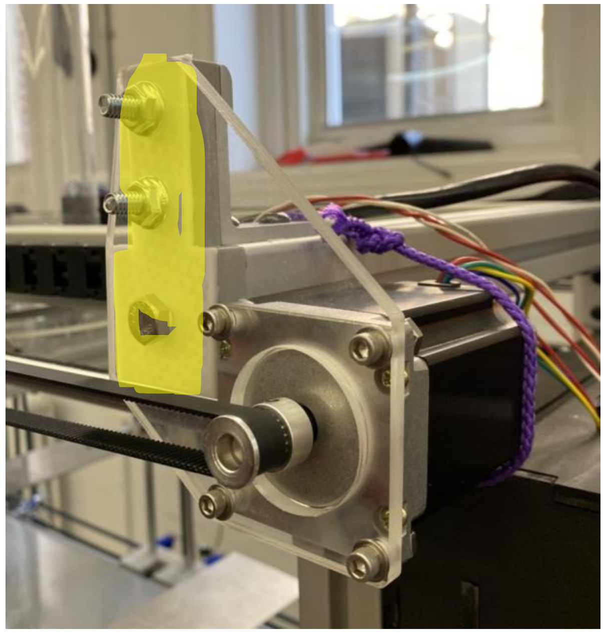


Figure 62: Corner pulley bracket

The motor mounts also used a laser cut plate and ABS 3D printed spacer. To eliminate vibrations transferred to the frame, a 3D printed TPU spacer was stacked with the ABS spacer which is shown in figure 63. The subassembly was attached to the frame with 8020 aluminum brackets and ¼-20 bolts. To further secure the motor mount, the center of the 8020-aluminum abutment was tapped to except an M8 bolt. Finally, the tension force in the belt created a moment around the motor mount attachment which was counteracted with a purple rope held in tension.



Vibration dampening TPU

Figure 63: NEMA 23 mounting bracket

The main piece of the spatula housing is a block of aluminum 6061 that was machined to meet specified geometry. A press fit was designed for both the axel and linear bearing. To do this, each hole was milled under size and then slowly increased in diameter with contour passes until the desired interference fit was met. An arbor press was then used to press the bearings into place. The tapped holes in the block were first drilled on the CNC mill before being tapped by hand. The gears that interface the NEMA 17 with the spatula shaft are composite with an ABS exterior 3D printed on an SLA printer and a steel inner collar that has been epoxied in place. To access the set screw a hole was then drilled through the gear giving access to an Allen key. The exterior 3d printed spacers are ABS plastic fastened into place with number 10 machine screws. The two other holes in the spacers accept number 8 machine screws that fastened down the pre purchased 9mm GT2 timing belt anchors. As with the other assemblies' the acrylic sheets have been laser cut and fastened in place. The rear acrylic sheet was tapped with an M3 thread to fasten the rotary wire couple in line with the spatula shaft. The spatula housing is pictured in figure 64.

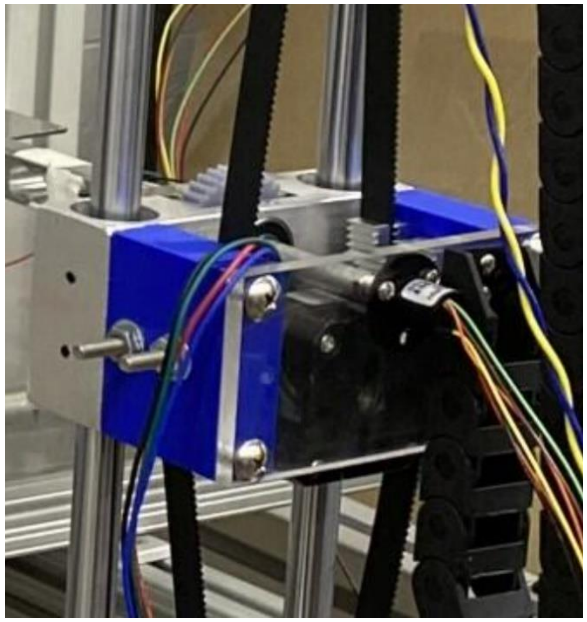


Figure 64: Spatula Housing

The last step in gantry assembly was aligning the linear rails and threading and tensioning the belts. Once the Y axis has been tightened down the gantry is moved back and forth in X to watch for alignment issues. When the X axis anchors no longer move to accommodate the back and forth of the Y axis, then they can be secured down to the frame. Exact alignment is not completely necessary as each of the rails were coplanar and the X axis motor mounts are rested against the frame.

There are two belts for each gantry that were cut to size and threaded through in a core XY configuration. These belts were slowly shortened until there was little play. The belts could then be anchored with the number 8 machine screws and 9mm gt2 clamps on the spatula housing. By loosening the top two M6 bolts on the corner bracket, an outward force of 70 Nwas measured by a handheld force gauge. The M6 bolts would then be re-tightened, uniformly tightening the belts and holding them in place. The fully assembled gantry is pictured in figure 65.

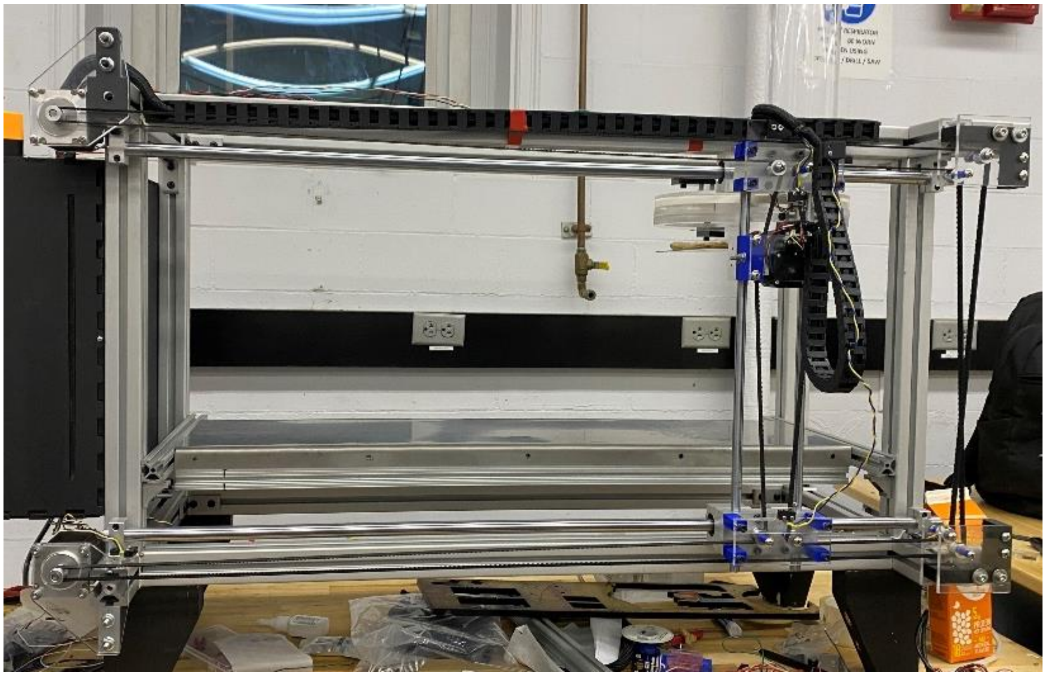


Figure 65: Fully Assembled of Gantry 1

7.4 Spatula Manufacturing and Assembly

The spatula itself was cut using an angle grinder from 16-gauge 304 stainless steel sheet metal. An 8mm 304 stainless steel shaft was then attached to the spatula and press fit into a modified aluminum load cell that was bored out on a CNC mill. The end of the spatula was constructed from AISI 1018 mild steel. To rout the strain gauge wires through the spatula the team bored a hole through the 8mm shaft. The shaft was set up on a Haas mini mill and trammed into alignment with a dial indicator. The figure below shows the spatula fully assembled. An entrance hole for the wire was then drilled out next to the load cell. The assembly of the spatula can be seen in figure 66.

Figure 66: Spatula Assembly

Once the spatula was fabricated, it was mounted into the spatula holder. While inserting the shaft, the wires from the rotary couple were threaded through the shaft inner diameter and soldered to the strain gauge wires. During this same process, the large composite gear was inserted and sandwiched by the thrust washers. Using a dial indicator and shifting the from acrylic bearing plate the spatula was trued into position, eliminating any run out as pictured in figure 67.

Figure 67: Spatula Alignment and Tramming

7.5 Sausage Distribution Manufacturing and Assembly

The MQP team collaborated with the B-term ME 4320 design team to fabricate and assemble the sausage distribution. The three rotary plates were laser cut from acrylic while the spur gears were 3D printed. And the center alignment shaft was cut to size and pressed into the inner diameter of the disk bearings. This assembly can be seen in figure 68.

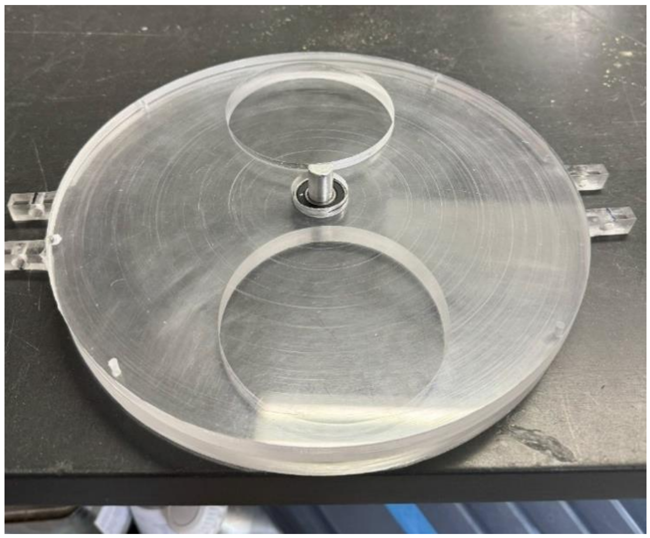


Figure 68: Sausage Disk Assemble

Once the disks were aligned, no. 4 threads were tapped into the acrylic. These holes were used to fasten the 3D printed outer gear to the top disk. The NEMA 17 motor and spur gear were then mounted to the top plate and interfaced with the outer gear. Once mounted with 8020 aluminum, a 3D printed coupler was used to hold the acrylic tube in place. The mounted sausage distribution can be seen in figures 69 and 70.

