Capstone Design Project Report

Serving Automation for Commons Dining Hall

Sodexo
Kit Smith

Semester One
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Rensselaer Polytechnic Institute

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Lastly, the team extends the utmost gratitude to Professor Kannathal Natarajan, the Project Engineer ("PE") for this project, and Professor Fred Willett, the Chief Engineer ("CE") for this project. Their mentorship and guidance were critical to the team's progress and success with this project.

Executive Summary

Commons Dining Hall at Rensselaer Polytechnic Institute serves thousands of meals every day to students, typically serving about 425 breakfasts, 1,000 lunches, and 1,600 dinners daily. Most of the serving stations in Commons Dining Hall have 1-3 workers standing there to serve food to students. These workers have to focus on serving food to students, preparing the food for service, and refilling the food containers as they are emptied during the serving process. Of these tasks, serving food to students is the most consistent and mundane. This consistency coupled with the need to have more portion control over the food served presents a perfect opportunity for the implementation of an automation system. The project's main goal is to reduce worker labor needed to serve food to students by implementing an automated serving system specifically for the Chef's Table station in Commons Dining Hall.

Through extensive research and discussion, the team determined that the best solution to this problem would be to create subsystems that individually addressed each step in the overall automated serving process. These subsystems include the following:

1. Kiosk system
2. Plate placement system
3. Conveyor belt system
4. Robotic arm system
5. Utensil design system
6. Master computer ("MC") system.

Each of these subsystems ensure that both student's (customer's) and worker's needs are met throughout the serving process.

Over the course of the semester, the team addressed the first five of the listed subsystems, creating the necessary computer-aided design ("CAD") models, process flow diagrams, electrical wiring diagrams, and a full Bill of Materials ("BOM"), which lists each item to be purchased for the completion of this design. This provides the calculations and documentation that will allow future teams to construct a full, physical prototype.

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Glossary

AC	Alternating Current
BDR	Board of Directors Review
BOM	Bill of Materials
CAD	Computer-Aided Design
CE	Chief Engineer
DC	Direct Current
DoF	Degrees of Freedom
EMI	Electromagnetic Interference
GIPO	General-Purpose Input Output
LDO	Linear Dropout Regulator
MC	Master Computer
PCB	Printed Circuit Board
PE	Project Engineer
REPO	Repository
ROS	Robot Operating System
SoC	System on Chip
UART	Universal Asynchronous Receiver-Transmitter
UI	User Interface
VAC	Voltage Alternating Current
VDC	Voltage Direct Current

1. Introduction

Commons Dining Hall at Rensselaer Polytechnic Institute serves thousands of meals every day to students. The project's main goal is to reduce worker labor needed to serve food to students by implementing an automated serving system specifically for the Chef's Table station in Commons Dining Hall. This automation would reduce the number of tasks required by each Commons staff member at the Chef's Table station by allowing all food service to be handled by an automated system. The automated system would not handle food preparation or the restocking of each food item, so those duties would still need to be fulfilled by the employees. The addition of this system would also require employees to update the menu for each meal in the MC.

The automated system proposed includes features that would keep track of the number of each meal item purchased by students, allowing the staff at Sodexo to have up-to-date, accurate data to generate their inventory. Robotic accuracy and precision coupled with intuitive utensil design allow for consistency in portion-control, which would allow for even more accurate inventory. Additionally, the kiosk system automatically counts how many times each food is ordered during every meal. Collecting this data would allow for more accurate inventory calculation for *Sodexo*, which would reduce food waste.

2. Project Overview

This project aims to develop a semi-autonomous system aimed at reducing human workload, setting a modern dining experience while being cost effective. This system must facilitate student food orders with minimal interaction between student and system to ensure both food safety and student health. To accomplish this objective, the project is segmented into six key subsystems: Kiosk, Robotic Arm, Plate Dispenser, Master Computer, Utensil Management, and Conveyor Belt.

2.1 Project Statement

This project has six (6) subsystems; a kiosk system (1), plate placement system (2), conveyor belt system (3), robotic arm system (4), utensil design system (5), and the MC system (6). Given the time for this project's completion and the client's goals, it was not feasible to work on the integration of the master control computer. As such, the MC subsystem will need to be designed by future teams. The continuation of this project, and specifically of the MC system, will require the implementation of a Robot Operating System ("ROS") communication system. Nevertheless an automated food plating system was designed using robotics and modular design to reduce labor, enhance efficiency, and fulfill variable orders in the food service industry. This will provide a cost-effective solution that integrates seamlessly with existing kitchen infrastructure to optimize both time and resources. An image of the proposed layout of the Chef's Table Station is shown in ***Figure 2.1.1*** below.

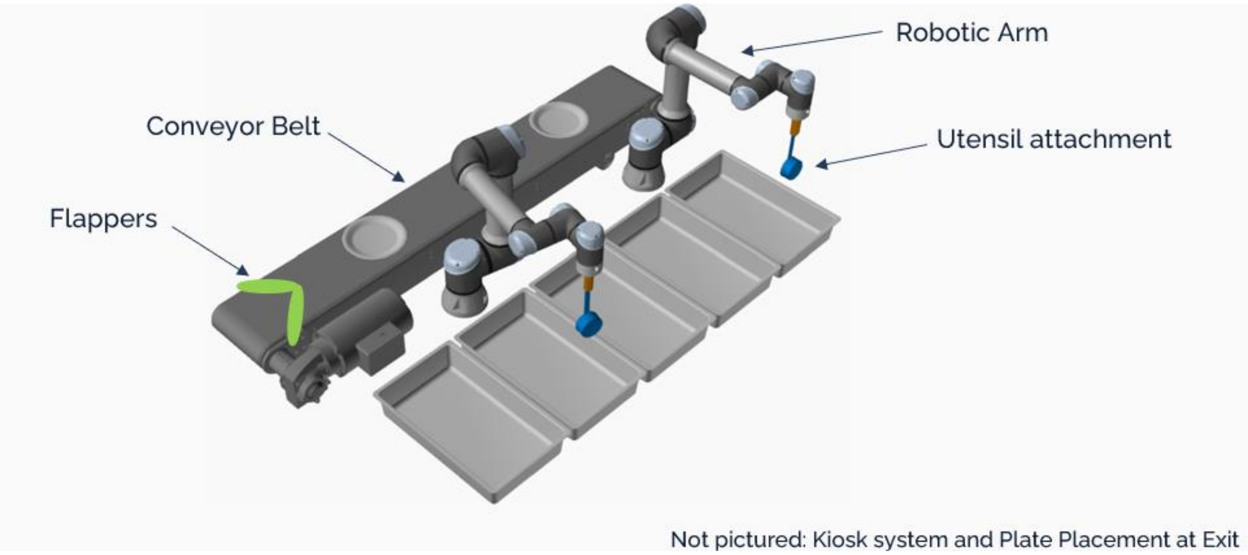


Figure 2.1.1: Proposed Layout of Chef's Table Station

2.2 Semester Primary Objectives / Deliverables

Following the project solution's creation, the team developed a list of goals aimed at attaining by the end of the semester, April 24, 2024. Along with these goals, the team developed a set of deliverables associated with each goal. This combination of goals and deliverables ensured that the team provided visible and tangible progress to the project for the client. These goals and their associated deliverables are shown in ***Table 2.2.1*** below.

Table 2.2.1: Semester Primary Objectives and Deliverables

Semester **Primary** Objectives	Deliverable
Kiosk System UI Design	Worker UI application for defining daily kiosk menu. Student-accessible UI for ordering food from the kiosk.
Kiosk Electrical System	Hardware to capture data for orders and transmit to other systems (master computer, conveyor, and serving system).
Workflow Simulation	Chef table throughput simulation.
Workflow Simulation	Plating data analysis (Plating data graphs of accuracy, speed) Food portion data statistics. (Food portion graphs of accuracy)
Plate Dispenser System Physical Design	CAD of plate dispenser.
Plate Dispenser System Electrical Design	Circuit design for plate dispenser.
Plate Dispenser Analytics	FEM analysis of plate dispenser to determine the weak points of the assembly.
Plate Delivery System Electrical Design	Circuit design for conveyor belt system.
Plate Delivery System Physical Design	CAD of conveyor belt system.
Grab/Place System Physical Design	Custom Utensil Design.
Grab/Place System Analysis	Simulated representation of Grab/Place.
Document Organization	Document hierarchy tree diagram

Following these goals and deliverables, the Plate Dispenser subsystem was redefined for this semester as a Plate Placement Subsystem (subsystem 2), whose goal was to ensure accurate placement of the plates along the conveyor belt's entrance and exit instead of physical dispensing plates onto the conveyor belt. This decision was made based on a reevaluation of the customer needs, and its redefinition allowed for the focus on higher priority needs identified by the customer.

With the redefining of this subsystem, the primary objectives and deliverables for the Plate Placement Subsystem (highlighted in ***Table 2.2.1***) were modified to match this redefinition. These revised objectives and deliverables are tabulated in ***Table 2.2.2***.

Table 2.2.2: Plate Placement Subsystem Semester Primary Goals and Deliverables

Semester **Primary** Objectives	Deliverables
Plate Placement System Physical Design – Conveyor Belt Entrance	CAD of full Plate Placement system at entrance including: – CAD of the "flappers" – CAD of the spring and pole – CAD of the bracket for attachment to the conveyor belt
Plate Placement System Physical Design – Conveyor Belt Exit	CAD of full Plate Placement system at exit including: - CAD of the ramp - CAD of the rollers

The team was able to meet all of the primary objectives and their associated deliverables as listed in ***Table 2.2.1***, except for the highlighted ones, which were replaced by the objectives and deliverables tabulated in ***Table 2.2.2***. These redefined objectives and deliverables were also met.

2.3 Semester Secondary Objectives / Deliverables

The team then developed a list of secondary objectives and deliverables, which would be addressed if time permitted during the semester. Unfortunately, there was not sufficient time for the team to begin addressing these secondary objectives and deliverables. These objectives do provide a good starting point for future teams when beginning work on this project.

Table 2.3.1: Semester Secondary Objectives and Deliverables

Semester **Secondary** Objectives	Deliverables
Physical Robot Integration	Integration of code into physical robot
Physical Kiosk Prototyping	Building a physical kiosk using custom Printed Circuit Board ("PCB") that was designed.

Physical Conveyor Prototyping	Building a prototype for a physical conveyor belt
Physical Plate Dispenser Prototyping	Building a physical plate dispenser.
Integration of Physical Product	Physical systems integrated together.
Testing and Improvement.	Have a simulated test with workers to get feedback for the product.
Kiosk Custom Electrical System	Linux System on Chip- (“SoC”) PCB design for kiosk.
Improvement in other serving options	Code for picking up food other than scoopable items, such as larger rigid items.

Like with the primary objectives and deliverables, all secondary objectives and deliverables associated with the Plate Dispenser Subsystem needed to be redefined. There was only one associated with this subsystem (highlighted), and it was redefined as shown in ***Table 2.3.2*** below.

Table 2.3.2: Plate Placement Subsystem Semester Primary Goals and Deliverables

Semester **Secondary** Objectives	Deliverables
Physical Plate Placement Prototyping	Building components of the Plate Placement subsystem at the entrance. Building components of the Plate Placement subsystem at the exit.

2.4 System Overview

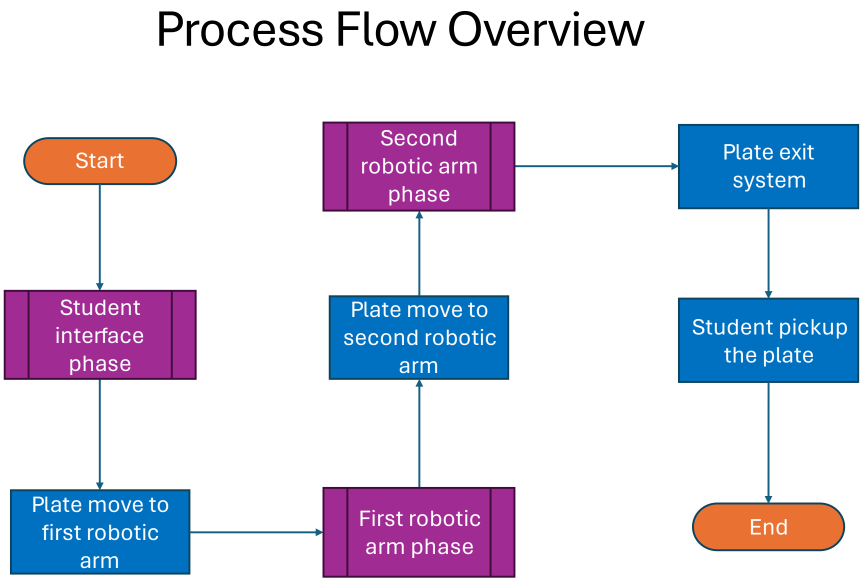


Figure 2.4.1: Overall System Block Diagram

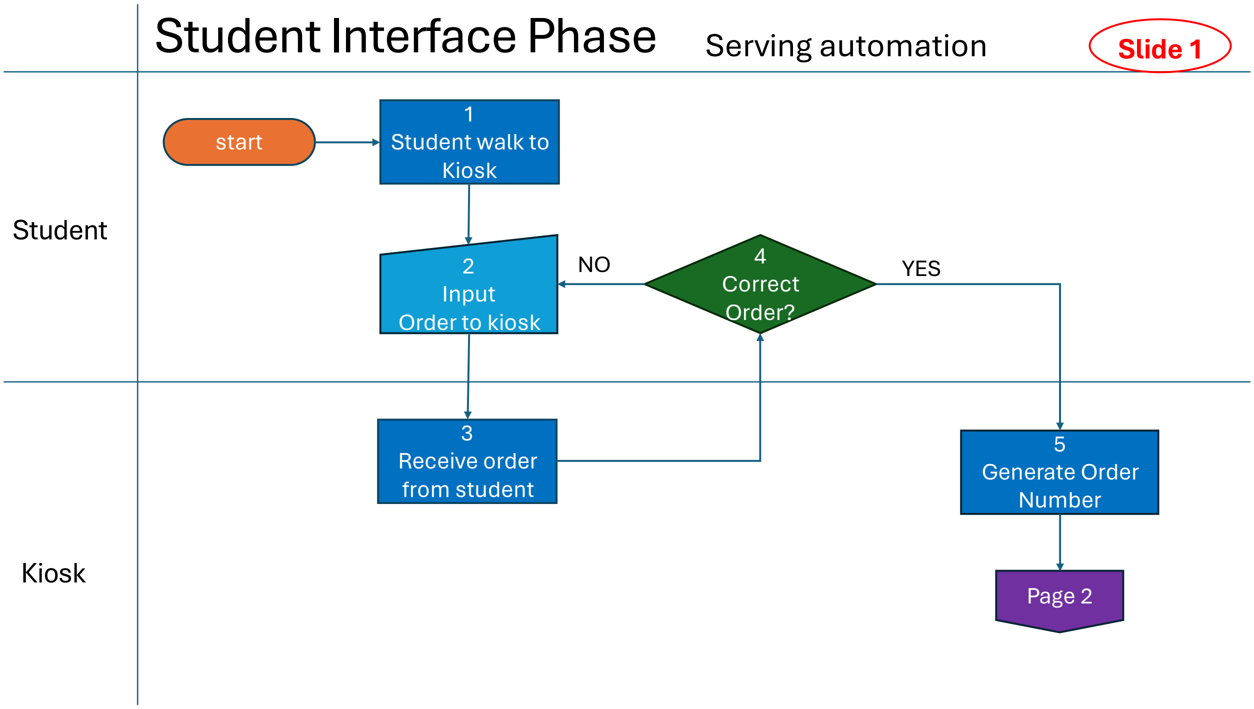


Figure 2.4.1.1: First Slide System Block Diagram

During the student interphase, student would walk to kiosk, input order into kiosk. Student would also have the opportunity to reselect their order if they change their mind. Once the order is finalized, kiosk would generate an oder number for that order so student can track their order.

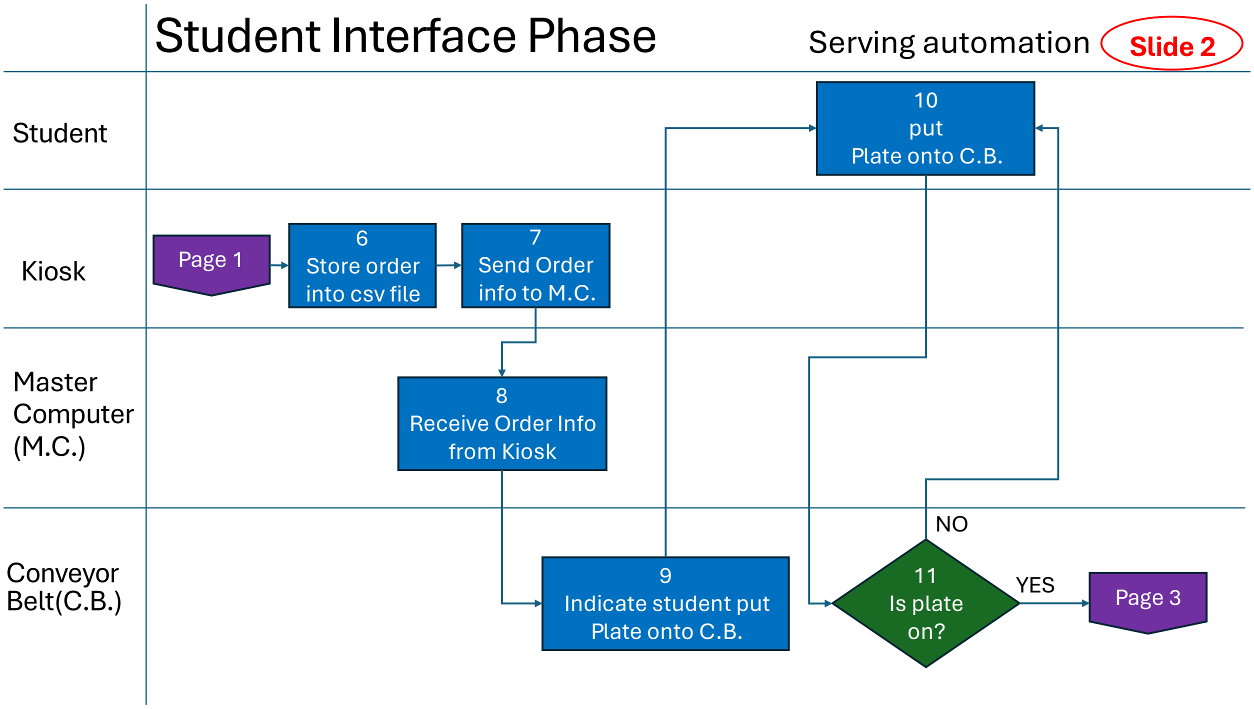
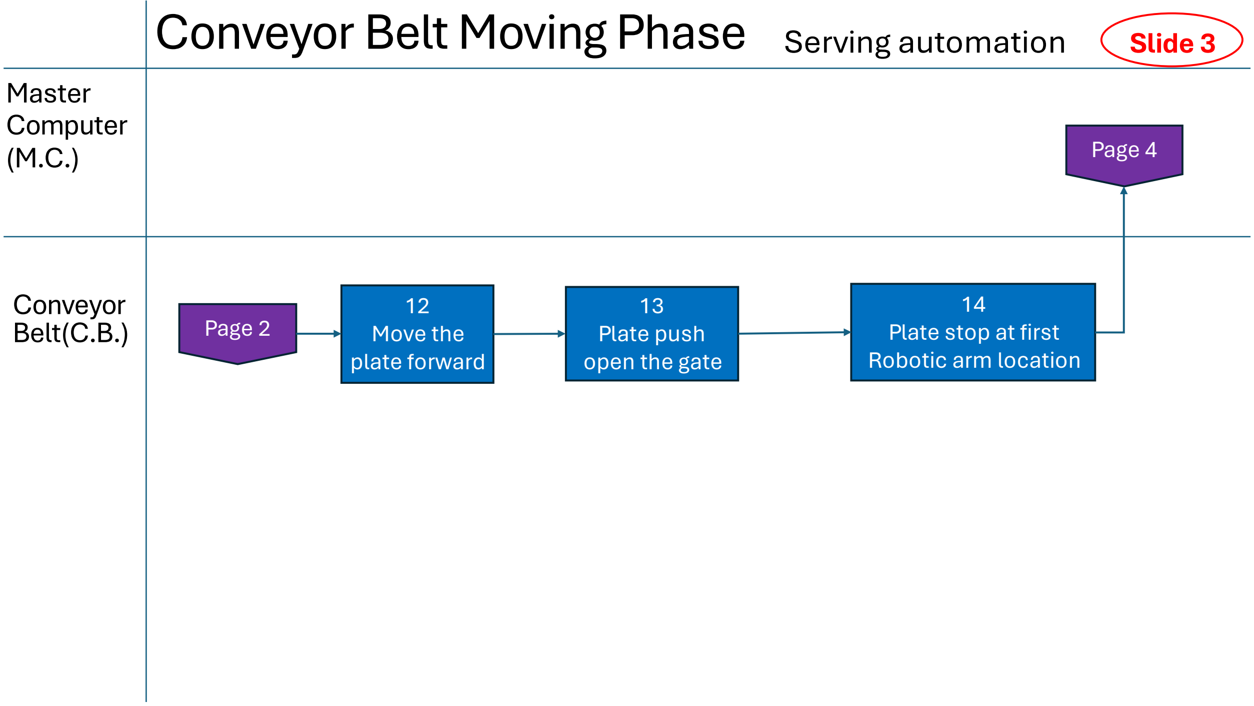


Figure 2.4.1.2: Second Slide System Block Diagram

Kiosk would store the order information into an CSV file that future team can use the data to run statistical analysis. Kiosk would then send the order information to the master computer. Master computer would then take information and tell student to place the plate onto conveyor belt.



Conveyor Belt Moving Phase

Serving automation

Slide 3

Master Computer (M.C.)

Page 4

Conveyor Belt(C.B.)

Page 2

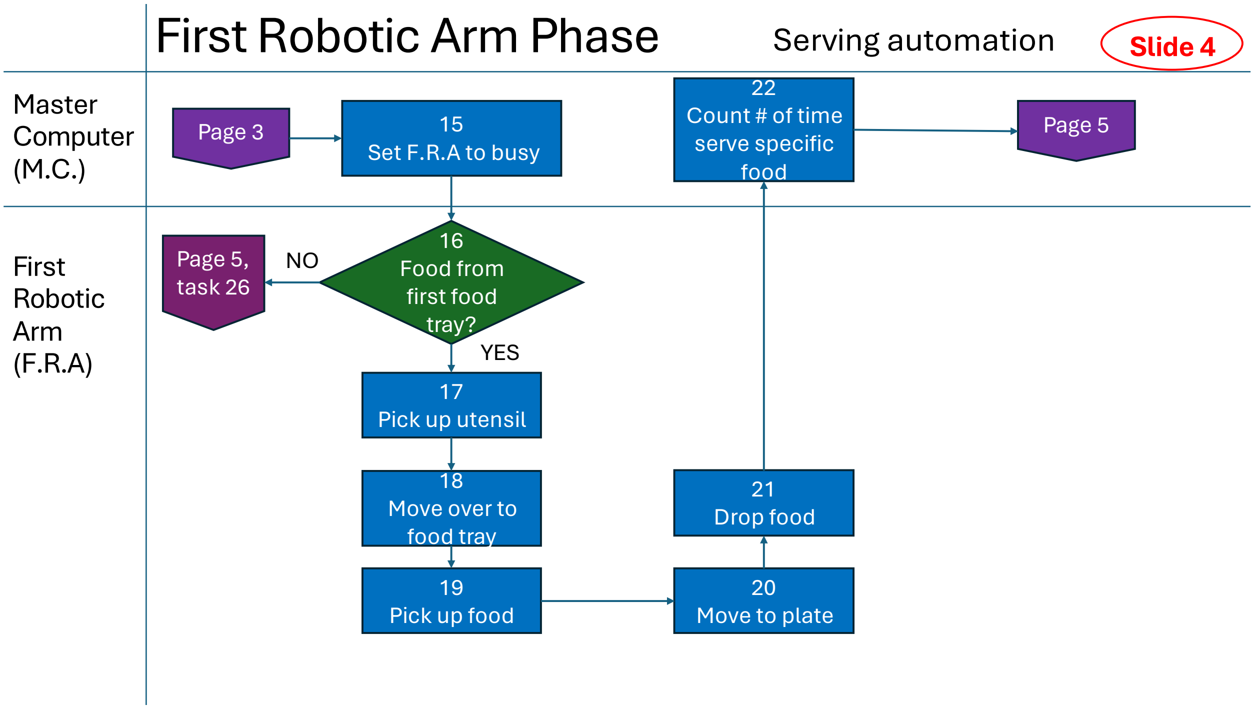
12
Move the plate forward

13
Plate push open the gate

14
Plate stop at first Robotic arm location

Figure 2.4.1.3: Third Slide System Block Diagram

Once the student have put the plate onto conveyor belt, conveyor belt will start moving. Plate will push open a gate and stop at the first robotic arm location.



First Robotic Arm Phase

Serving automation

Slide 4

Master Computer (M.C.)

Page 3

15
Set F.R.A to busy

22
Count # of time serve specific food

Page 5

First Robotic Arm (F.R.A)

Page 5, task 26

NO

16
Food from first food tray?

YES

17
Pick up utensil

18
Move over to food tray

19
Pick up food

20
Move to plate

21
Drop food

Figure 2.4.1.4: Fourth Slide System Block Diagram

Once the plate have arrived at first robotic arm location, master computer will then set the robotic arm to busy. Then there is the logic process that did the student order food from the first food tray? If not, robotic arm will then go to task 27. If yes, robotic arm will pick up the utensil for that food tray, move over to the food tray, pick up food from fist food tray, move over to the plate, drop the food onto plate and count number of time this robotic arm have serve this specific food.