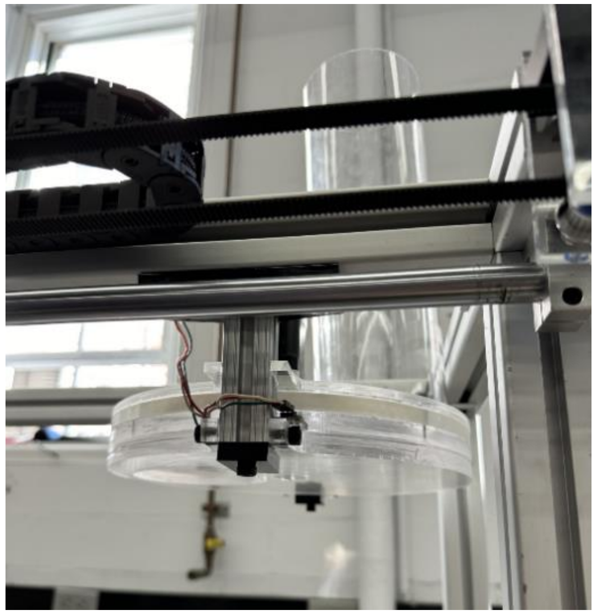


Figure 69: Mounted Sausage Distribution Side View

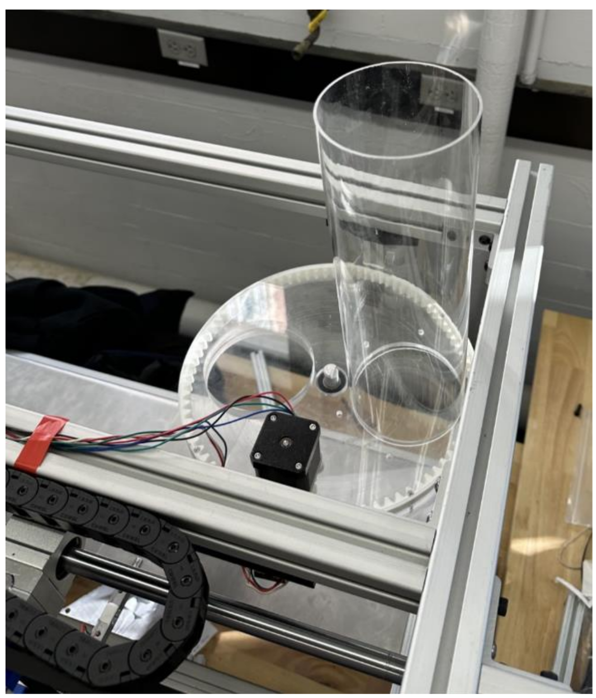


Figure 70:Mounted Sausage Distribution Top View

7.6 Egg Distribution Manufacturing and Assembly

The Egg Distribution was prototyped but never fully implemented within the system. The two main plates are laser cut acrylic that sandwiches the linear bearings with 3D printed Nylon spacers. The pan handle was bent in a vice to accommodate the shape of the pan shaft and then was screwed into the rotary shaft. Figure 71 below shows the egg distribution assembly mounted to the robot.

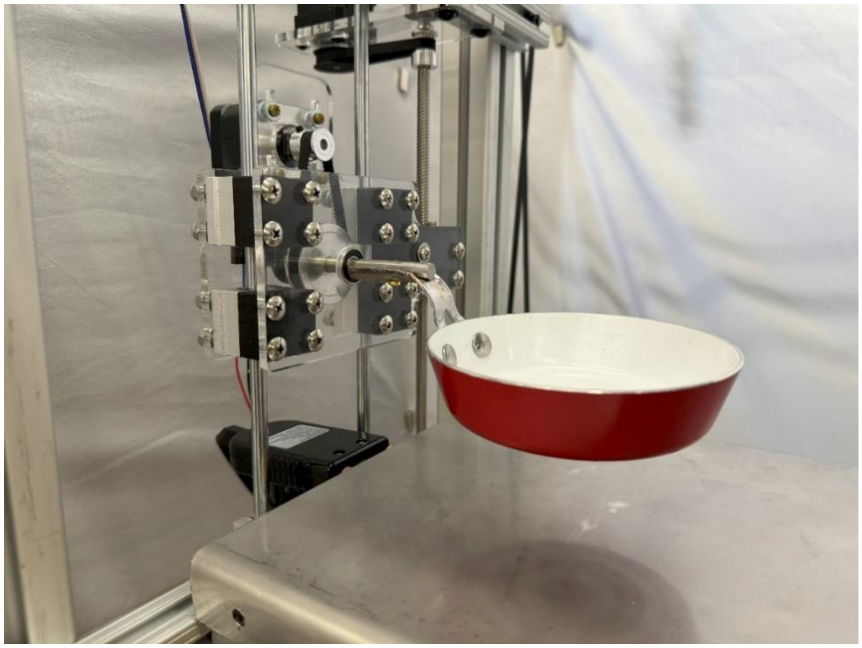


Figure 71: Egg Distribution Assembly

7.7 Work Surface Manufacturing and Assembly

The Breakfast Sandwich Robot work surface was made from a 16-gauge (1.6mm) AISI 304 stainless-steel sheet, cut to size with a shear as shown in figure 72. A break was then used to bend the flanges on the worksurface to grab ono the frame. The frame consisted of 1-in 8020 aluminum extrusion that were cut to size with a vertical band saw. Each section was then bolted together with T-slot hardware as pictured in figure 73.

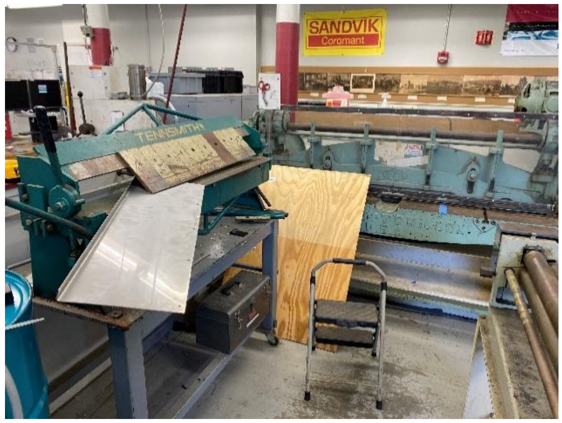


Figure 72: Work Surface Bending Operation

Figure 73: Heat Source Attachment to work surface

To attach the heat source to the bottom of the work surface, the griddle attachment was sandwiched under the frame of the worksurface and tightened in place using screws to press the heat source firmly against the stainless steel. The work surface attached to the frame is pictured in figure 74.

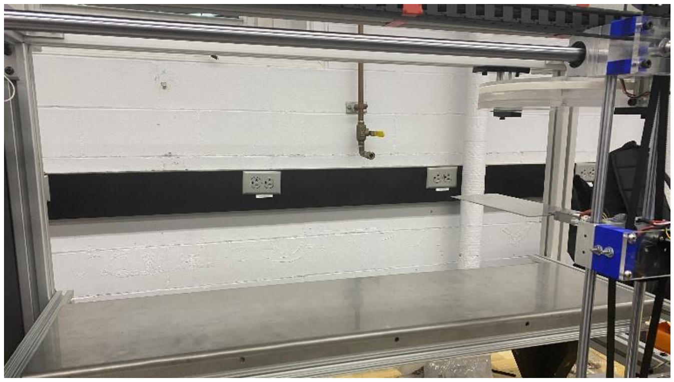


Figure 74: Assembled Worksurface

8 Electronic Hardware Design

8.1 Electronic Implementation

All the electrical components are stored in a wooden electrical box as shown in Figure 75, which is attached to the chassis of the machine.

Figure 75: Electrical Box

There are two gantries, each equipped with two NEMA 23 stepper motors for translation about the X and Y axis, and one NEMA 17 stepper motor which is responsible for the angle of the spatula. There are four limit switches for each gantry each placed at the ends of the x and y axes, as well as one hall effect sensor for each spatula. These sensors are used to set a ‘home’ position. The sausage distribution system has one NEMA 17 stepper motor and the bread distribution system has one NEMA 23 stepper motor each, with a hall effect sensor to determine the home position. The egg distribution system uses a peristaltic pump powered by a 24 V stepper motor and two NEMA 17 stepper motors for actuation. The system is controlled by an ESP-32 microcontroller through the ESP-IDF, a framework for the ESP-32. Power for the ESP-32 was sourced from the Raspberry Pi's 3.3 V pin, and it established a connection with the Raspberry Pi via UART communication. The Raspberry Pi itself received power from an LM2596 DC-DC Buck Converter, which transforms the 24 V from the DC power supply to a safe 5 V that the Raspberry Pi can use. A circuit diagram of the entire robot can be found in figure 76 below.

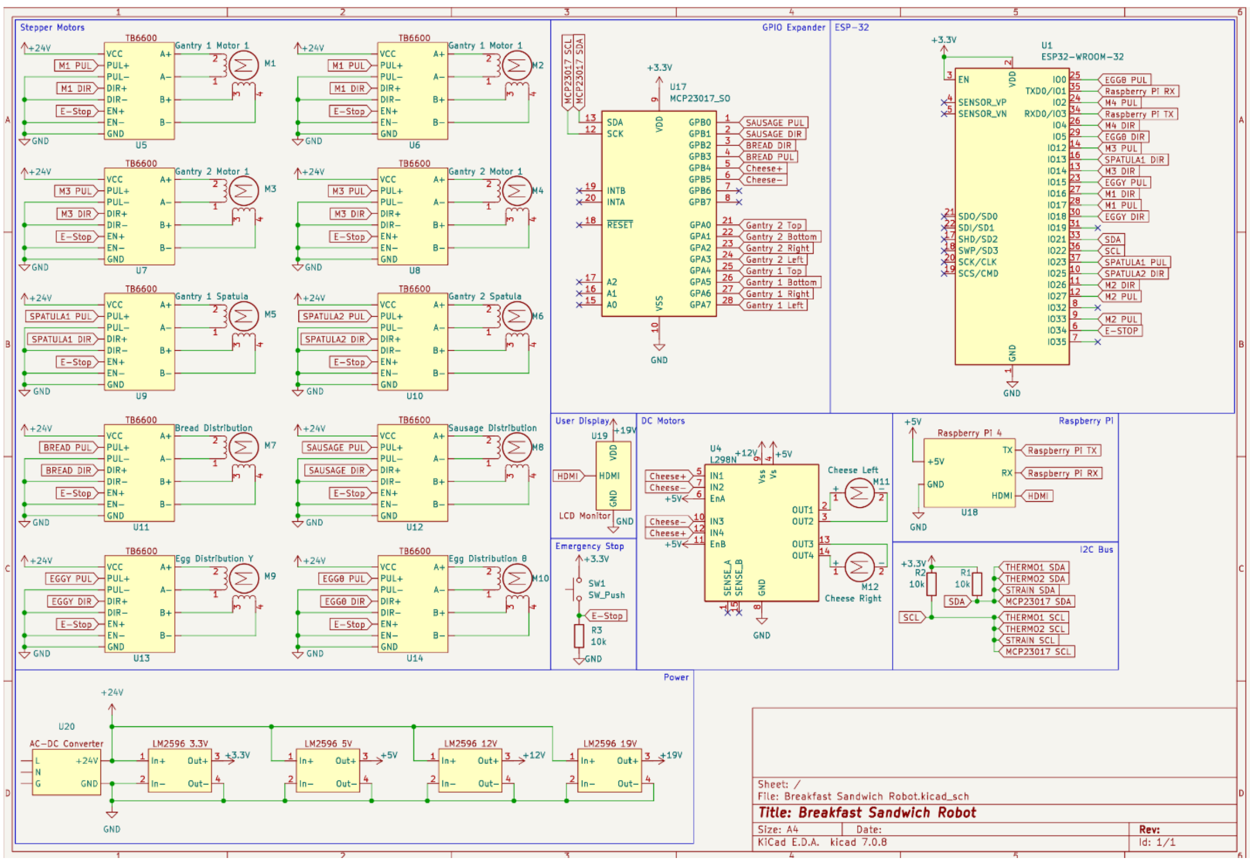


Figure 76: Complete Circuit Diagram

The NEMA 23 and 17 stepper motors are driven by TB6600 drivers, which can run from 9 to 42V, and supply up to 4 A/phase. These drivers can also micro-step up to 1/32, meaning they can have a resolution higher than the stepper motors built in resolution. Since each stepper motor has 200 steps, micro-stepping allows for 6400 total steps, drastically increasing the precision in the system. The system is powered by a switch-mode power supply. This transforms the AC power from mains into DC power that the system can use. Using the power derivation of Ohm's law, $P = IV$ system's maximum power consumption was calculated to find the needed power supply ratings.

- The 4 NEMA 23 stepper motors run at a maximum of 24 V at 3 A, requiring 288 W.
- The 4 NEMA 17 stepper motors run at a maximum of 24 V at 1.5 A, requiring 144 W.
- The peristaltic pump runs at a maximum of 24 V at 1.8 A, requiring 43.2 W.
- The 2 DC motors run at a maximum of 12 V at 1 A, requiring 24 W.
- The ESP-32 runs at a maximum of 3.3 V at 0.25 A, requiring 0.825 W.
- The Raspberry Pi runs at a maximum of 5 V at 3 A, requiring 15 W.

This means the minimum power required for the system is 515 W, with a 643 W power supply required with a 20% safety buffer. For prototyping purposes, we used what we had available, which were two 24 V power supplies, wired in parallel to achieve a total output of 830 W.

To facilitate development of the prototype, it was helpful to keep components as modular as possible, as to make isolation of any issues that arise as streamlined as possible. The team achieved this by the creation of dongles using wire ferrules on one end and bullet connectors on the other end. The wire ferrules minimized the damage done to wire from screw terminals, which facilitated the reusability of these wires, and the bullet connectors allowed "plug and play", where the motors can be plugged in and out without any special tools, which is not the case for screw terminals. This system combines the stability and security of wire terminals and the replaceability that comes with bullet connectors, which made development easier for this team and future teams as well. As for the wires that connect from the gantry to the electrical box, they are managed by cable drag chains which attach to the 80/20 chassis and are also organized by braided cable sleeves. Finally, the DC power is wired in series with a singlepole single-throw switch, which turns on the entire system. Figure 78 pictures the electrical hardware inside of the electrical box.

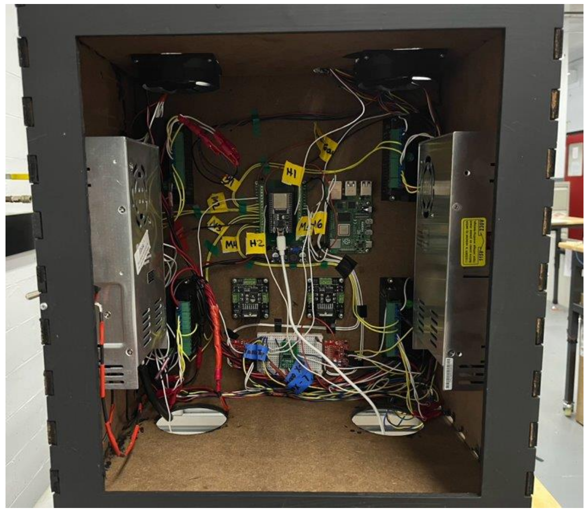


Figure 77: Current State of Wiring

8.2 System Architecture

Table 14: Microcontroller Design Matrix

		Design Ideas		
Design Criteria	Weight (Importance 0%-100%)	Arduino Mega 2560	ESP-32	Teensy 4.1
High Instruction Speeds	60%	3	6	7
Affordability	70%	3	10	4
Ease of Development	30%	7	7	3
Adequate GPIO	50%	5	7	5
TOTAL		10.6	16.2	13.2

Table 15: Microcontroller Design Matrix Reasoning

Design Matrix Reasoning				
Design Criteria	Weight (Importance 0%-100%)	Arduino Mega 2560	ESP-32	Teensy 4.1
High Instruction Speeds	Higher instruction speeds allow for more processes to be done simultaneously in a reliable manner.	The Arduino Mega 2560 runs on a single core ATmega2560 at 16 MHz running at 16 DMIPS.	The ESP-32 runs a dual core Xtensa LS6 at 240 MHz, and performing up to 600 DMIPS	The Teensy 4.1 runs a single core ARM Cortex-M7 600 MHz
Affordability	A constrained prototype budget makes cost a significant factor.	$50	$10	$40
Adequate GPIO	Needs enough general-purpose input/output to control peripherals and read sensors.	54	34	21

As seen in the design matrix, the ESP-32 met the system's requirements, and was chosen for the microcontroller. The dual core system allows for simultaneous communication and computation to talk to the Raspberry Pi and drive the motors at the same time. To make parallelization possible in a deterministic way, the system uses a Real-Time Operating System (RTOS) (Cedeño, 2007). This is different from the traditional super loop as seen in other embedded systems as it has numerous tasks running concurrently, rather than looping through set instructions continuously. Figure 79 shows the General-Purpose Input Output (GPIO) assignments for the ESP-32. The I2C bus allows multiple “slave” devices to connect to the microcontroller through only two wires: one for clock signals, and the other for data signals (Figure 79). This conserves the amount of available GPIO in the ESP-32, and facilitates the use of our sensors, as they can be abstracted away by the libraries that come with the ADC’s. The sensors that we will take advantage of this with will be the strain gauge and thermocouples. The system uses an emergency stop button, which is hardwired to the enable pins of every stepper driver. This ensures that the motors will stop every time regardless of the state of the software, which is crucial for the safety of the operators of the machine. This emergency stop button also sends a signal to an input pin of the ESP-32, which then sets a state flag of 0x0400, which corresponds to “SYSTEM_FAILURE”.

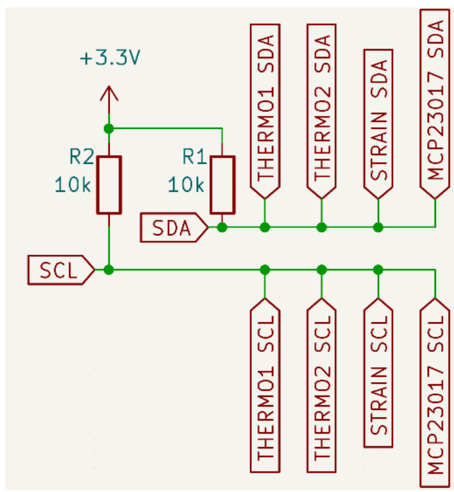


Figure 78: I2C Bus

9 Software Control

The software structure followed in this project relies on using a microcontroller with a Real Time Operating System (RTOS) in combination with a Raspberry Pi to receive sensor data and time motor operations. Use of an RTOS in this project was necessary due to the number of tasks that were necessary to run in unison within the system, as shown by the State flowchart diagram found in appendix D. The state flowchart diagram was designed using the Unified Modeling Language (UML) state/activity schema. The main states of this diagram are initialization, idle, network update, sandwich cooking, bread preparation, egg preparation, sausage preparation, sandwich assembly, and return to idle. Each of these overarching states progress through multiple of the system states described below and this diagram was used to determine the order of actions for the machine to complete.

States are both on the ESP-32 and the Raspberry Pi in unison and multiple states can be run in parallel. Control of the states are communicated between the ESP-32 and Raspberry Pi in two bytes, where each flag is either a one when active or a zero when inactive. This system allows for bit operations to quickly activate and deactivate singular states while other states are active in parallel (shown in figure 80).

```
enum States {
    GANTRY_1_MOVING = 1,           // ---- ---- ---- ---X 0x0001
    GANTRY_2_MOVING = 2,           // ---- ---- ---- --X- 0x0002
    OVEN_HEATING = 4,              // ---- ---- ---- -X-- 0x0004
    WATER_BOILING = 8,             // ---- ---- ---- X--- 0x0008
    CALIBRATING = 16,              // ---- ---- ---X ---- 0x0010
    CLEANING = 32,                 // ---- ---- --X- ---- 0x0020
    POLLING = 64,                  // ---- ---- -X-- ---- 0x0040
    CHEESE_DISPENSING = 128,       // ---- ---- X--- ---- 0x0080
    SAUSAGE_DISPENSING = 256,      // ---- ---X ---- ---- 0x0100
    BREAD_DISPENSING = 512,        // ---- --X- ---- ---- 0x0200
    SYSTEM_FAILURE = 1024,         // ---- -X-- ---- ---- 0X0400
    FLIP = 2048,                   // ---- X--- ---- ---- 0X0800
};
```

Figure 79: State Byte Description

Differentiation of the data packets are described by the first byte of the package specifying the type of data contained. The current types of data sent from the Raspberry-Pi to the ESP-32 are state, motion, and data request. While the current type of data sent from the ESP-32 to the Raspberry Pi are state, sensor data, gantry motion data confirmation packets for coordination, and the flip data confirmation packet. This design allows for multiple distinct types of packages to easily be unpackaged between the Raspberry Pi and the ESP-32 microcontroller while maintaining packet interpretability.

Motion of the gantry was accomplished by use of interpolated motion and the ESP-Fastaccelstepper Arduino library documentation provided in Appendix J. Interpolated motion was achieved with inputs of future position, acceleration, and velocity in mm to complete the motion and use of inverse kinematics. An array is returned from the function that contains the future position, acceleration, and velocity for the two motors and spatula motor in the target gantry. Data returned is packaged and sent to the ESP-32 and stored until the state of motion is selected for that specific the gantry. C++

Class structure was developed for both the C++ environment of the ESP-32 and the Python environment of the Raspberry Pi code. In each environment, there is a data packaging class to handle the specific protocols sent between the two. While there is a gantry class on both sides, the ESP-32 is designed to handle preplanned trajectories and distribute to the three motors of the gantry and on the Raspberry Pi trajectories are planned and created. In the system, the Raspberry Pi handles most of the computing and the ESP-32 handles and interprets sensor data while simultaneously controlling the motors to move in unison. Each environment utilizes a controller class that handles interpretation and storage of information.

9.1 Circular Gantry Motion

Circular gantry motion with the stepper motors was the most difficult software design task. Coordination of both gantries in real time was critical as they were rotating around the same axis with an ingredient held between them which would fall out if constant pressure were not applied. The fastaccelstepper library was chosen for its speed within the ESP-32 environment but did not provide dynamic acceleration or velocity change in motion. The team had to develop software that could interact with the low-level access stepper motor queue of the library. This queue was limited by the approximate 65,000 ticks and 255 steps it could perform per entry. The tick's maximum represented a 4 millisecond pause in between the next step. Utilizing the max tick size per queue entry, a size can be generated for a vector that contained the highest number of steps possible within 4ms periods allowing for a higher resolution of the circular path. Completing this task relied on the formula below.

$$r \;=\; radius,\; v_t = \tan v\,elocity,\; pc \;=\; 39.9767665169,\; phase = -\frac{\pi}{4}$$

$$v_t = 12mm \cdot \pi$$

$$time \;=\; \frac{(r \cdot \pi)}{v_t}$$

$$arraysize \;=\; \frac{time \cdot 16{,}000{,}000}{65{,}535} + 1$$

$$d\theta = \pi \cdot radius$$

$$dstepmagnitude = \frac{2 \cdot r \cdot \sin\left(\frac{d\theta}{2}\right) \cdot \sqrt{2} \cdot 1600}{pc}$$

$$m1steps(i) = \sum_{i=0}^{arraysize} round\big(\big|dstepmagnitude \cdot -\sin\big((dtheta \cdot i) - phase\big)\big|\big)$$

$$m2steps(i) = \sum_{i=0}^{arraysize} round\big(\big|dstepmagnitude \cdot \cos\big((dtheta \cdot i) - phase\big)\big|\big)$$

9.2 Developer interface

The developer interface was implemented to allow easier control of the robot for the development of motion control of the dual gantry manipulation system. To record and implement the motion tested on the developer interface, runs are written to csv files for each move or interaction. These moves are not necessarily specified exact movements but rather a set of instructions that rely on the internal sensing provided by the code in the ESP-32. This mix of developer input motion planning and internal sensing are fed back to the machine after calibration once an order is placed to cook and assemble the breakfast sandwich.