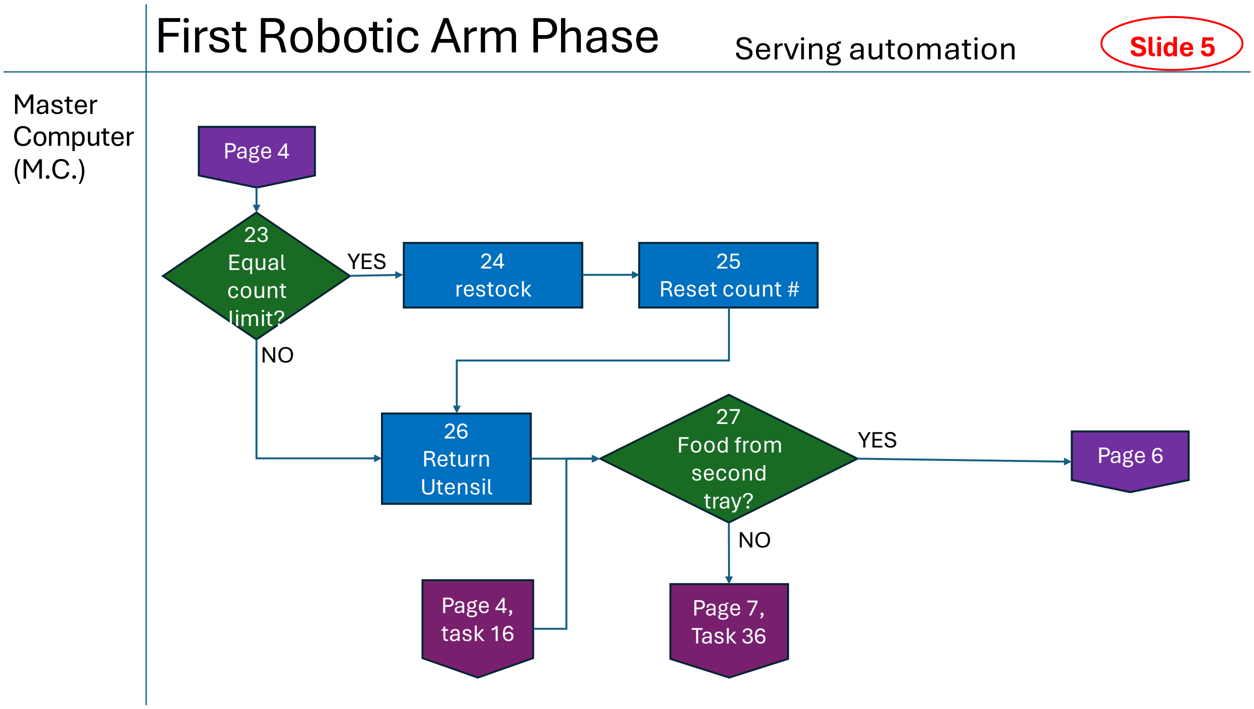
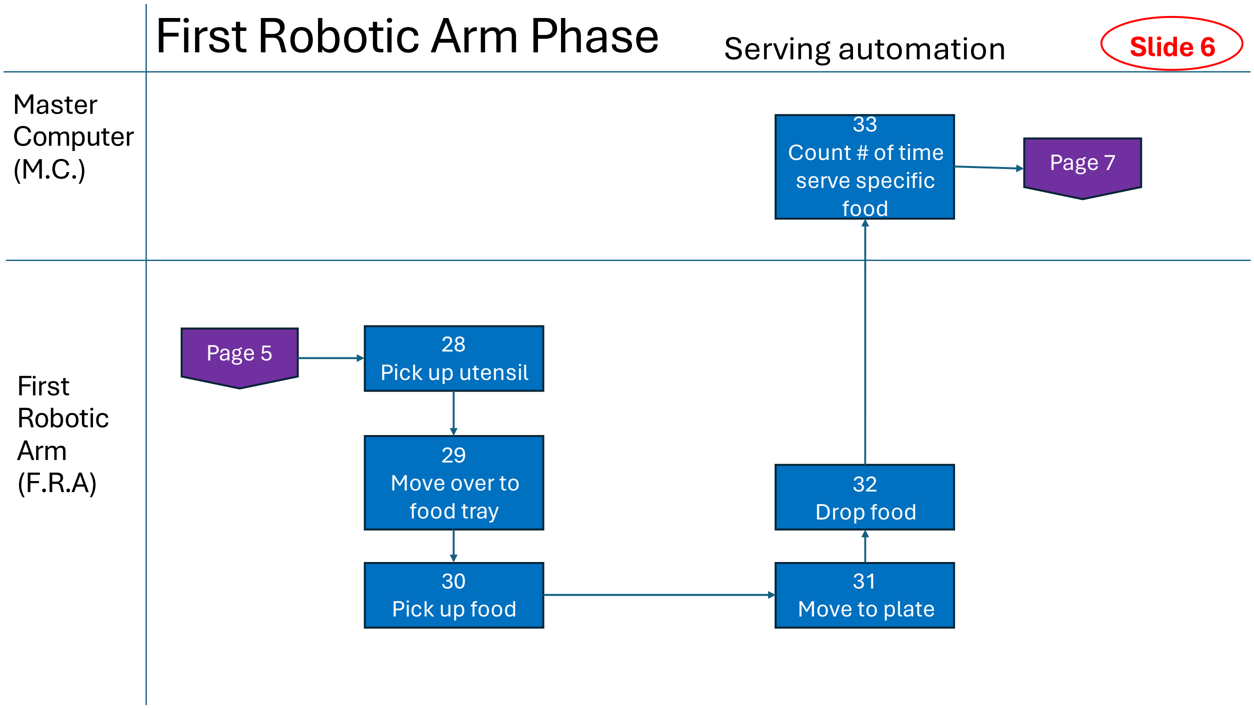


Figure 2.4.1.5: Fifth Slide System Block Diagram

If the number count is over a set limit, it will indicate to the worker that this specific food tray needs to be restock. After Reset count # is complete or it does not equal to count limit, it will then return utensil. Then it checks if it needs food from the second food tray.



First Robotic Arm Phase

Serving automation

Slide 6

Master Computer (M.C.)

33
Count # of time serve specific food

Page 7

First Robotic Arm (F.R.A)

Page 5

28
Pick up utensil

29
Move over to food tray

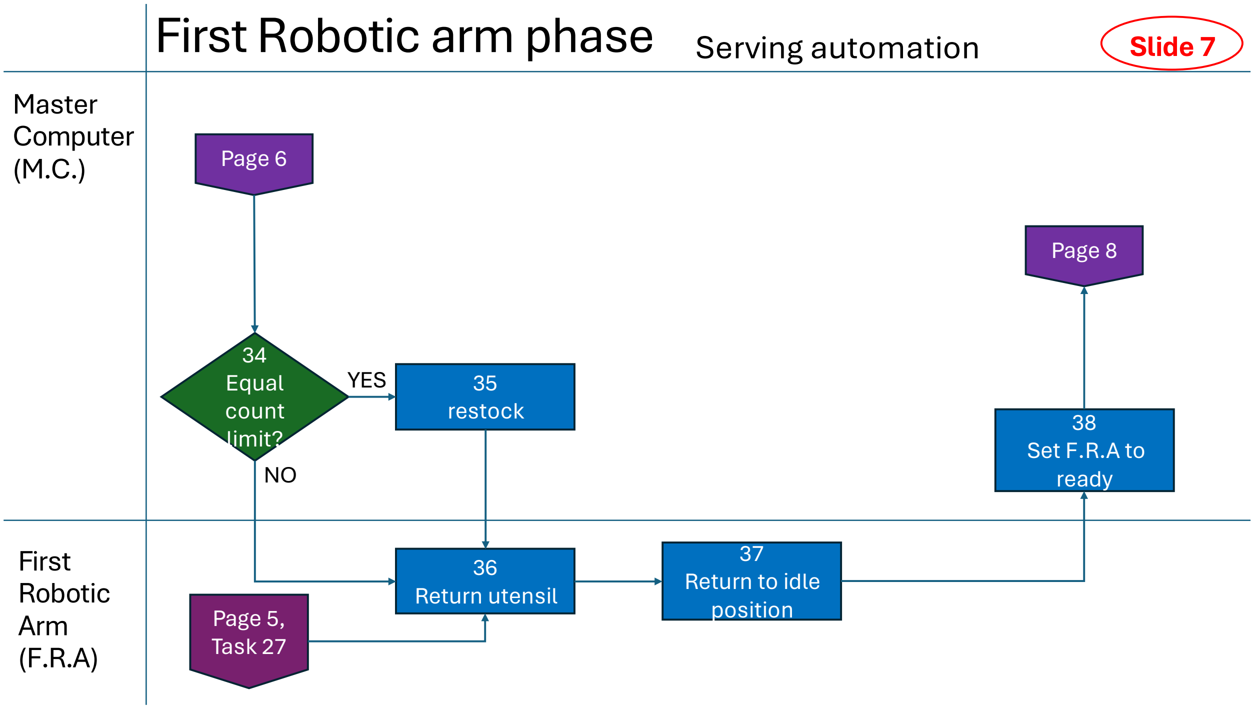
30
Pick up food

31
Move to plate

32
Drop food

Figure 2.4.1.6: Sixth Slide System Block Diagram

If food is needed, the first robotic arm will then pick serve food from the second food tray to the plate.



First Robotic arm phase

Serving automation

Slide 7

Master Computer (M.C.)

Page 6

34
Equal count limit?

YES

NO

35
restock

Page 8

38
Set F.R.A to ready

First Robotic Arm (F.R.A)

36
Return utensil

37
Return to idle position

Page 5, Task 27

Figure 2.4.1.7: Seventh Slide System Block Diagram

If will count and check if food needs to be restocked. Once the process is complete, it will return the utensil and return to its idle position. Master computer will then set first robotic arm to ready.

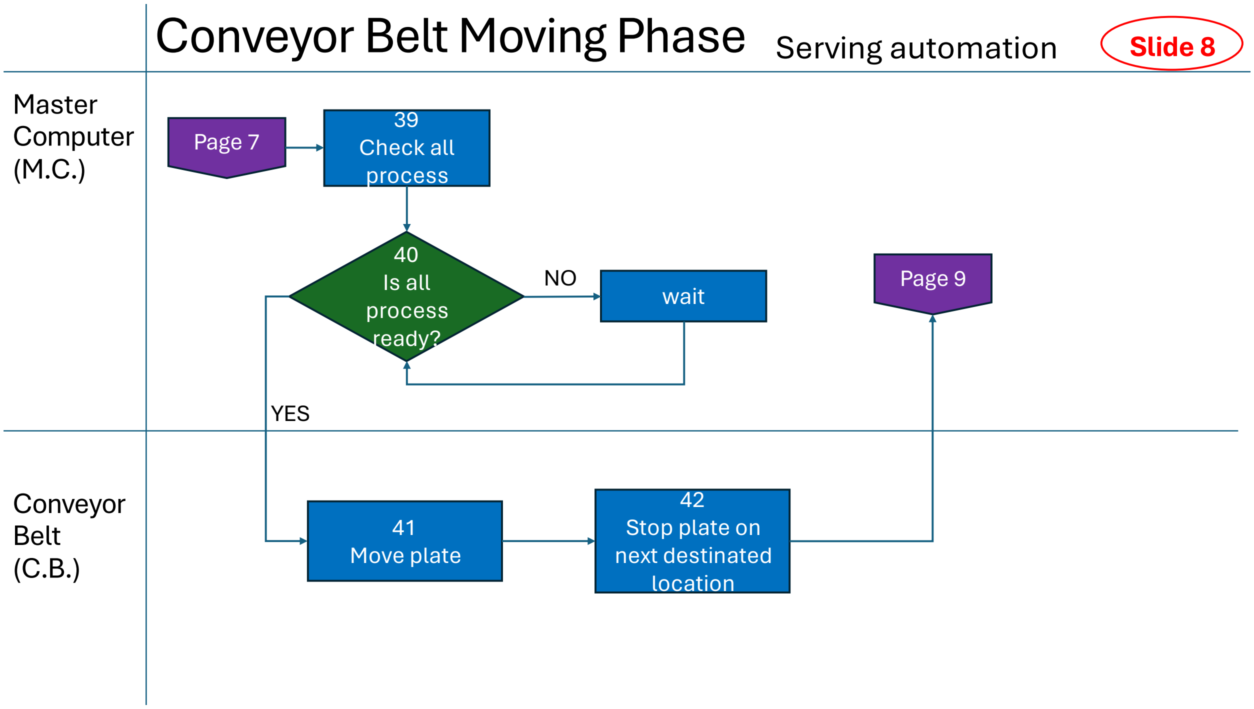


Figure 2.4.1.8: Eighth Slide System Block Diagram

Master computer will then check if all process is complete, if all process is completed, it will then move the plate into next station.

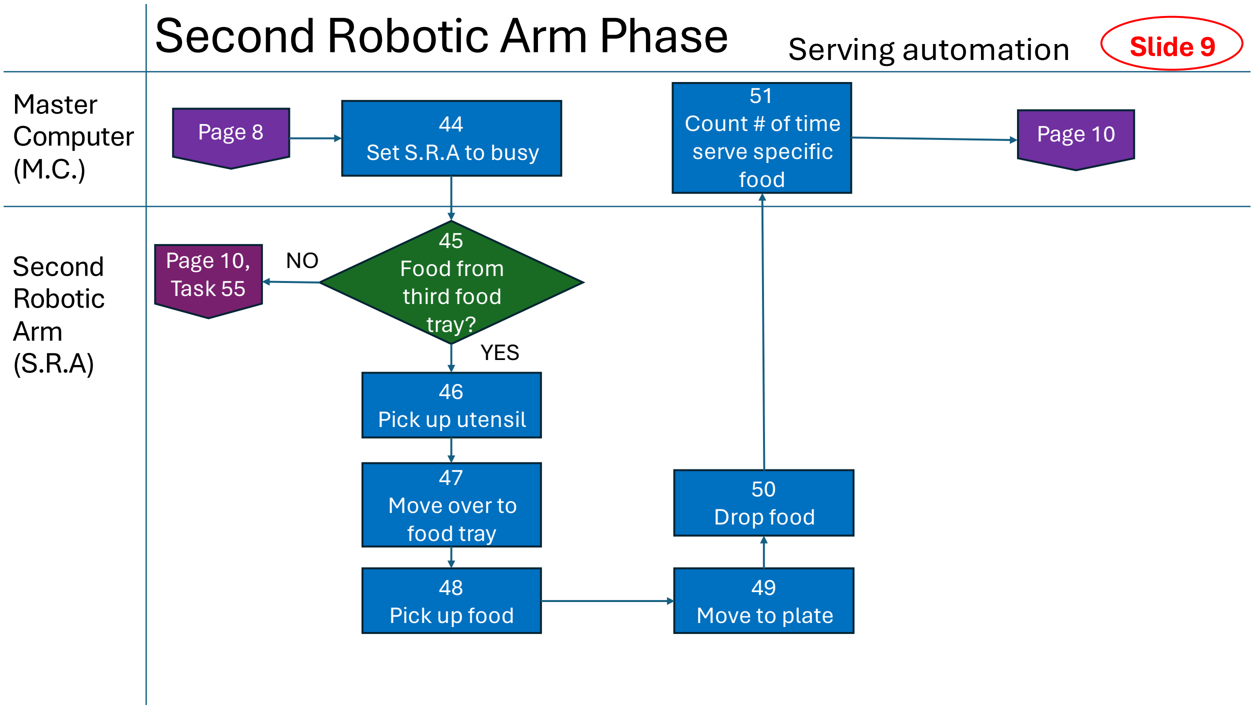


Figure 2.4.1.9: Ninth Slide System Block Diagram

Once Plate arrives at the second robotic arm location, the master computer will then set the second robotic arm to busy. If food is needed from the 3rd food tray, the second robotic arm will then pick up utensil, move over to 3rd food tray, pick up food, move over to the plate and drop the food onto plate. If food is not needed from the 3rd food tray, go to task 55.