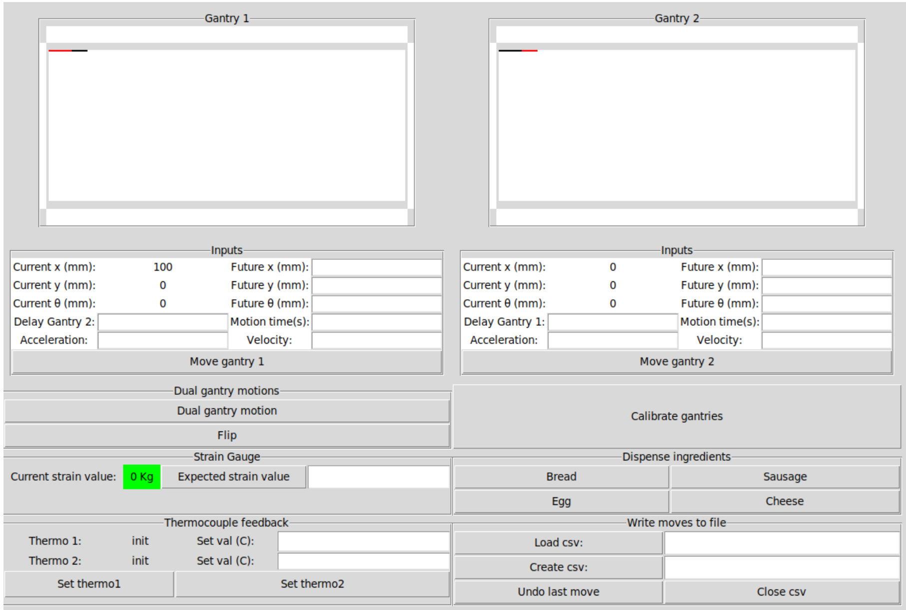


Figure 80: Breakfast Sandwich Robot development application.

Figure 81 shows the developer interface layout. It represents each gantry on a canvas with black as that side's spatula and red as the opposing side's spatula, with side bars that light up for the corresponding limit switch. Each gantry is then able to have its position input, a time of motion, and a delay added to the other gantry which defaults to the time of motion. When the button move gantry x is pressed, only that gantry will move. If dual gantry motion is pressed, both gantries will move in unison for their specified periods of motion. The flip motion will dynamically flip the spatulas around each other and align in x. It is possible to specify a strain gauge expected value and both thermocouples' values in degrees Fahrenheit. All dispensing is linked to a button which will dispense one of each specified ingredient. The csv to be written to can be loaded or created. Loading, which will configure the gantries to the last specified position of each and append to the csv file for each move. Creating will make a new blank csv and start the gantries in their respective start positions. There are buttons to undo the last move in a csv which will also move the gantries to prior position if the last move is a gantry move command, and a button to close the csv file.

10 Breakfast Sandwich Robot Testing & Discussion

10.1 Breakfast Sandwich Robot Testing 1st Iteration:

The goal of the first iteration of our robot was to move one gantry to the sausage distributor, dispense a sausage patty, and then move to a final position. To achieve this goal, the team first tested the spatula leveling system to ensure that our spatula was level when picking up the sausage. This test was successful as the spatula was level every time the algorithm was run. Next, the gantry's homing state was tested. The gantry homed by moving in the -X direction until it hits a limit switch. The gantry then moves in the +Y direction until it hits a limit switch. This test was successful as the gantry was able to consistently hit the limit switches in both directions.

After homing, gantry movement was tested. The gantry moved to specific positions using interpolated movement. This test was mostly successful as we were able to move the gantry from its initial position to the sausage distributor. However, it failed to meet our speed requirements, which was likely due to the bottleneck of the ESP-flexystepper library used in this phase of the project.

Sausage dispensing was the last test we ran for our first iteration. Our test was partially successful as we were able to dispense a sausage onto the spatula. However, we could not continuously dispense sausage in this iteration due to behavior surrounding the hall effect sensor and bugs in code at the time.

10.2 Gantry Testing

The objective of the Gantry Accuracy Test is to ensure that both gantries can move in the X and Y directions accurately. This test was necessary because the gantries must be positioned exactly where we tell them to go. Inaccuracies in the positioning of the gantries can lead to issues with the system. Examples of these issues would be dispensed ingredients missing the spatula, the breakfast sandwich falling off the spatula, or the gantries running into obstacles.

For this test to be successful the following requirements must be met:

- Each gantry must be able to drive in ±X and Y directions within a tolerance of ±1.30 mm (50 thou)
- Each gantry must be able to complete the test within 5 seconds
- Each gantry must achieve a max velocity of 0.5 m/s and acceleration of 0.35 m/s^2

To perform our test, we placed the Sharpie in the holder and put painters tape on the bottom. We then put a piece of painters tape on a spatula and superglued it to the painters tape on the holder. We then zip tied a piece of wood to the side opposite the electrical box and taped a piece of paper to it.

For the X direction test, we turn the spatula -15° and draw a line 15 cm long in the positive X direction three times (see figures 81 and 82).

The materials used for this test were:

- Both Gantries
- Sharpie
- Custom Sharpie holder
- Wood board
- Painter's tape
- Super Glue

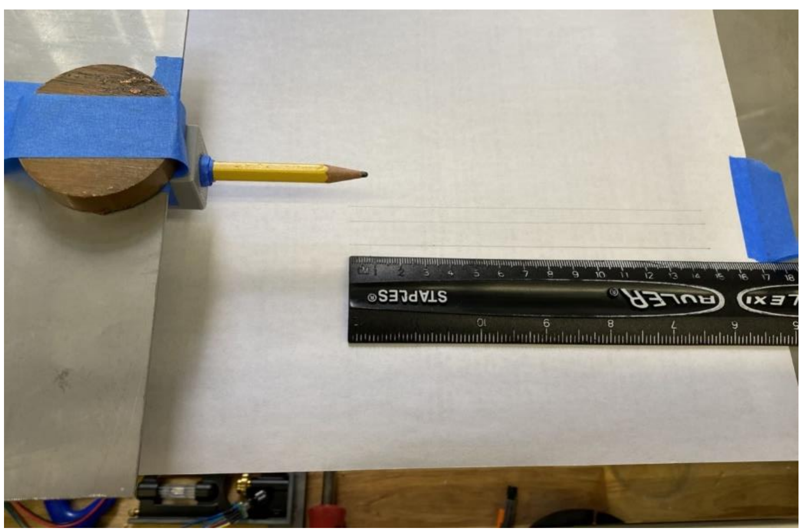


figure 81: Gantry Motion Testing in X Direction

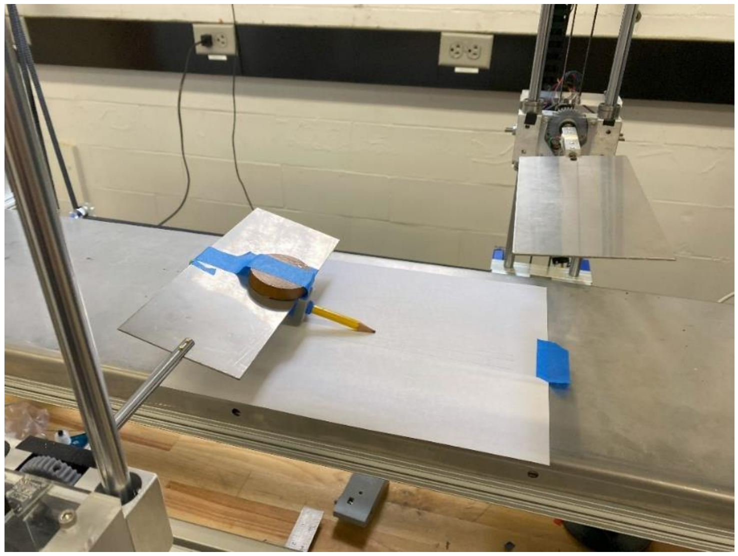


Figure 82: Gantry Motion Testing in X Direction

Using a caliper, each test was measured at a negligible variation of 15mm meeting the requirement of +/- 1.3mm. A dial indicator was used to further test the accuracy in the X direction with no significant in accuracy (see figure 83). Further test with higher precision equipment were found unnecessary due to the requirements already being met.

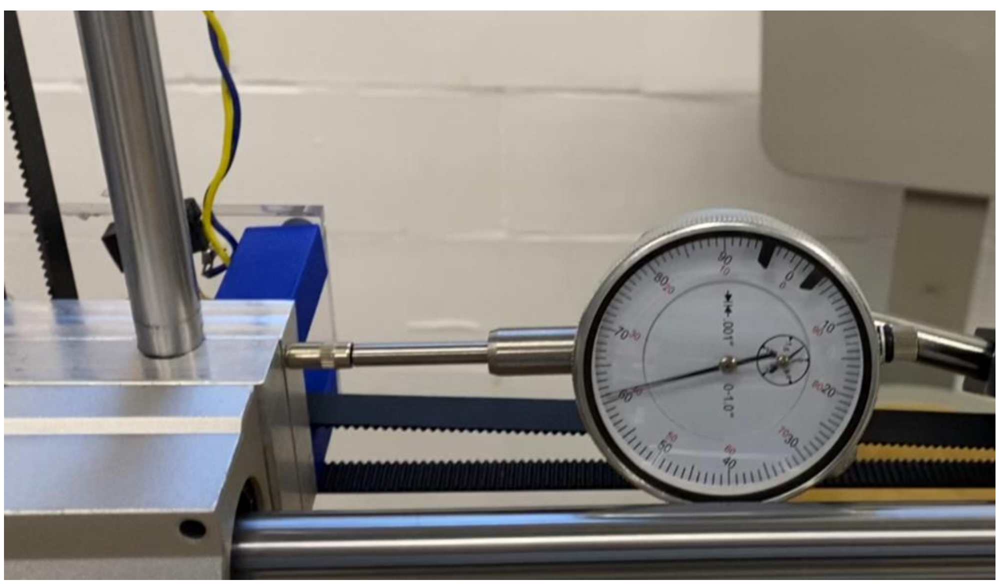


Figure 83: Dial Indicator Test on X axis.

10.3 Work Surface Testing

Two separate temperature tests were performed on the worksurface to ensure the specified thermal design requirements were met.

The first test looked at the time for the worksurface to meet steady state conditions when set to 177 °C (350°F) (see figure 84). This followed a simple procedure of reading out thermal couple values every 0.75 seconds until the temperature increase reached an asymptotic limit. This limit was quantified as a less the 1 deg change over a 20 second period.

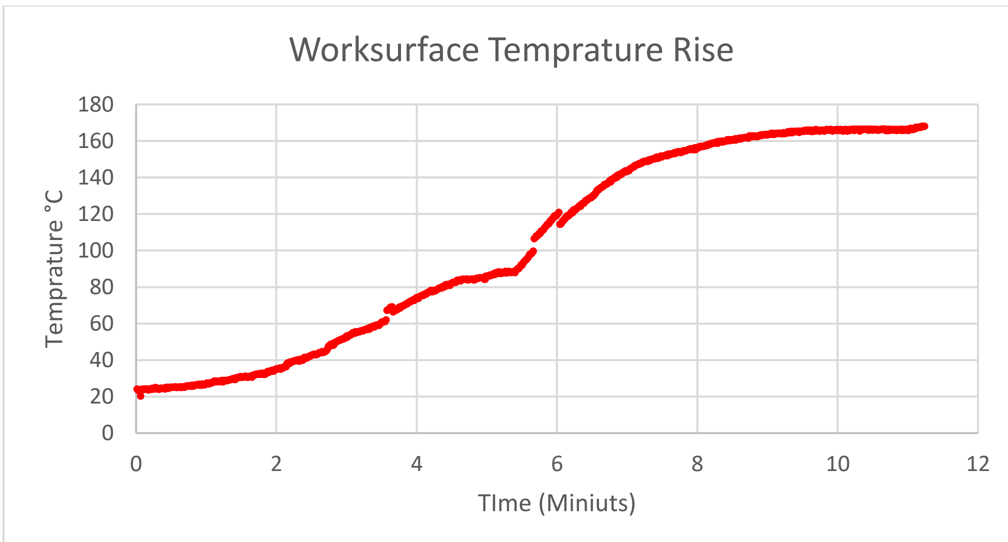


Figure 84: Worksurface Temperature Rise Over Time

From these tests it was found to take **9:20** minutes to reach the previously defined steady state condition. It should be noted that data before the 100 °C mark is likely skewed by the thermal couple's slow reactivity at low temperatures. As the temperature increases past 100°F the thermal couples can keep up with the temperature change.