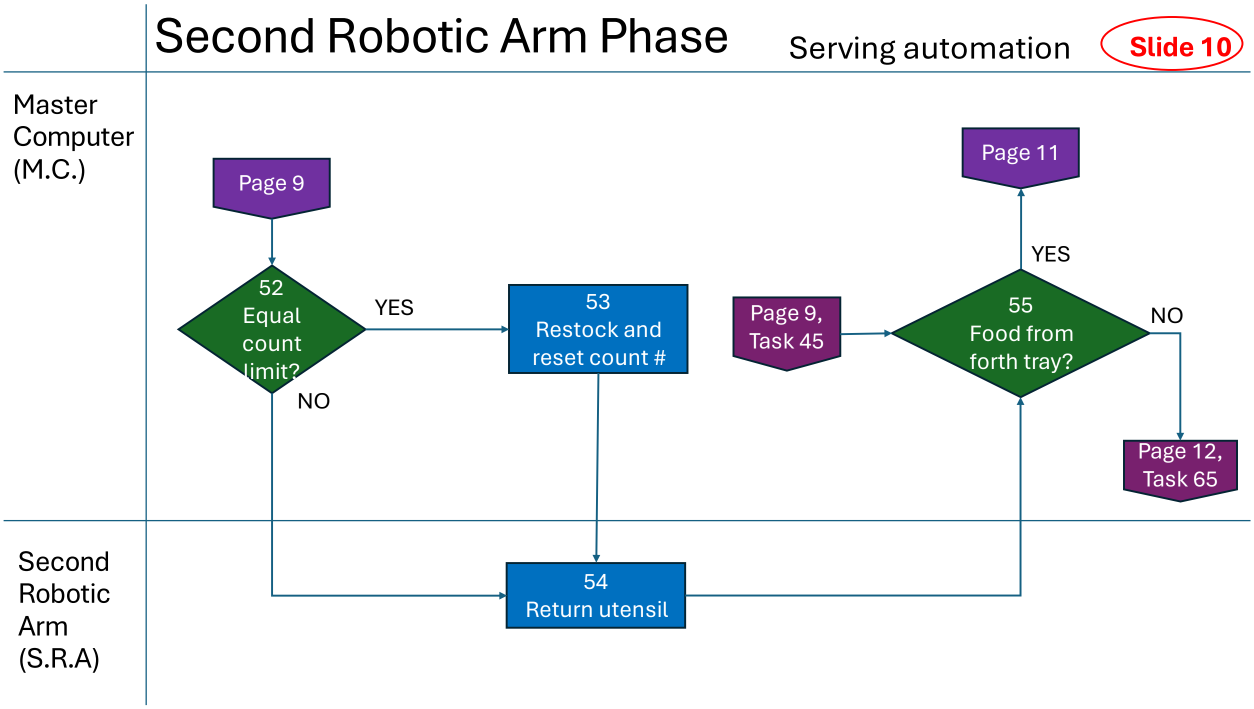


Figure 2.4.1.10: Tenth Slide System Block Diagram

If its equal to the count limit, then restock, if not skip. Return the utensil to its original location, then check for is 4th food tray is needed. If not go to task 65.

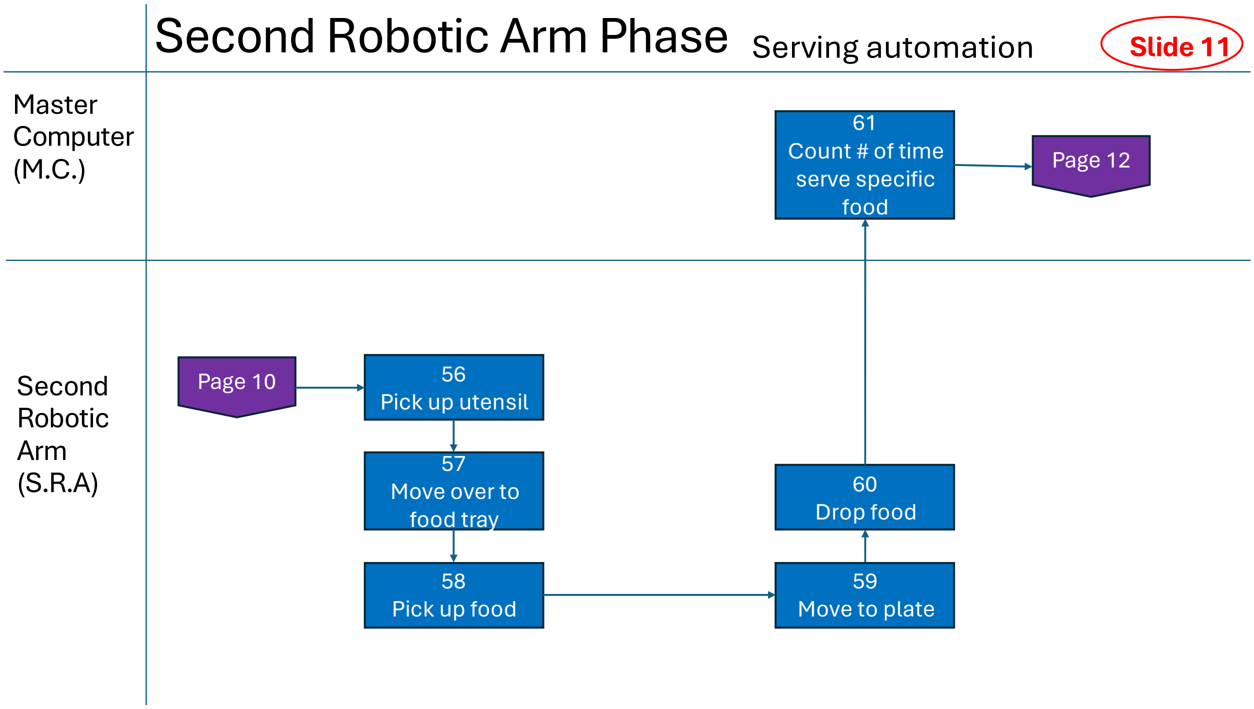


Figure 2.4.1.11: Eleventh Slide System Block Diagram

If food is needed from the 4th food tray, second robotic arm will then go through the process again, put food onto the plate and master computer will count number of time it serve 4th food tray by master computer.

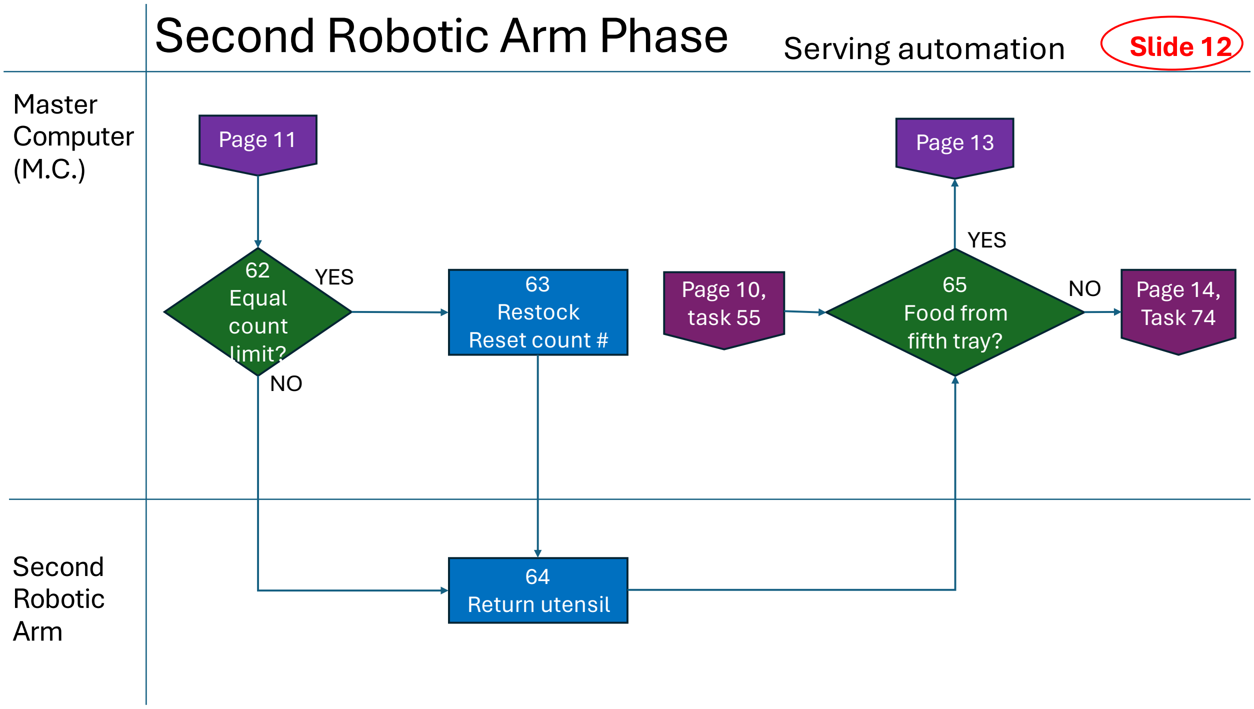


Figure 2.4.1.12: Twelfth Slide System Block Diagram

If its equal to count limit, then it will tell worker to restock and reset count number for fourth food tray, if its not need then skipped this process. It will then return utensil to its holder and check if 5th food tray is needed. If not go to task 74.

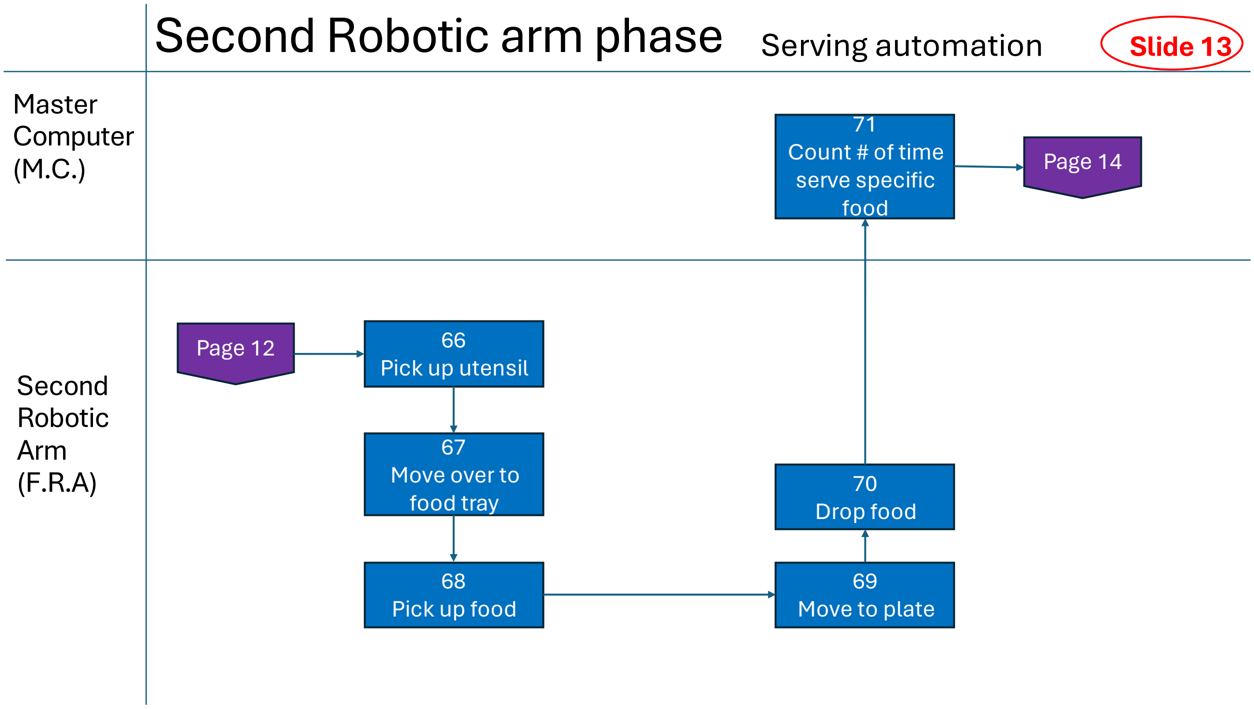


Figure 2.4.1.13: Thirteenth Slide System Block Diagram

If food is needed, the second robotic arm will then go through the process and drop food onto the plate and master computer will count number of times it serve 5th tray.

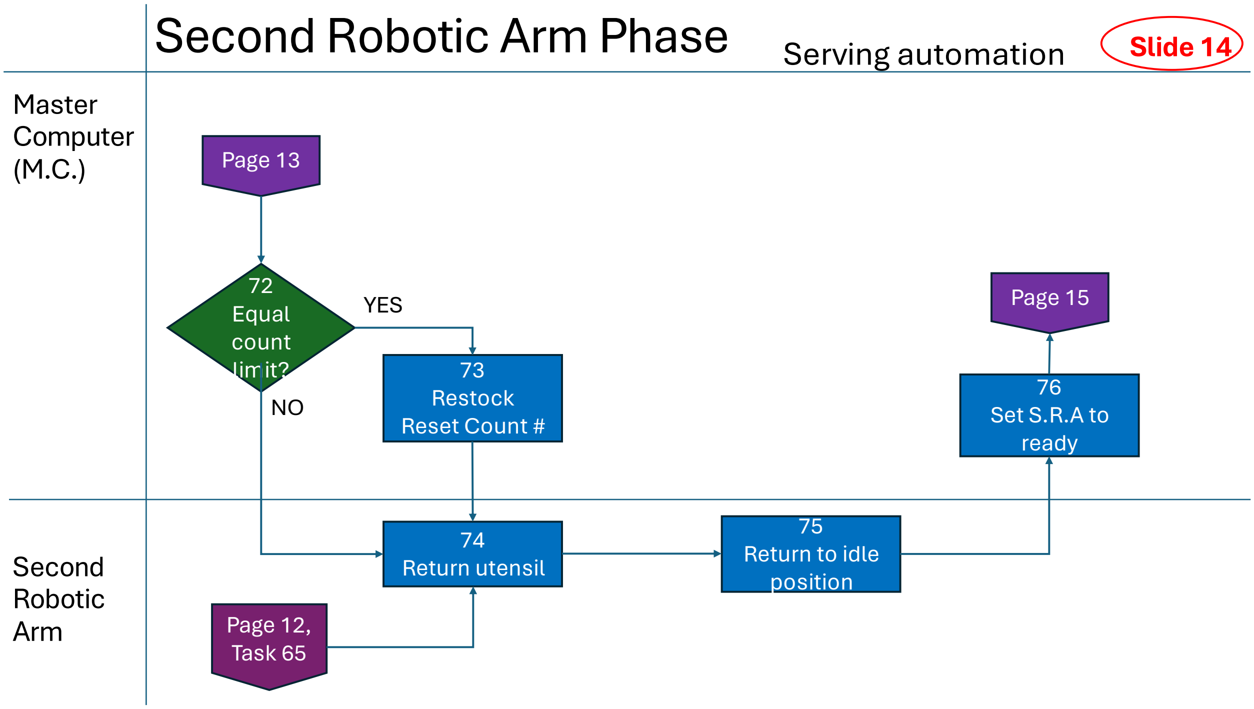


Figure 2.4.1.14: Fourteenth Slide System Block Diagram

If its equal to count limit then it will then restock and rest the count number, if it’s not needed then skip. After the process is complete, it will return the utensil and the second robotic arm will return to its idle position and set the second robotic arm to ready.

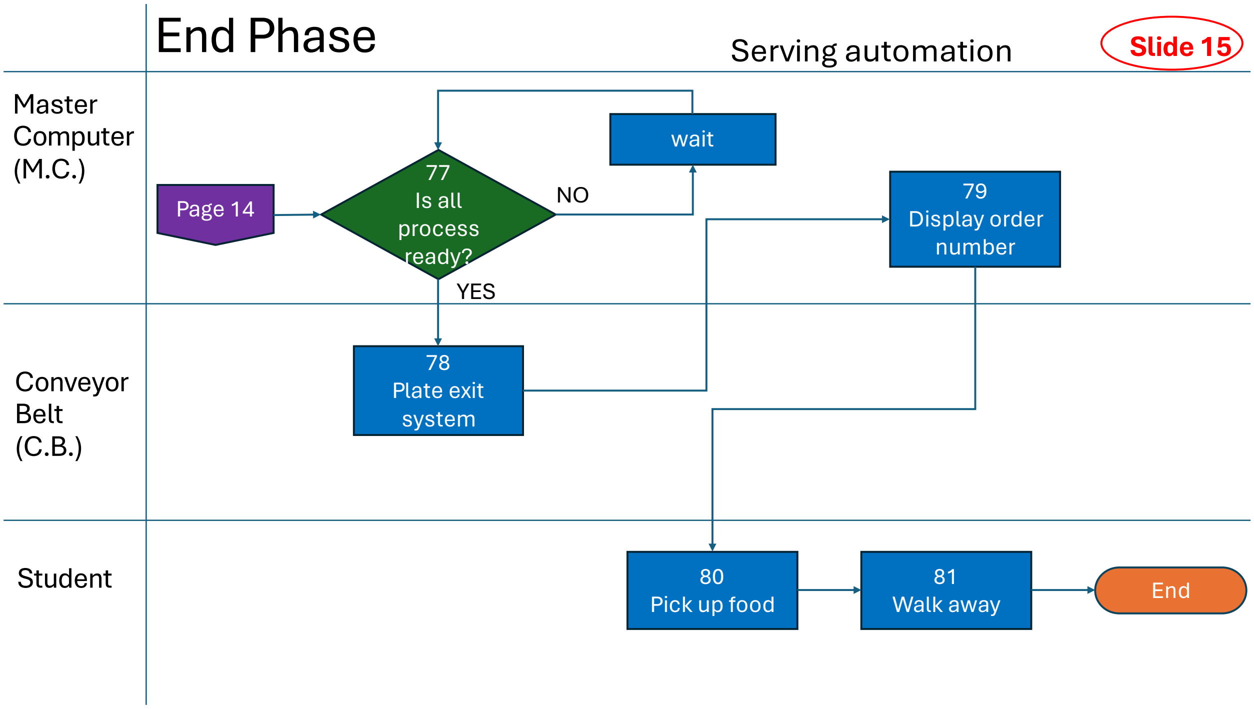


Figure 2.4.1.15: Fifteenth Slide System Block Diagram

Lastly, the master computer will check if all the process is ready, if not it will wait until all process is ready to go. When all process is ready, conveyor belt will move the plate forward and left the system. Master computer will then display order number, student now can pick up the food and walk away from the system.

3. Customer Needs and Engineering Design Requirements

Before discussing potential designs for the automated food serving system, both the students' and workers' needs were identified. This ensured that the system would be as compatible as possible with the current system in Commons Dining Hall. The team narrowed down that initial list to the highest priority needs and requirements as shown in ***Table 3.1*** below. The worker's needs are highlighted pink, student needs are highlighted blue, and needs for both are highlighted purple.

Table 3.1: High Priority Customer Needs and Engineering Design Requirements

Customer Need	**Priority (1 - 5)**	**Requirement**
Product needs to serve food automatically	1	Be able to serve food on the plate to customers without human interaction.
Product needs to serve permutable menu items per given day	1	Be able to serve protein, starch, veg/texture item through modular utensils
Can fit in the space	1	Device must fit within the space during the entire serving process
Students cannot interact with the plate while food is being served	1	Plate is kept behind a glass barrier until ready
Compatible with existing menu	2	Serving utensils used are compatible with all foods currently served on the menu
Accurate placement of food on the plate	2	Each food item is placed on a separate location on the plate
Minimum number of possible robots per space	3	Use the fewest number of robots possible in the space to properly serve food
Robot is movable	4	The robot must be able to be easily moved by an employee
Serves customers in a timely manner	5	No change to current serve times

4. System Concept Development

The team determined that the Robotic Arm subsystem was the central subsystem for the project’s success, as such, the time spent as a group on concept development was focused specifically on the Robotic Arm subsystem. This concept development focused on the type of automation used (free-standing robotic arm, robotic arm on tracks, “slushie machine” -like dispenser, and piping bag dispenser) and the number of each type of automation incorporated into the system. The team came up with six concepts, shown in ***Figure 4.1*** below.

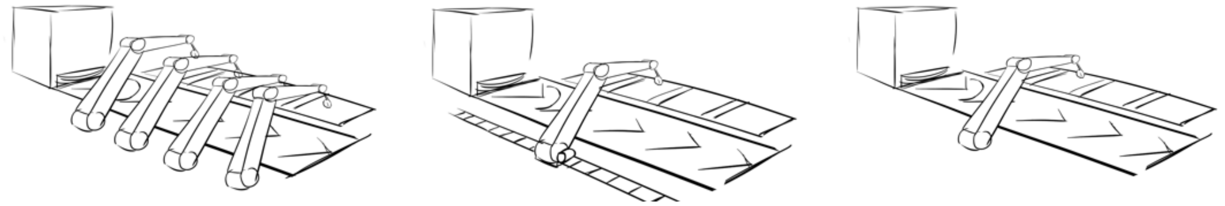


Figure One: One Arm per Food Item

Figure Two: One Arm All Items (Track)

Figure Three: One Arm All Items (Stationary)

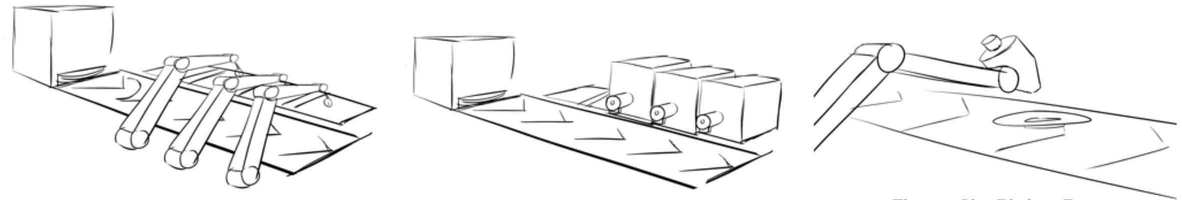


Figure Four: One Body Three Arm

Figure Five: "Slushie Machine" Dispenser

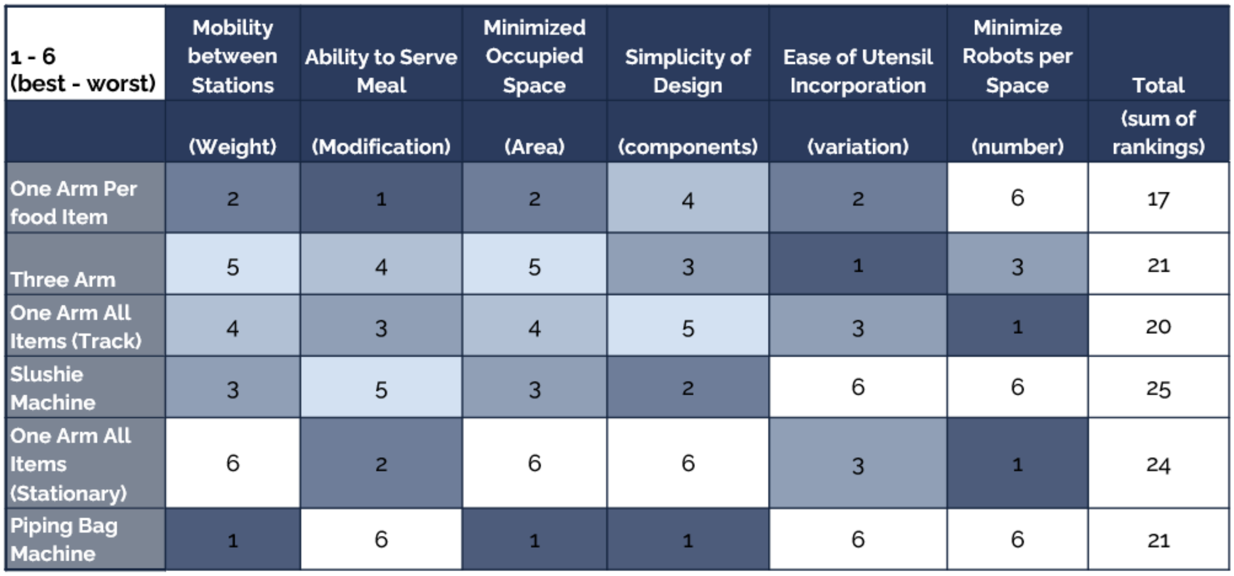
Figure Six: Piping Bag

Figure 4.1: Robotic Arm Subsystem Concept Design

These six concepts were then compared against each other using the criteria outlined in ***Figure 4.2*** below. These criteria were developed using the customer needs and requirements and include the following:

- Mobility between stations
- Ability to serve full meals (can it serve every single food item type)
- Minimize occupied space
- Simplicity of design
- Ease of utensil incorporation
- Minimize the number of robots per space

The concept ideas were ranked against each other from best to worst, with 1 being the best and 6 being the worst. These rankings were then added together to create a sum of rankings for each concept to help determine which would be the best option for the system. As all of these needs were identified as high priority, they were equally weighed against one another.