The purpose of the second test was to examine the thermal profile of the worksurface. For this test the heat source was set to 190.5 °C (375 °F) and 10 data points were collected across the x axis (see figure 85).

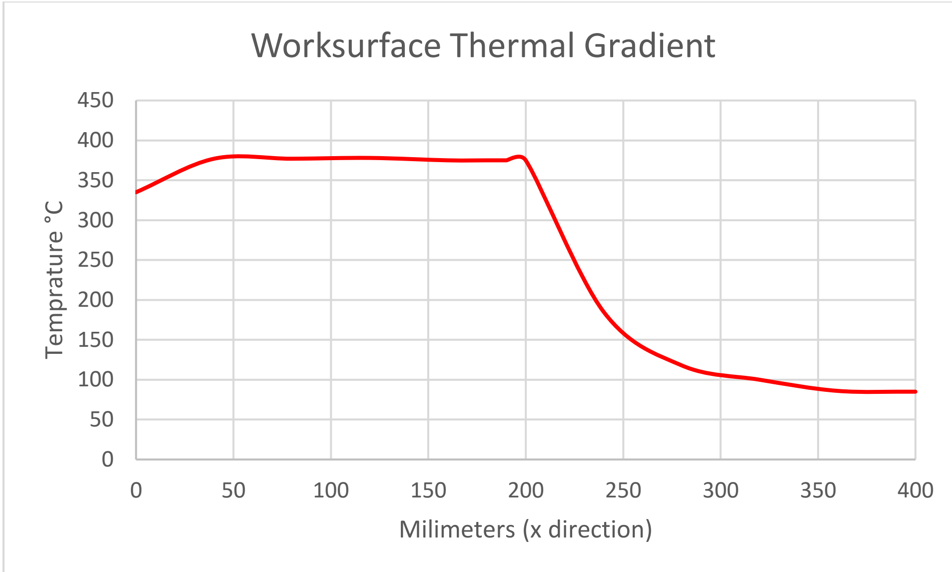


Figure 85: Worksurface Thermal Gradient

Above shows the results of the thermal gradient test. This test validates the thermal boundary conditions set in the design specifications; however, it does reflect a much faster temperature dissipation after the 200 mm mark than what was predicted in simulation. This is likely due to a higher convection coefficient than previously predicted.

10.4 Circular motion testing:

Circular motion required rigorous testing of its calculations, motion paths, and synchronization of the gantries. We tested our MATLAB path planning algorithms by comparing their outputs to those calculated on the ESP-32 for pre-motion planning. Only the speed of the motors was defined by this calculation due to their storage type of unsigned 8-bit integers. The direction of the motors was then divided by the quadrant of the circle that the end effector would be in. The path of each end effector was recorded in slow motion and tracked to ensure the proper path was followed. The timing of the spatula rotation was also confirmed using slow motion video to ensure proper synchronization. The distances were confirmed by marking the start point of the spatula housing on the linear rail and a measurement of the final position from that point. Finally, the spatulas were aligned and had the distance between them measured at the beginning and end of motion to confirm the motion executed properly.

Initially, it was believed that the motion was incorrect as there was an approximate 2 mm change in distance between the two spatulas. After further adjustments to the spatula's alignment, the motion performed within the design requirements.

10.5 Stepper Library:

Originally, a fork of the FlexyStepper library specifically for the ESP-32 was used to drive the stepper motors. This library allowed for the real-time dynamic allocation of velocities. It was desired as it allowed for the generalization of complex motion. However, this feature caused the library to consistently have overhead calculations. These overhead calculations caused a bottleneck in the processor and drastically affected the maximum speed of the motors. The library was switched to the FastAccelStepper library to eliminate these issues.

10.6 Camera Testing:

The camera required robust testing to ensure that the image differencing and blob detection algorithms worked accurately and reliably to detect food items. In a successful test, the camera accurately detected food items by drawing a square around them. It also drew a cross at the center of the food item, indicating the food item’s location. It also can print an error message when the food item starts to hang over the edge of the spatula with the strain gauge. Or when the food item becomes only partially in view of the camera.

Since our spatulas were made of stainless steel, testing needed to be done to determine if reflections from the spatula would cause issues with the camera. To test for reflections, the camera took pictures of an empty spatula continuously. No detection algorithms were run for this test. The team then analyzed the pictures to see if there were any reflections that blinded the camera. After testing, there were no reflections that caused significant issues.

A second reflection test was then conducted to simulate a bright environment (such as being in front of a window on a sunny day for example). A light was shined directly on the spatula to simulate the given environment. After testing, the camera did pick up reflections from the light, but they were not significant enough to disrupt the camera's view.

To test the detection algorithms, the gantry with the strain gauge was moved to the coordinate (229, 42) mm. This coordinate was chosen as it was easiest for the camera to detect food with minimal noise. An English muffin bottom was placed on the spatula. It was then moved to ten random positions, five of which were misalignments, and five that were properly aligned. The test was then repeated with five additional English muffin bottoms. The camera was then tested with English muffin tops and sausage, following the same procedure. After performing these tests, we found that the detection algorithms were successful in masking out the background. However, inconsistent lighting prevented accurate blob detection. To address this issue, we developed a lighting system for the camera. A 3D printed holder was created so that LED strip lights could be stuck to its perimeter. A piece of Lexan was also placed below the lights to act as a diffuser. A hole was also cut out for the camera to see through. The lighting display mounted to the robot can be seen in Figure 87 below.

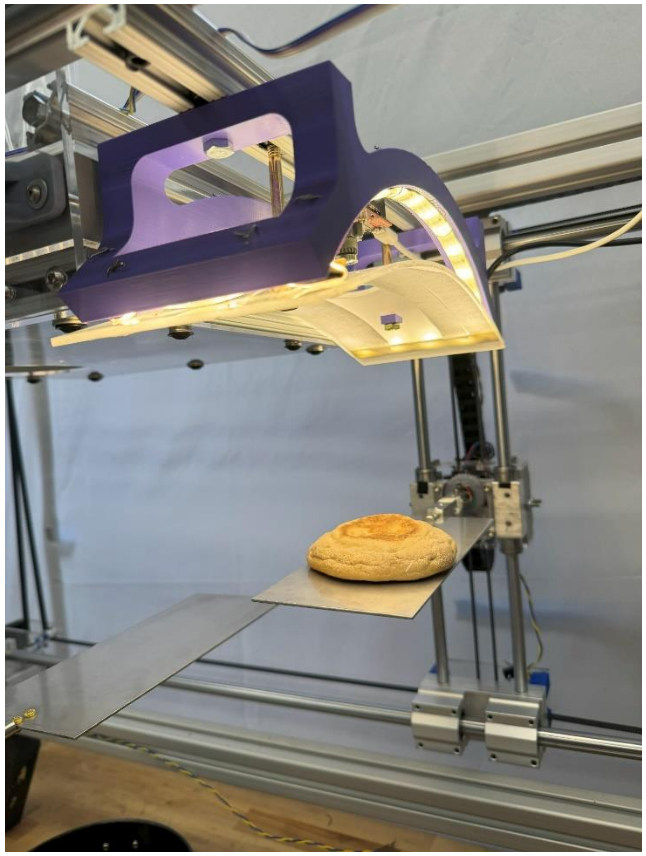


Figure 86: Camera Lighting System

Implementing the lighting system drastically improved blob detection success, but it did have one minor drawback. Reflections off the spatula caused the light and dark areas of food items to be inverted. This caused the camera to see the negative images. That was why food items appeared blue under the camera. This was not a major issue as we implemented a line of code to invert the light and dark areas back to normal. The camera was still left seeing only the image negative, but the inversion correction allowed the camera to see images like normal.

After numerous trials, the ideal thresholds for each algorithm were found. For image differencing, the blending threshold was set to 128, which provided the best background masking. For the English muffin tops and sausage, the lighting threshold was set to [(14,100)]. For English muffin bottoms it was set to [(9,100)]. With these thresholds, the camera could detect English muffin bottoms and sausage anywhere within the cameras view. It could also detect English muffin bottoms anywhere within the camera's view ~75% of the time.

10.7 Breakfast Sandwich Robot Testing 2nd Iteration:

The goal of the robot in its 2nd iteration was to autonomously assemble a sausage sandwich with error detection. The robot would make use of the state machine, circular motion, camera, and strain gauge to accomplish the goal.

The team failed to accomplish the goal of the 2nd iteration. What we were able to accomplish was a demonstration of both gantries homing and then picking up an English muffin. The English muffin sat at a specified place marked with blue tape on the worksurface. Once picked up it was flipped over and put back on the worksurface. This is what we presented for Project Presentation Day. However, this demonstration was not reliable during Project Presentation Day due to loose wire connections and software bugs. As a backup, a video was played of the robot working. Error detection with the camera was successful but was not integrated into our demonstration due to time constraints. Error detection with the strain gauge was never finished again due to time constraints.

11 Broader Impacts

Throughout this chapter the team looks to recognize the societal impacts of their work and its importance outside the context of the MQP.

11.1 Societal and Global Impacts

The Mechanical Engineering Code of Ethics asks all engineers to use their knowledge and skill for the enhancement of human welfare, be honest and impartial, serving their clients and the public with fidelity while striving to increase the competence and prestige of the engineering profession. The Breakfast Sandwich Robot MQP Strives to bring value to society, rethinking how food is prepared. Our team is looking to do the engineering profession justice by creating automated solutions outside the current research and development within the industry.

11.1.1 Positive Impact on Health

By automating the preparation of breakfast sandwiches, you can invest more capital in higher quality ingredients, as the money saved from labor costs can be used for that investment. For instance, options for whole-grain bread and lean proteins will reduce the overall calorie and fat content of the sandwiches. Fresh sandwich ingredients free from preservatives will allow the sandwiches consumer to confidently make these healthier options without the worries of food filled with preservatives. The convenience and availability of healthier breakfast options will encourage people to make better food choices, positively impacting their long-term health of those that would not otherwise make healthy decisions.

11.1.2 Improved Food Safety

Automation can significantly reduce the risk of foodborne illnesses and contamination by maintaining strict hygiene standards. Robots can follow precise food safety protocols, increasing the safety of these prepared meals. On a larger scale, reduced risk of foodborne illnesses may result in a decrease in healthcare costs, benefiting both individuals and the healthcare system.

11.1.3 Cultural Impact

Culturally, the introduction of automation in food preparation is sure to receive pushback. The idea of robots replacing humans in traditional food preparation may create short term concerns. Automation has the potential to grow the artistic side food preparation culture; as large-scale food preparation is tackled by robots more value could be associated with human prepared food at smaller scales. The current fast-food workforce could transition to more impactful sectors or reskill and transition to other roles, both in the foodservice sector and in other industries.

The current 9-5 culture has perpetuated a fast service breakfast industry governed by commuting hours. The increase in accessibility of breakfast options for people with busy schedules or those who lack easy access to traditional breakfast establishments could continue to develop the commuting culture around breakfast foods.

11.2 Environmental Impact

Automation can lead to more efficient resource utilization, potentially reducing food waste and energy consumption in the preparation process. The manufacturing industry is developing the “internet of things” (IoT); this technology is designed to integrate automated manufacturing processes with data analytics. Product yield can then be directly driven by supply chain and consumer trends. These concepts can be applied to automated food preparation. The automated Breakfast Robot will have a built-in program that keeps track of the number of breakfast sandwiches sold per day. These data could be leveraged by artificial intelligence to buy the ideal number of ingredients per day from food distributors, reducing overall waste.

11.3 Codes and Standards

The Breakfast Sandwich Robot's involvement in food and robotics subjects it to abide by the FDA Code of Federal Regulations (CFR), Title 21:

- Food Safety Standards
- Electrical and Mechanical Standards
- Safety Standards
- Sanitary Standards
- Environmental Standards

On top of abiding by these standards, the Breakfast Sandwich Robot will need to receive Certifications of Compliance from the National Sanitation Foundation (NSF) before providing sandwiches to consumers. See Appendix K for other relevant ISO Standards.

11.4 Economic Factors

The Innovation that the team is pursuing, if successful, will open opportunities to develop a product for the consumer market.

The global quick service breakfast industry is currently valued at 29.43 billion USD with an expected growth rate of 6.8 percent annually from 2021 to 2028 (Million Insights). The global quick service restaurant industry is currently valued at 972.74 billion USD in 2021 and projected to grow to 1,467.04 billion USD by 2028. (Fortune Business Insider)

The projected growth of the industry does not necessarily reflect its current state. Bloomberg reported in March of 2023 that 60% of fast-food chains are understaffed. While wages have continued to increase steadily over the last 10 years this demand for staffing continues to elevate wages across the United States, driving up food prices within quick service restaurants.

Although increasing wages and vacancies are good for workers' pay, it is a byproduct of an undesirable job. Working in the quick service, food preparation industry is not a desirable career while pay-roll continues to be the highest expense in the quick service industry. Companies are forced to purchase cheap ingredients and increase costs for consumers. Using the breakfast sector as an example, in the US a breakfast sandwich costs 5x the amount of raw ingredients and coffee costs 12x the cost of raw ingredients. This leaves a potential for increased revenue for the machine's owner by decreasing labor costs through automation.

The introduction of automation would create immense value within the industry, driving down the largest cost, while replacing undesirable jobs in the economy. The value of automation within the industry has led to the research and implementation of fully automated robotic systems to prepare food. These companies fall into two categories: automation within existing infrastructure and robotic assembly line systems built from the ground up. An example of “automation within existing infrastructure” would be large robotic arms emulating human employes, operating preexisting fryers, ovens and grills. This automation strategy has large upfront cost, little capability and high complexity while still requiring the cost of preexisting infrastructure. Examples of “robotic assembly line systems” would be pizza, burger or salad robots that rely on large assembly line systems. These also require large upfront costs, maintenance and footprint, while having little versatility and flexibility in food preparation.

The current cost to automate food preparation is currently too great for most commercial operations because of high upfront investment and little versatility. For example, Flippy the food preparation robot can only operate an air fryer. In addition, automating that one simple task with Flippy would cost $60,000 (Bishop, 2019). To get restaurants to adopt food automation, the price of these robots needs to come down and they need to be more versatile. Our breakfast sandwich making robot solves these issues as it is versatile. It can make multiple entire breakfast sandwiches. It is also much cheaper than a robot like Flippy with a total cost for our robot of an estimated $10,000.

11.5 Benefits to the Consumer

The benefits of our approach are reduced cost to the consumer and convenience. To start with, we can highlight McDonalds largest expenses: Labor, Food, Facility Rent, Facility Maintenance, Equipment and Franchise Payments. By introducing our model of automation to the industry we are greatly reducing labor and facility cost, targeting the largest expenses within the industry. These reduced expenses would allow prepared food prices to be reduced.

On top of reducing prepared food costs there are a few more important benefits to note. Developing the Breakfast Sandwich Robot for a low infrastructure food trailer model will allow for greater locational density, decreasing commute times for customers. This model would also allow locations to change, taking advantage of seasonal market changes or large events. None of this is currently possible with the large stationary infrastructure of McDonalds and Dunkin Donuts.

11.6 Market Competition

Currently there are no "enclosed system" automation efforts within the breakfast space. Any direct automated competition will come from other sectors of the restaurant industry. The main competition within the market comes from Dunkin Donuts, McDonalds and other fast-food options that are providing cheap breakfast options. For adopters of automation to distance themselves from well-established competitors like Dunkin Donuts or McDonalds we foresee an attempt to break into the health food sector, leveraging savings on labor to invest in healthier ingredients.

Additionally, we can bring value to the consumer that Dunkin Donuts and McDonalds cannot. Automation allows for reduced infrastructure cost. Specifically, a lean business model and limited staffing drive down the largest cost of putting a breakfast sandwich in the hands of the consumer.

12 Future Work

The team made significant strides toward developing a Breakfast Sandwich Robot within the constraints of the project. However, they recognize limitations and improvements to the project that should be addressed in the future.

12.1 Software Infrastructure:

To support a network of robots along with user platforms, there will be a need for scalable software infrastructure. Each machine will need to access and maintain internet access to communicate properly with its order database. Notifications will be sent to the machine when an order is received and returned when it is completed. Users can order sandwiches through an ordering application or directly on the machine. When their order is ready, they can scan the machine's quick response (QR) code to confirm pick up. A second type of user would perform maintenance on the machine such as cleaning and stocking ingredients. Servers would have connections to machines as well as users, monitoring amounts of ingredients in each machine with accurate location to display for users.

12.2 Dedicated Hardware:

With a higher budget, the entire electrical system can be integrated on a single printed circuit board (PCB). This would reduce the number of wires needed for the system, which would increase the reliability and portability of the system. This circuit board would house every main electrical component, including the computer (Raspberry Pi), microcontroller (ESP-32), analog-to-digital converters, (HX711/MAX6675), GPIO expanders (MCP23017), and motor drivers. With a higher budget, the system would also be actuated by servo motors instead of stepper motors. This would allow closed loop control of the end effectors and increase the system's reliability.

12.3 Cleaning System:

For the system to be fully autonomous, a cleaning system would need to be implemented to prevent buildup of residue, as this can lead to contamination. Systems would have to be put in place to take care of egg residue in the egg distribution system tubing and frying pan, sausage grease on the cooking element, and breadcrumbs in the bread distribution system. To keep the tubing for the egg distribution clear from egg residue, a switching valve system which toggles between liquid egg, and a soapy water solution would be put in place, followed by a rinsing phase to eliminate any excess solution. To keep the bread distribution and the worksurface clear of breadcrumbs, a ventilation system with pressurized air would be put in place to flush the surface. As for sausage grease, the cooking surface would be slightly convex with channels that lead to a collection tray. This collection tray would be replaced during maintenance. Due to the nature of the sausage distribution's design, this system cannot be cleaned autonomously and will have to be cleaned during maintenance.

12.4 Error Detection:

The camera software will need to be fully integrated into the robot. It will be connected to the Raspberry Pi and communicate via serial. Methods to pack and unpack data on the camera end are currently written. However, code will need to be written on the Raspberry Pi to interpret the data from the camera.

The robot can sort of spot the egg and cheese, though not as well as it handles sausage and English muffin tops. It's alright at picking out English muffin bottoms, but not consistently.

The robot will also need to know what to do when a misalignment occurs. In the future, a robotic apparatus will correct misalignments in the Y direction via a linear actuator. For the X direction, code will be written to allow the unoccupied spatula to turn 90 degrees and then nudge the food back to the correct location.

For the strain gauge, its feedback will be implemented into the main code. The robot will perform an automated check to match the values on the strain gauge to an anticipated value based on the robot's state. If the robot receives unexpected values, it will trigger an emergency stop. The correct food item will then be placed on the spatula with the strain gauge and the emergency stop can be reset.

Currently there is a method written for the camera that allows it to determine which food item is on it based on its area. Eventually, this will be combined with the stain gauge to give more robust feedback to the robot.

Computer vision can serve another purpose in the machine, leveraged as a visual quality control inspection before serving the sandwich. A camera can be trained to see defects in the food leveraging machine learning techniques already employed in the food processing industry. Artificial Neural Networks have proven to be a quality control technique for food distributors, as it can detect differences between ripe and unripe food (Kakani, 2020). Techniques like this one could be implemented on our machine in the future to check for defects and improper cooking to prevent customer dissatisfaction.

12.5 Failure Detection:

The thermocouples and their respective ADCs will need to be wired into the heating element. Once completed, the thermocouples will then need to be integrated into the main code. Two methods will need to be considered. One will be to maintain a consistent cooking temperature for the heating element. The other method will trigger an emergency stop if the heating element exceeds 260°C.

In the future code will be added to put the robot in an emergency stop state when the emergency stop button is pressed. In this state the robot will idle until the button is released. Once released, the robot will enter the state before the stoppage and continue where it left off. This eliminates the need to restart the system anytime the emergency stop button is pressed.

13 Conclusion

In A term of 2023 the team set out with the ambitious goal to design, build, assemble, program, and test a breakfast sandwich robot. The project made large strides in developing the infrastructure to fully cook and prepare a sandwich to the specified requirements. One of the notable successes was putting together a demo to pick up, flip and place an English muffin onto the worksurface with the opposing gantry technology. The team also received a provisional patent protecting their technology filed under No.: 63/635,879. In the future the team looks to continue to integrate and develop the robot, adding to the existing demo. The continuation and implementation of this technology in industry will help automate the quick service industry, decreasing the cost of prepared food and solving rising staffing shortages.

13.1 Reflections

The following section is personal reflections from each member of the team on the challenges and real-life applications from courses on problems for this Major Qualifying Project.

13.1.1 Ethan

This project has given me a lot of experience and required me to put what I have learned at WPI to use. My first takeaway is that I should always document errors that are happening and what was changed to eliminate them. In my time working on smaller projects, it was rare to see the same issue twice and I often remembered exactly how to fix them; in this four-term project I encountered similar issues months apart and had to resolve complex issues, which could have been avoided with proper documentation. Another takeaway of mine was to handle versioning and proper specification of libraries early on in development. After our team chose a non-suitable stepper motor library and integrated it into our code, I had to spend an additional two weeks re-versioning our libraries to integrate a new stepper motor library. I drew experience from my software engineering, analysis of algorithms, distributed computing systems, and computer networking classes to develop the software architecture and infrastructure involved to operate and automate the machine. Overall, my experience with this project was positive and I am a much more versatile computer scientist because of it.

13.1.2 Samson

This MQP was by far the largest and most complicated project I had ever worked on, and it required me to draw on all my knowledge gained at WPI. This project had taught that failure is bound to happen while working on a project of this scale, and that multiple revisions were necessary to achieve all objectives. During my RBE coursework, if the robot failed to meet the objective set out in the lab, I would have received a failing grade. Whereas with this project, I was able to test multiple approaches to find the ideal way to detect errors in the system. Both with the camera, strain gauge, and thermocouples. Another thing I learned was that robust testing and repeatability is required to ensure that designs meet the requirements. For example, there were plenty of times where I would have had a detection algorithm working for a sausage patty. But if I moved the sausage patty or put a different one on the spatula, the detection algorithms broke. I had to spend numerous weeks perfecting my strategy and code, until everything finally worked as required.