1 - 6 (best - worst)	Mobility between Stations	Ability to Serve Meal	Minimized Occupied Space	Simplicity of Design	Ease of Utensil Incorporation	Minimize Robots per Space	Total
	(Weight)	(Modification)	(Area)	(components)	(variation)	(number)	(sum of rankings)
One Arm Per food Item	2	1	2	4	2	6	17
Three Arm	5	4	5	3	1	3	21
One Arm All Items (Track)	4	3	4	5	3	1	20
Slushie Machine	3	5	3	2	6	6	25
One Arm All Items (Stationary)	6	2	6	6	3	1	24
Piping Bag Machine	1	6	1	1	6	6	21

Figure 4.2: Robotic Arm Subsystem Concept Comparison

Following this concept evaluation, client identified the “one arm per food item” concept as his preferred choice. This preference was discussed at length, but it was determined that the ideal solution would have fewer robotic arms within the system to reduce cost. As such, a system with two robotic arms for the Chef’s Table Station was identified as the optimal solution. This solution was chosen because the cost of each robot arm was around $10,000. A robot arm was sourced for $10,499.00 with a reach of 850mm, meaning that only two of these robots would be needed based on the dimensions of the Chef’s Table Station and the size of the hotel pans used in Commons Dining Hall. This robotic arm, the UFactory450 also had the necessary six degrees of freedom (“DoF”) to replicate the motion of the human arm during food service.

5. Final Design

5.1. Kiosk Subsystem Final Design

The Kiosk subsystem was originally intended for basic order transmission from the customer to the robot arms to plate the customer's desired food. This evolved into a feature-filled suite of applications and hardware that allows for not only order transmission to the "Master Computer" (the system which coordinates the conveyor belt and robot arms to plate food) but also presents the customer with an intuitive user interface comprising of the existing menu that can be modified by a worker before service starts.

The first step of the process comes from the workers in the dining hall. While they are setting up the kiosk and placing the trays of food in the heaters, the worker can open the UI application (shown in ***Figure 5.1.1***) on a workstation and change what food items are appearing on the kiosk from the customer's perspective.

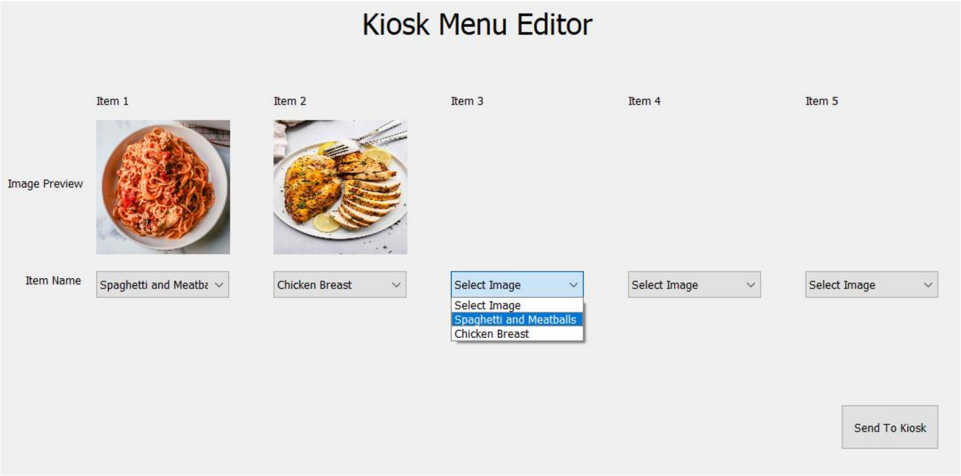


Figure 5.1.1: Worker-side Kiosk Menu Editor

After setting up the menu for the Kiosk, the worker can click "Send to Kiosk" to transfer the current view of the UI to the Kiosk. An example of the submitted menu (shown in ***Figure 5.1.1***) is displayed on the Kiosk (shown in ***Figure 5.1.2***).

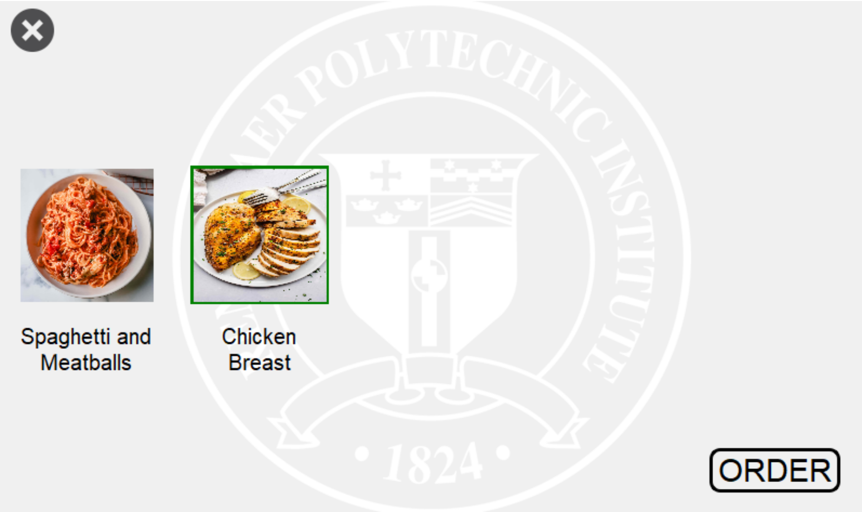


Figure 5.1.2: Customer-Side Kiosk Order Selection

After making a selection (highlighted by a green square), the customer can either continue selecting more items (clicking more options on the touchscreen), select the cancel button to clear all selections (clicking the "X" button at the top left corner of the touchscreen) or clicking the "ORDER" button, which will send the order to the master computer and show the order number and a summary of the order to the customer (as seen in ***Figure 5.1.3***).

Order Number 1 Placed

Chicken Breast

Figure 5.1.3: Customer-Side Kiosk After Placing Order

To accommodate many options of communication between devices as well as presenting different ways to have the hardware for the Kiosk, we decided to design a custom schematic and PCB (seen in ***Figure 5.1.4*** and ***Figure 5.1.5***, respectively) to be used in conjunction with a Raspberry Pi Touchscreen. This device would allow all information for the Kiosk's current menu to be received and to send the order and log data on the orders placed in each serving period. A Bill of Materials can also be seen in Appendix D for the physical creation of this PCB.

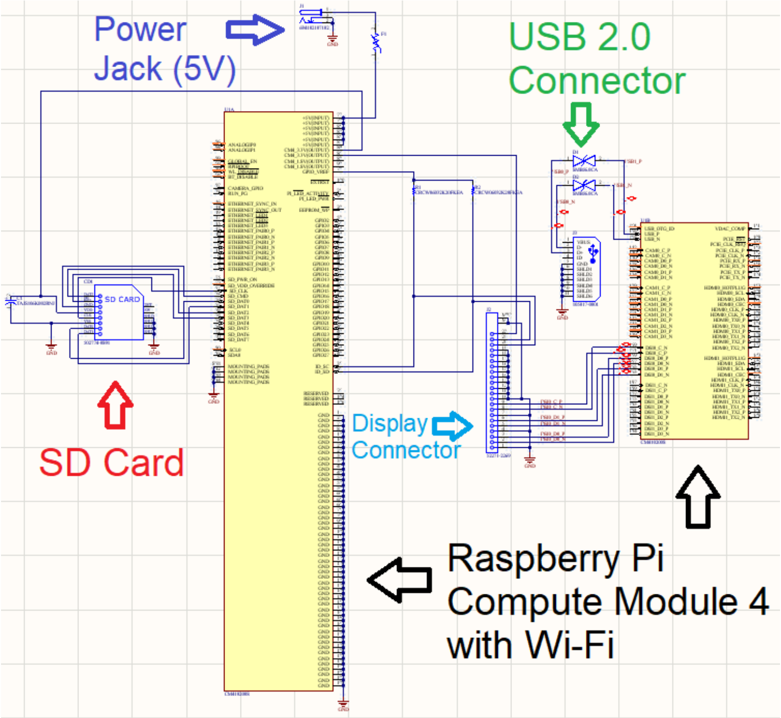


Figure 5.1.4: Schematic Overview of Custom Kiosk Hardware

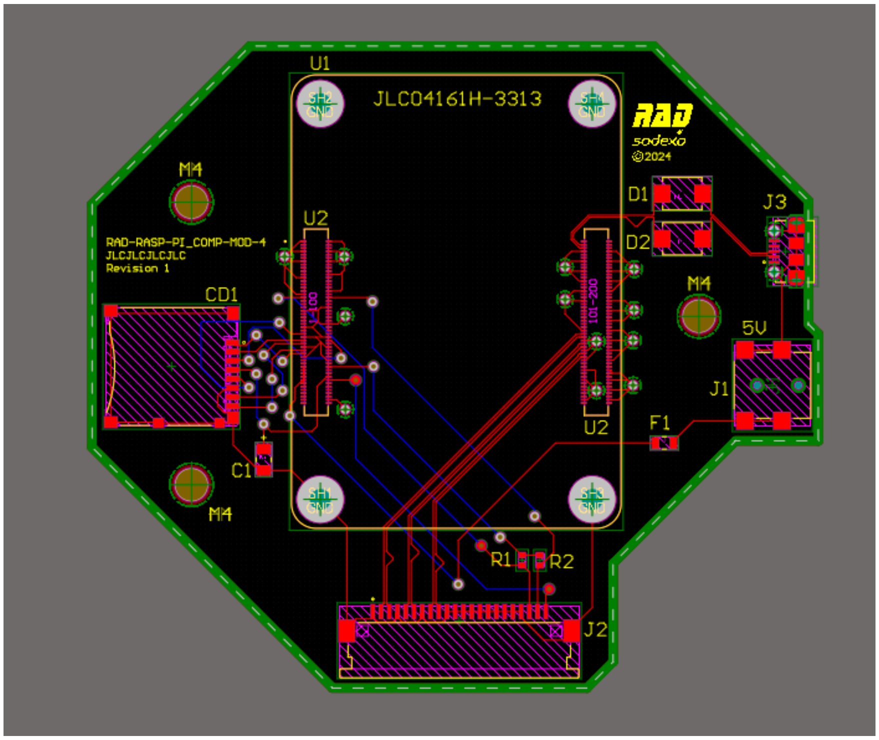


Figure 5.1.5: PCB Overview of Custom Kiosk Hardware

5.2. Plate Placement Subsystem Final Design

5.2.1. Plate Placement Subsystem – Conveyor Belt Entrance

The plate placement subsystem has the main objective of ensuring proper placement of the plates on the conveyor belt. The flapper placement in the context of the whole system is shown in ***Figure 2.1.1.*** This subsystem utilizes a spring-loaded flapper system, shown in ***Figures 5.2.1.1*** and ***5.2.1.2*** below, to align the plate along the center of the conveyor belt.

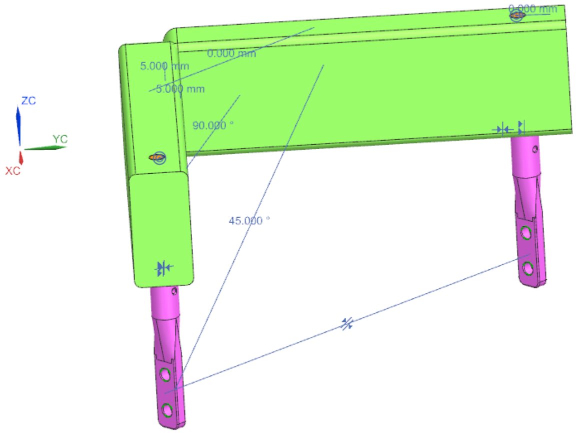


Figure 5.2.1.1: Flapper for Plate Placement Subsystem

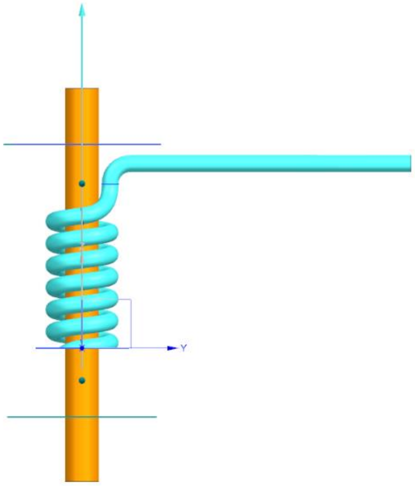


Figure 5.2.1.2: Spring in Flapper for Plate Placement Subsystem

This flapper will be adhered to the conveyor belt via the bracket on the side. The bracket will be drilled into the side of the conveyor belt to ensure proper adherence. .he materials needed for its construction have been outlined in the BOM found in Appendix D.

5.2.2. Plate Placement Subsystem – Conveyor Belt Exit

Proper plate placement is as crucial at the exit of the conveyor belt as it is at the entrance. As such, the Plate Placement subsystem includes a portion at the end of the conveyor belt, where its main goal is to keep plates moving at the end of the conveyor belt to prevent the collision of plates. This goal was achieved through the design shown below, which includes an inclined plane at the end of the conveyor belt with an angle of incline equivalent to 10° and rollers along the surface of the inclined plane. This angle was chosen because it provides a length that fits within the remaining counter space available. The complete accuracy of this angle cannot be fully assessed until it undergoes testing. There is more room on the counter should a smaller angle need to be chosen following testing, but this angle allows room for that decision to be made. This combination allows the plates to slide down the inclined plane at a safe speed until they reach the counter, where the students can pick up their plates. The design of this portion of the Plate Placement subsystem can be seen in ***Figures 5.2.2.1.*** below.