To successfully use the camera, strain gauge, and thermocouples for error detection, I had to use all the knowledge I gained from my RBE, controls engineering, and programming classes. Especially RBE 2002 & 3001 for my robotics courses as both had units on computer vision, and because our final project in RBE 2002 utilized an OpenMV camera. My controls engineering classes allowed me to figure out how to incorporate sensor feedback into the robot, thus closing the control loop. My programming classes, especially software engineering, allowed me the necessary skills to break down complex coding problems into small, easy to tackle problems.

Overall, I had a positive experience working on this MQP. I thought this project properly prepared me for what engineers do in the real world, as I worked with an interdisciplinary team to accomplish a common goal. That is exactly what engineers do in industry. I felt this project allowed me to grow immensely as a robotics engineer as there was plenty of room for me to fail, learn from my mistakes, and then move forward with a more successful approach.

13.1.3 Matthew

This MQP has been a great engineering experience. Due to the project's interdisciplinary nature, our team was comprised of students from different majors, which contrasts with prior projects where every student is in the same or related field. Effective communication was an essential skill for this project since we had to solve problems together, bringing in different perspectives from our respective domains. This collaboration simultaneously turned me into a more versatile and stronger electrical engineer. Real-Time Digital Signal Processing (ECE 4703) was a useful course as it taught me how to optimize embedded systems for real-time DSP applications. Unified Robotics I,II,III (RBE 2001 ,2002, 3001) were useful since they provided practical experience designing and working with mechatronic systems. Embedded Systems (ECE 2049) was beneficial for this project since it taught computer architecture for embedded systems and basic communication protocols. Controls Engineering (ECE 3012) was important since it taught basic control theory. Other general skills like circuit analysis, prototyping circuits, soldering, programming, were also useful for this project.

13.1.4 Trevor Faber

The interdisciplinary aspect of this MQP project created a great environment for learning. With one member of ME, CS, ECE and RBE respectively, everyone had to be their own expert. This meant that collaborative work required a working understanding of each other’s fields. This is where I did the most learning; from understanding circuitry and electronics to helping with low level code, I was exposed to fields of study I would have otherwise avoided. The biggest individual skill that I learned was machining and fabrication. The group was reliant on me to build most of the physical infrastructure for the project which helped me greatly improve my machining, 3D printing, metal work and assembly skills. The large scope of the project set me up to utilize the technical skills I had been acquiring in my classes at WPI.

While creating the electric griddle for the system I needed to apply my understanding of heat transfer which I had developed through both my undergrad and graduate courses. The motor sizing for many of the moving systems required an understanding of forces acting on different parts of the robot, and I was able to apply my course work in statics and dynamics to solve these problems. Advanced Engineering Design (4320) was instrumental in preparing me for the structure of MQP as well as introducing me to the iterative design and prototyping process.

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15 Appendices

15.1 Appendix A – Gantry Calculations

15.1.1 Gantry Parameters

```
MPulleyR = 0.006; % m
MPulleyCircum = 0.02*MPulleyR*pi; %m
Load  = .35; % kg
CarageMass = 1; %kg
GantryBeam = 4; %kg
y_axis_buffer = 1;  % Adjust this value to control the buffer size
BeltFriction = 10 % Newtons
```

```
BeltFriction = 10
```

15.1.2 Position and time Inputs

```
% Input parameters
start_point = [.2, .25];     % Starting point (x, y)
end_point = [.8, .25];     % Ending point (x, y)


total_time = 3;% Total time for the motion (in seconds)




max_vel = .5 %m/s Straight Line, this number gets divided in half when moving in a diagonal
```

```
max_vel = 0.5000
```

15.1.3 Calculate Gantry Acceleration

```
time = linspace(0, total_time, 1000);  % Create a time vector with more points for smoother curves
%Calculate Distance Traveled


dx = end_point(1) - start_point(1)
```

```
dx = 0.6000
```

```
dy = end_point(2) - start_point(2)
```

```
dy = 0
```

```


t1 = ((max_vel*total_time) - abs(dx))/max_vel
```

```
t1 = 1.8000
```

```
xAcceleration_value = (max_vel/t1)
```

```
xAcceleration_value = 0.2778
```

```
% Initialize acceleration as a step function
xAcceleration = xAcceleration_value * (time <= t1) + (-xAcceleration_value) * (time > (total_time-(t1)))
```

```
xAcceleration = 1×1000
```

```
t2 = ((max_vel*total_time) - abs(dy))/max_vel
```

```
t2 = 3
```

```
yAcceleration_value = (max_vel/t2)
```

```
yAcceleration_value = 0.1667
```

```
% Initialize acceleration as a step function
yAcceleration = yAcceleration_value * (time <= t2) + (-yAcceleration_value) *
(time > (total_time-(t2)))
```

```
yAcceleration = 1×1000
```

```
plot(time, xAcceleration, 'b')
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
title('xAcceleration vs. Time');
y_axis_limitsA = [min(xAcceleration) - y_axis_buffer, max(xAcceleration_value) +
y_axis_buffer];
ylim(y_axis_limitsA);
```

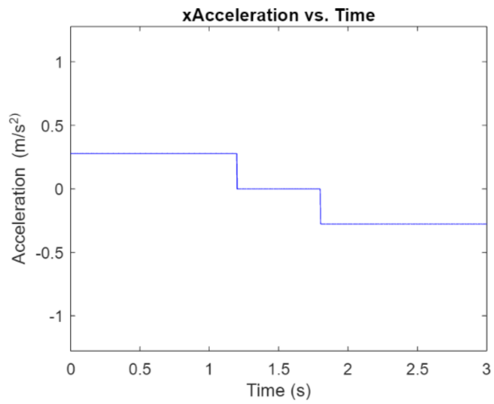

Figure 87: End Effector Acceleration in X Direction

```
plot(time, yAcceleration,'b')
xlabel('Time (s)');
ylabel('Acceleration (m/s^2)');
title('yAcceleration vs. Time');
y_axis_limitsA = [min(yAcceleration) - y_axis_buffer, max(yAcceleration_value) +
y_axis_buffer];
ylim(y_axis_limitsA);
```

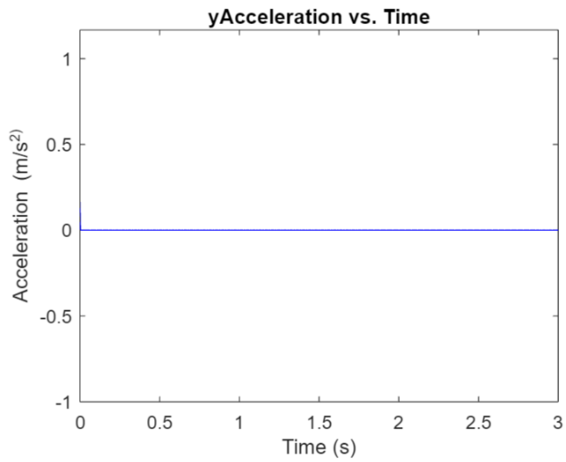

Figure 88: End Effector Acceleration in Y Direction

Calculate and Plot Gantry Velocity

```
% Calculate velocity as a function of time
xVelocity = cumtrapz(time, xAcceleration);
yVelocity = cumtrapz(time, yAcceleration);


plot(time, xVelocity, 'r')
xlabel('Time (s)');
ylabel('Velocity (m/s)');
title('xVelocity vs. Time');
```

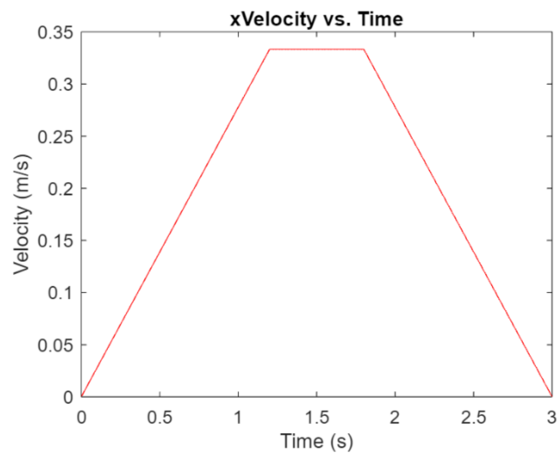

Figure 89: End Effector Velocity in X Direction

```
plot(time, yVelocity, 'r')
xlabel('Time (s)');
ylabel('Velocity (m/s)');
title('yVelocity vs. Time');
```

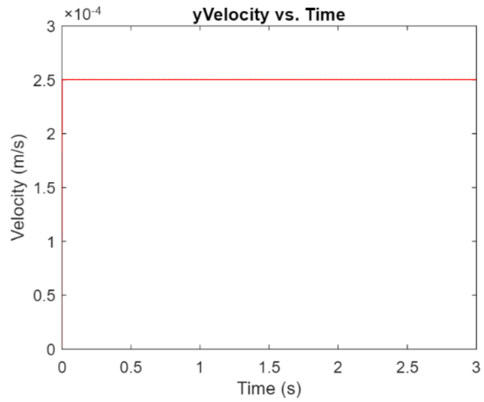

Figure 90: Endifector Velocity in Y Direction

15.1.4 Calculate and Plot Gantry Position

```
% Calculate position as a function of time
position_x = cumtrapz(time, xVelocity)+start_point(1);
position_y = cumtrapz(time, yVelocity)+start_point(2);


% Normalize the position to match the endpoint
position_x = position_x * (end_point(1) / position_x(end));
position_y = position_y * (end_point(2) / position_y(end));
```

15.1.5 Create plot showing travel path

```
plot(position_x, position_y, 'b-', 'LineWidth', 2);
hold on;
plot(start_point(1), start_point(2), 'ro', 'MarkerSize', 5, 'MarkerFaceColor',
'r');
plot(end_point(1), end_point(2), 'go', 'MarkerSize', 5, 'MarkerFaceColor', 'g');
xlabel('meters');
ylabel('meters');
title('PathTraveled');
xlim([0, 1]);
ylim([0, .5]);
hold off;
```

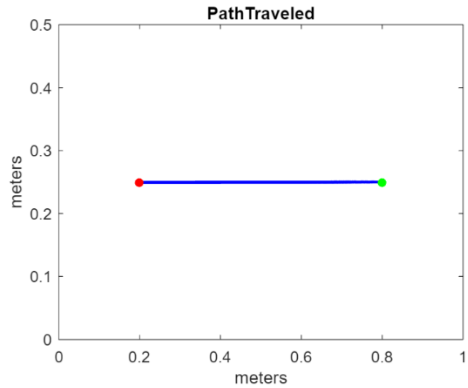

Figure 91: Linear Endefector Travel in X Direction

```
plot(time, position_x, 'r', time, position_y, 'b');
xlabel('Time (s)');
ylabel('Position (m)');
legend('Position_x', 'Position_y');
title('Position vs. Time');
```

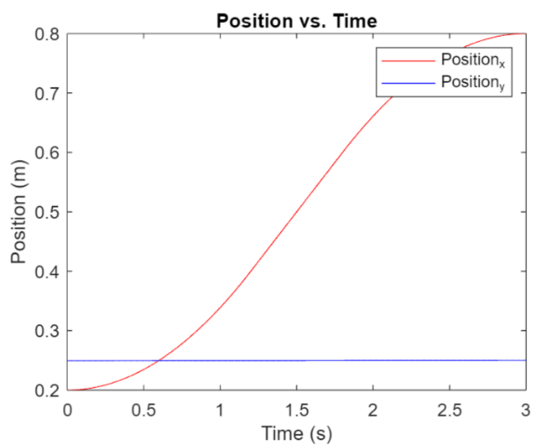

Figure 92: Motor Cartesian Position Over Time

15.1.6 Calculate and Plot Gantry Position

```
% Core xy Inverse Kinimatics
da = dx + dy;
db = dy - dx;


Motor1FinalPosition = -da/MPulleyCircum; %revolutions
Motor2FinalPosition = -db/MPulleyCircum; %revolutions


%Inverse Kinimaticsto find motor position
Motor1Position = (position_x + position_y)/MPulleyCircum;
Motor2Position = (position_y - position_x)/MPulleyCircum;
```

```
plot(time, Motor1Position,'r', time, Motor2Position, 'b');
xlabel('Time (s)');
ylabel('Revolutions');
legend('Motor1 Position', 'Motor2 Position');
title('Motor Position');
```