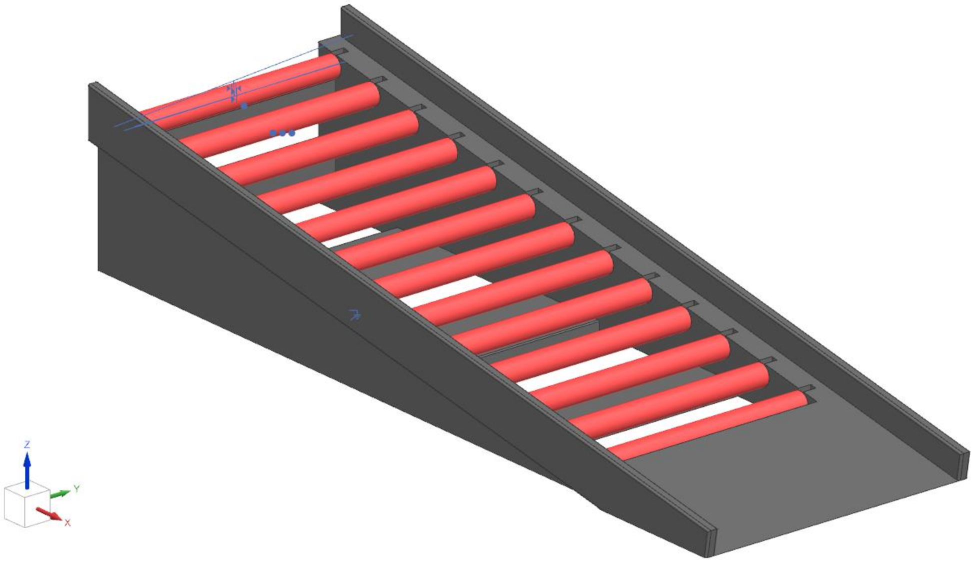


Figure 5.2.2.1: Inclined Plane and Rollers

The materials needed for this inclined plane's construction have been outlined in the associated BOM in Appendix D.

5.3. Conveyor Belt Subsystem Final Design

5.3.1 Conveyor Belt Physical System CAD

The CAD design for this system was based on the dimensions of the Chef's Table station at commons. As seen in ***Figure 5.3.1.1: Chef's Table Dimensions***, the Chef's Table spans 65 inches, which is why the length dimension of the conveyor is 75.59 inches. Furthermore, the width dimension of the conveyor is 9.84 inches because the average plate width at commons is 9 inches. Lastly, the height dimension of the conveyor is 6 inches because it does not want to get in the way of the robot arm. Therefore, the final dimensions chosen for the physical system are 250 mm (9.84in) wide, 1920 mm (75.59in) long, and 152.4 mm (6 in) tall. Some features of the conveyor belt are its lockable/unlockable wheels at the bottom for easy use and its modular plastic belt that can be removed to clean after a day of use.

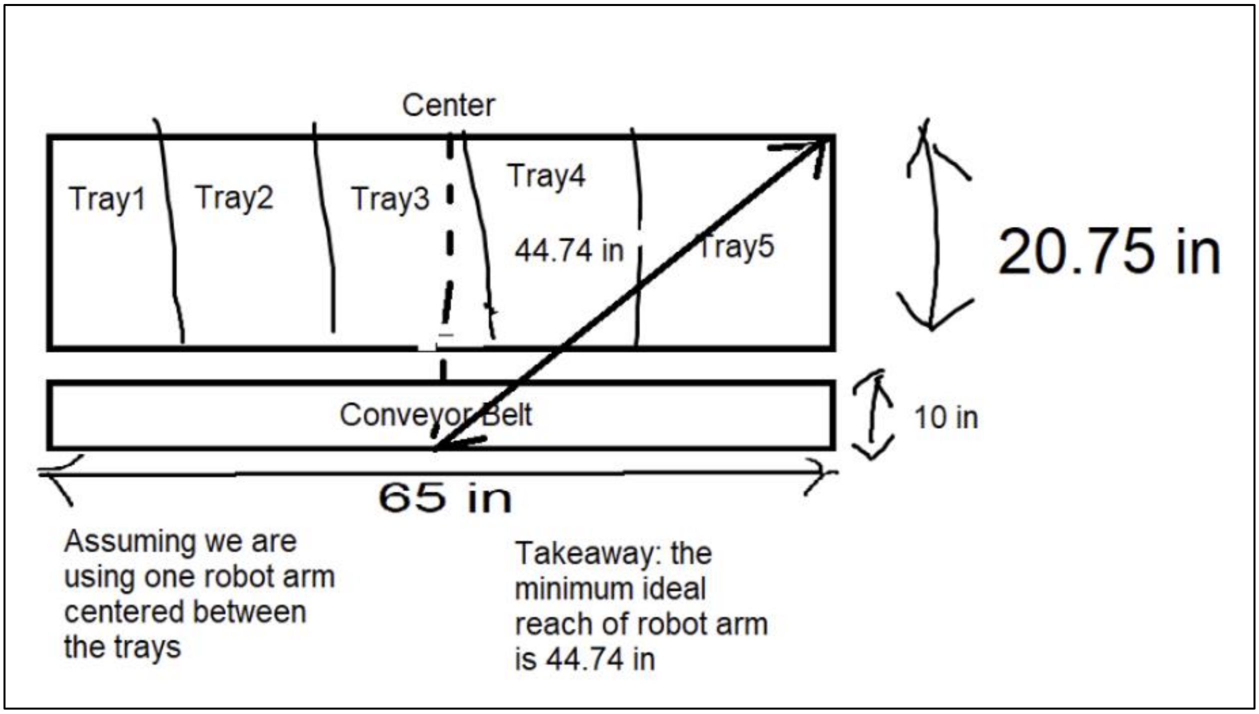


Figure ***5.3.1.1: Chef's Table Dimensions***

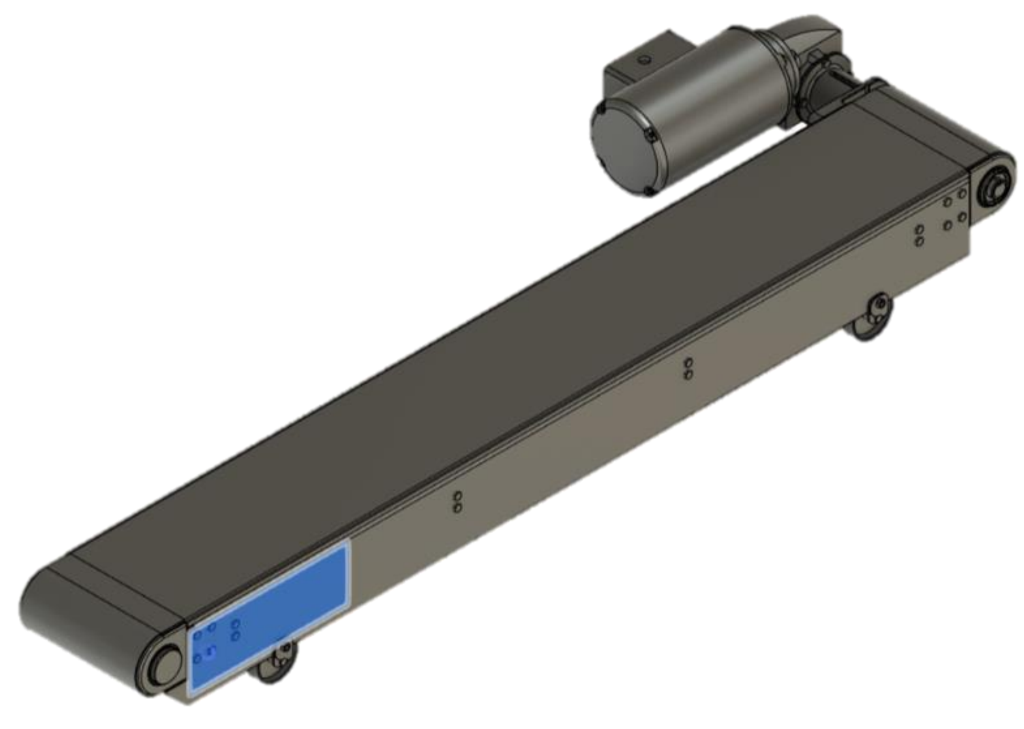


Figure ***5.3.1.2: Donor/HM Cross & Sons Conveyor Physical Design***

5.3.2 Conveyor Belt Electrical System Design

5.3.2.1 Overview of Electrical Design

The Electrical Design PCB consists of three main parts, the alternating current (“AC”) to direct current (“DC”) converter power circuits, microcontroller communication circuit, and gate driver motor control circuits as seen in ***Figure 5.3.2.1.1: Circuit Block Diagram***. The main purpose of the Electrical Design PCB is to provide a way to control the speed, direction, and breaks of an AC motor through code. The PCB also provides a way to communicate to a ROS capable system to be able to seamlessly automate serving at commons.

The process for this electrical design started with choosing the main component for the gate driver control circuit. Then based on the power needs for it, the AC to DC power circuits were chosen to power it. Furthermore, a step-down transformer and rectifier was chosen to power the smaller parts of the gate driver circuit and the microcontroller circuits. To visualize the inputs, outputs, and innerworkings of the PCB refer to ***Figure 5.3.2.1.1: Circuit Block Diagram*** and ***Figure 5.3.2.1.3: 3D PCB of Conveyor Electrical System Top View Without Components***.

There are two outputs, Master Computer Terminals (J2, J3) and the 3-pin motor terminal, and one input which is the 3-pin terminal for an 120V Outlet. ***Figure 5.3.2.1.5: PCB Box Connection Diagram*** shows how to assemble the AC power connector and connect it to the 3-pin terminal on the PCB board. This is crucial to get right when making an encloser for the PCB because it is the safe way to connect a wall outlet to a PCB. Therefore, the encloser for the PCB must have 3 holes for the corresponding input and outputs in ***Figure 5.3.2.1.1: Circuit Block Diagram***. Future steps for this encloser are to pick a connector that connects to the master computer and a connector for the 3-phase induction motor.