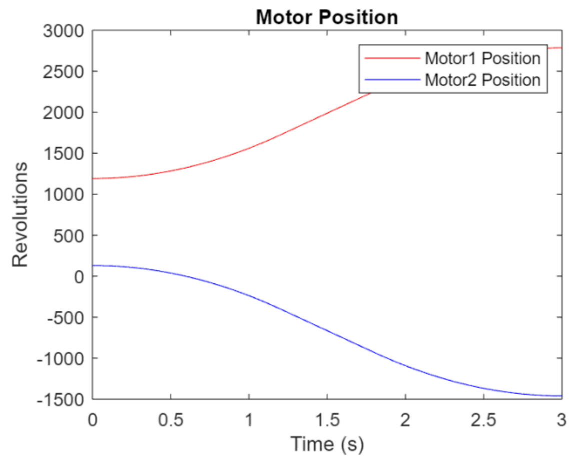

Figure 93: Motor Angular Position Plot Over Time

15.1.7 Calculate Motor Angular Velocity

```
Motor1velocity = (yVelocity + xVelocity)/MPulleyR %diff(Motor1Position) ./
diff(time);
```

```
Motor1velocity = 1×1000
```

```
plot(time, Motor1velocity)
xlabel('Time (s)');
ylabel('Rad/sec');
title('Motor1 Velocity');
```

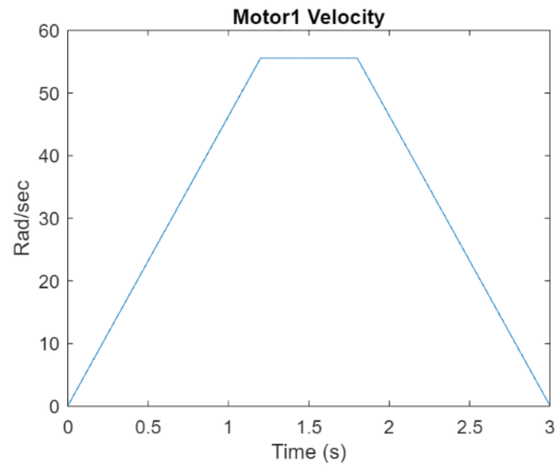

Figure 94: Motor 1 Velocity Curve

```
MaxMotor1Velocity = max(abs(Motor1velocity))*9.5492968 %rpm
MaxMotor1Velocity = 530.7820


Motor2velocity = (yVelocity - xVelocity)/MPulleyR
Motor2velocity = 1×1000
plot(time, Motor2velocity)
xlabel('Time (s)');
ylabel('Rad/sec');
title('Motor2 Velocity');
```

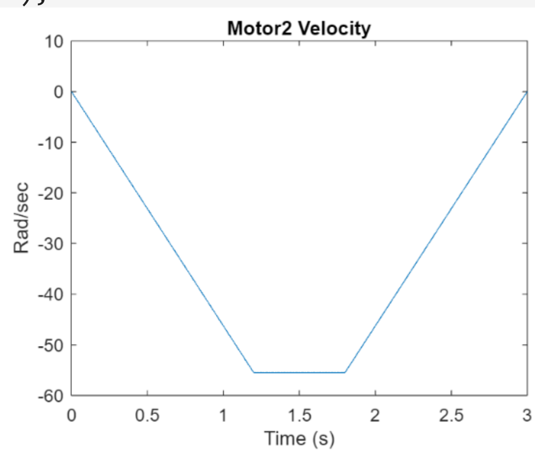

Figure 95: Motor 2 Velocity Curve

```
MaxMotor2Velocity = max(abs(Motor2velocity))*9.5492968 %rpm
MaxMotor2Velocity = 529.9854
```

15.1.8 Calculate Forces Within the System

```
yInertia = (Load+CarageMass)*(yAcceleration);
xInertia = (GantryBeam +Load + CarageMass)*(xAcceleration);
yBeltTension = (yInertia + ((Load+CarageMass)*9.8)/2) + BeltFriction %Newton
yBeltTension = 1×1000
xBeltTension = (xInertia) + BeltFriction
xBeltTension = 1×1000
```

```
TorqueMotor1 = abs((xBeltTension + yBeltTension)*(MPulleyR));
TorqueMotor2 = abs((xBeltTension + yBeltTension)*(MPulleyR));


plot(time, TorqueMotor1)
xlabel('Time (s)');
ylabel('Nm');
title('Motor1 Torque');
```

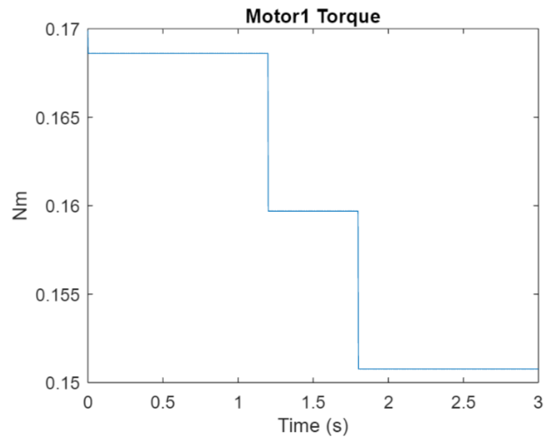

Figure 96: Motor 1 Torque Curve

```
plot(time, TorqueMotor2)
xlabel('Time (s)');
ylabel('Nm');
title('Motor2 Torque');
```

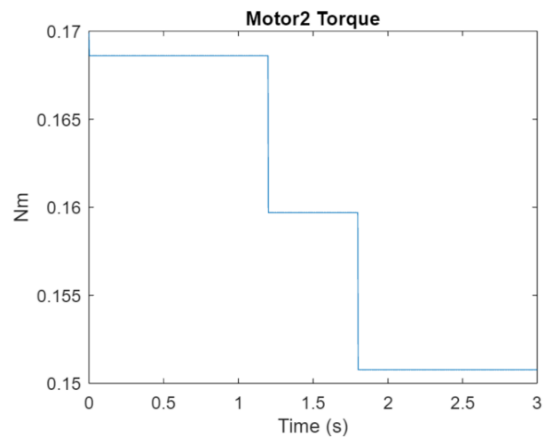

Figure 97: Motor 2 Torque Curve

```
Motor1MaxTorque_Nm = max(TorqueMotor1) %Nm
```

Motor1MaxTorque_Nm = 0.1700

```
Motor1MaxTorque_inoz = Motor1MaxTorque_Nm*141.61193
```

Motor1MaxTorque_inoz = 24.0679

```
Motor2MaxTorque_Nm = max(TorqueMotor2) %Nm
```

Motor2MaxTorque_Nm = 0.1700

```
Motor2MaxTorque_inoz = Motor2MaxTorque_Nm*141.61193
```

Motor2MaxTorque_inoz = 24.0679

15.2 Appendix B – Thermocouple chart detailing Temperature ranges and Accuracies (Omega, 2023)

Thermocouple Tolerances
(Reference Junction at 0°C)

American Limits of Error ASTM E230-ANSI MC 96.1

ANSI Code		Standard Limits†		Special Limits†	
J	Temp Range	>0 to 750°C	>32 to 1382°F	0 to 750°C	32 to 1382°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
K	Temp Range	>0 to 1250°C	>32 to 2282°F	0 to 1250°C	32 to 2282°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	2.2°C or 2.0%	4.0°F or 2.0%		
T	Temp Range	>0 to 350°C	>32 to 662°F	0 to 350°C	32 to 662°F
	Tolerance Value	1.0°C or 0.75%	1.8°F or 0.75%	0.5°C or 0.4%	1°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	1.0°C or 1.5%	1.8°F or 1.5%		
E	Temp Range	>0 to 900°C	>32 to 1652	0 to 900°C	32 to 1652°F
	Tolerance Value	1.7°C or 0.5%	3°F or 0.5%	1.0°C or 0.4%	1.8°F or 0.4%
	Temp. Range*	-200 to 0°C	-328 to 32°F		
	Tolerance Value	1.7°C or 1.0%	3°F or 1.0%		
N	Temp Range	>0 to 1300°C	>32 to 2372°F	0 to 1300°C	32 to 2372°F
	Tolerance Value	2.2°C or 0.75%	4.0°F or 0.75%	1.1°C or 0.4%	2.0°F or 0.4%
	Temp. Range*	-270 to 0°C	-454 to 32°F		
	Tolerance Value	2.2°C or 2.0%	4.0°F or 2.0%		
R S	Temp Range	0 to 1450°C	32 to 2642°F	0 to 1450°C	32 to 2642°F
	Tolerance Value	1.5°C or 0.25%	2.7°F or 0.25%	0.6°C or 0.1%	1°F or 0.1%
B	Temp Range	800 to 1700°C	1472 to 3092°F	Not Established	
	Tolerance Value	0.5%	0.9°F		
G*C*D*	Temp Range	0 to 2320°C	32 to 4208°F	Not Established	
	Tolerance Value	4.5°C or 1.0%	0.9°F		

** Not official symbol or standard designation* *† Whichever value is greater.*

Note: *Material is normally selected to meet tolerances above 0°C. If thermocouples are needed to meet tolerances below 0°C, the purchaser shall state this as selection of material is usually required.*

15.3 Appendix C – Market Analysis Calculations

Table 16: Estimated Commercial Development Price per Unit

Estimated Commercial Development Price per Unit	
Desired Annual Return	12%
Food Distribution	5000
Cleaning	4000
Annual Maintenance	10000
Avg Profit per Serving	0.75
Daily Customers	105
Net Profit	9743.75
Allowed Manufacturing Unit Cost	81197.91667

15.4 Appendix E – State flowchart

https://lucid.app/lucidchart/e9a95c02-fddc-43b2-99cf-40784898c3f7/edit?viewport_loc=-1569%2C-423%2C4218%2C2191%2C0_0&invitationId=inv_413a18ff-b861-4ead-812a-59017f71d1fa

15.5 Appendix F – Code Repository

https://github.com/Breakfast-sandwich-robot

15.6 Appendix G – Spatula manipulation testing video

IMG_2456.MOV

IMG_2449.MOV

15.7 Appendix H – ME 4320 Sausage Distribution Report

ME 4320 - B 2023 - Breakfast Sandwich Robot Team

15.8 Appendix I – ME 4320 Cheese Distribution Report

ME 4320 - D 2024 - Breakfast Sandwich Robot

15.9 Appendix J – FastAccelStepper Source Code

https://github.com/gin66/FastAccelStepper

15.10 Appendix K – Relevant ISO Standards

- ISO 10218 series: Safety requirements for industrial robots and robotic systems.
- ISO 13849 series: Guidelines for safety-related control systems in machinery.
- ISO 14121 series: Standards for risk assessment and reduction techniques.
- ISO 22000: Requirements for food safety management systems.
- ISO 18385: Requirements for sterile product production.
- ISO 3471 series: Ergonomic requirements for machinery design.