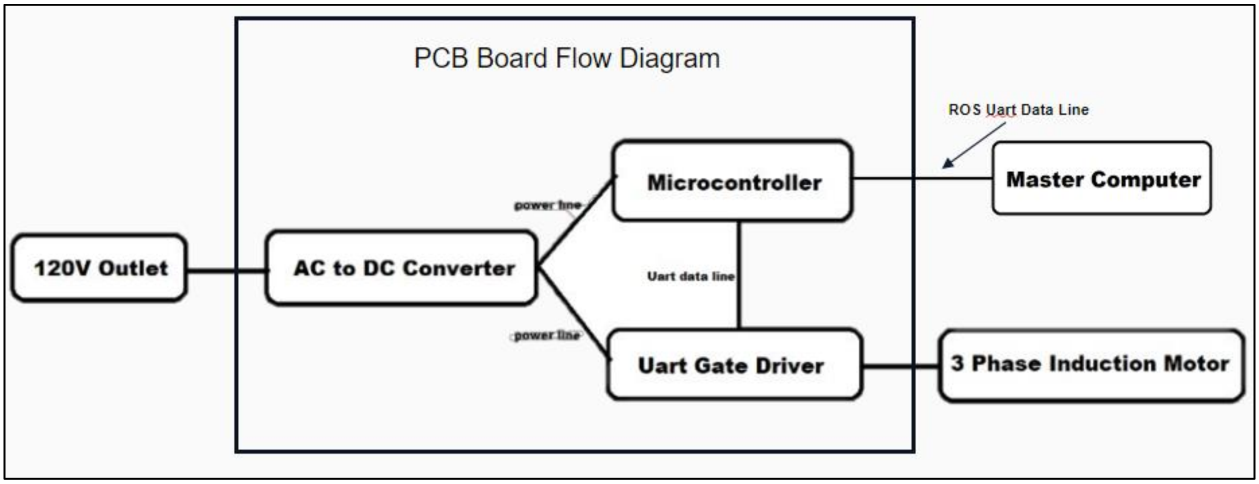


Figure 5.3.2.1.1: Circuit Block Diagram

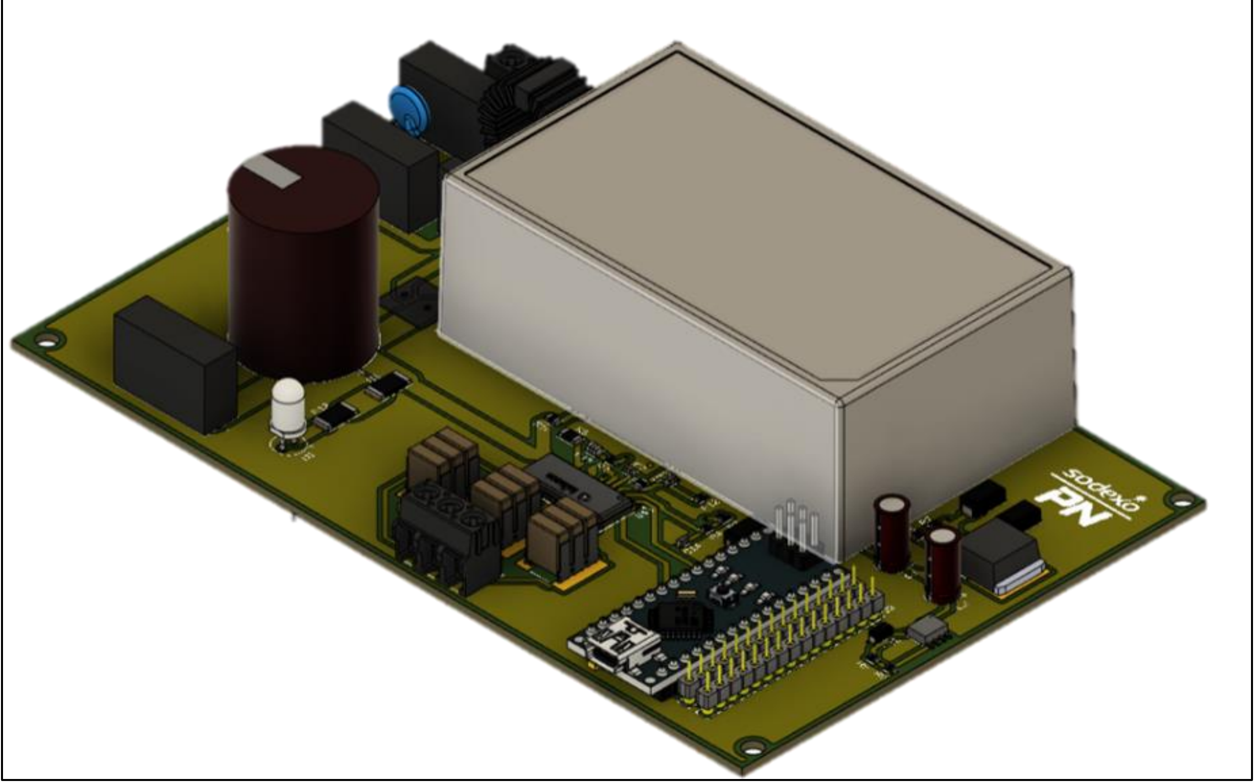


Figure 5.3.2.1.2: 3D PCB of Conveyor Electrical System

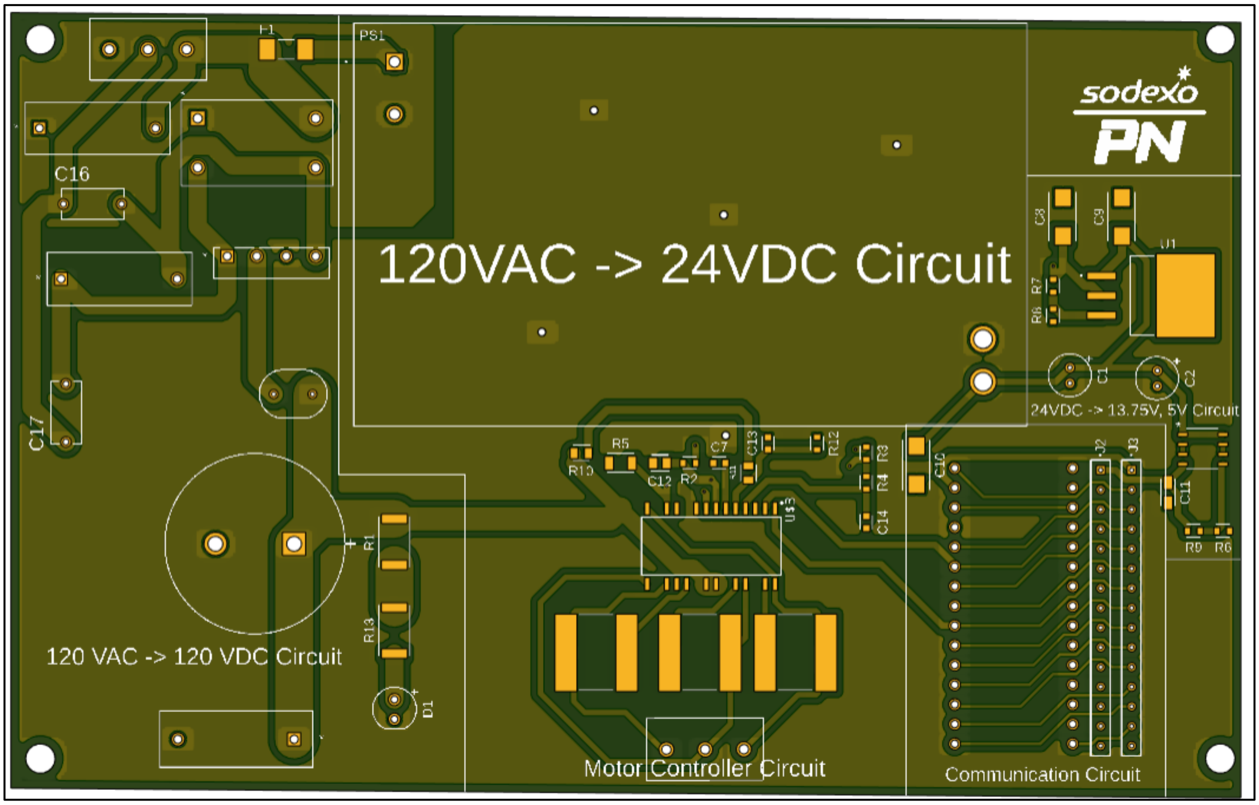


Figure 5.3.2.1.3: 3D PCB of Conveyor Electrical System Top View Without Components

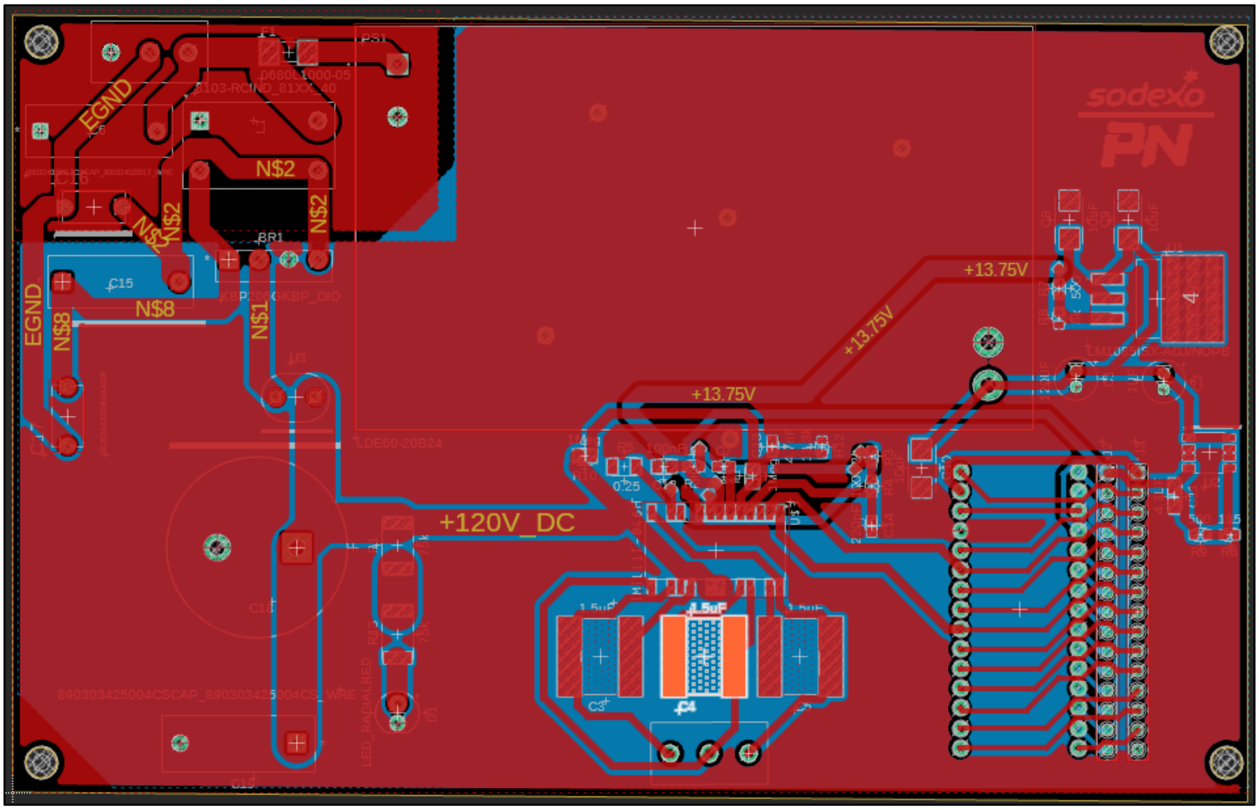


Figure 5.3.2.1.4: 2D PCB of Conveyor Electrical System Gerber File for Manufacturing

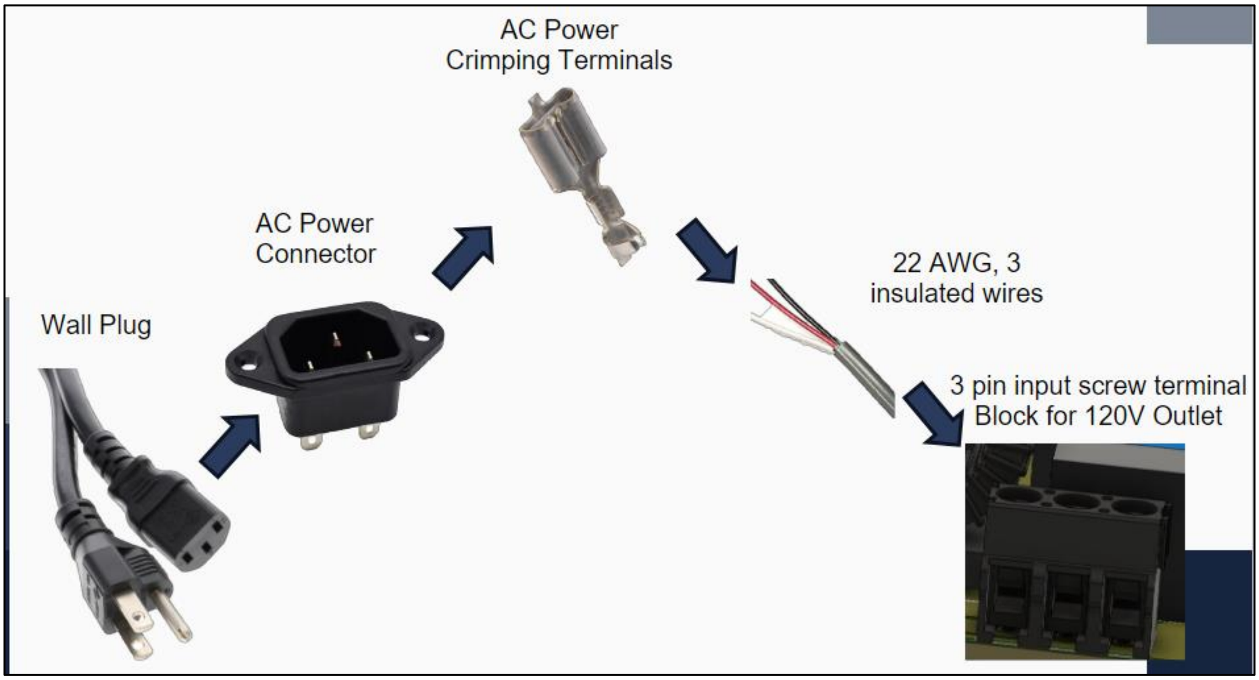


Figure 5.3.2.1.5: PCB Box Connection Diagram

5.3.2.2 Motor Controller Circuit

The IMI111T chip provides 70W of power to the 3 phase motor output pins. The switch capacitors C3, C4, C5 are rated for 600V so the motor rated voltage can be up to 600V. Pin1 and Pin2 in the IMI111T chip is the way the microcontroller communicates through UART to send commands to the motor. In the reference schematic the manufacturer of the IMI111T chip uses galvanic isolation around the microcontroller and a digital isolator for the universal asynchronous receiver-transmitter ("UART") communication lines. However, the PCB design for the electrical system of the conveyor belt eliminates that part since the microcontroller is in a separate PCB.

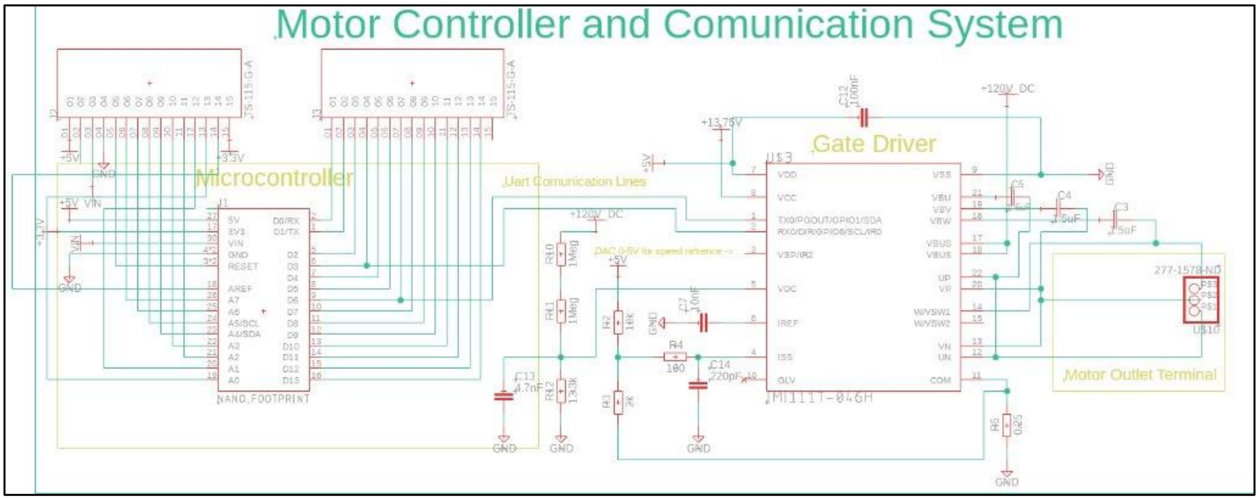


Figure 5.3.2.2.1: Motor Controller and Master Computer Communication System Circuit

5.3.2.3 Communication Circuit

The Arduino Nano is being used to communicate to the IMI111T Gate Driver chip through D3 and D6 which are GPIO pins that capable of PWM and will carry the UART Communication Protocol. The Terminals J2 and J3 were made to connect to every pin of the Arduino for easy breadboarding access for the master computer system connection.

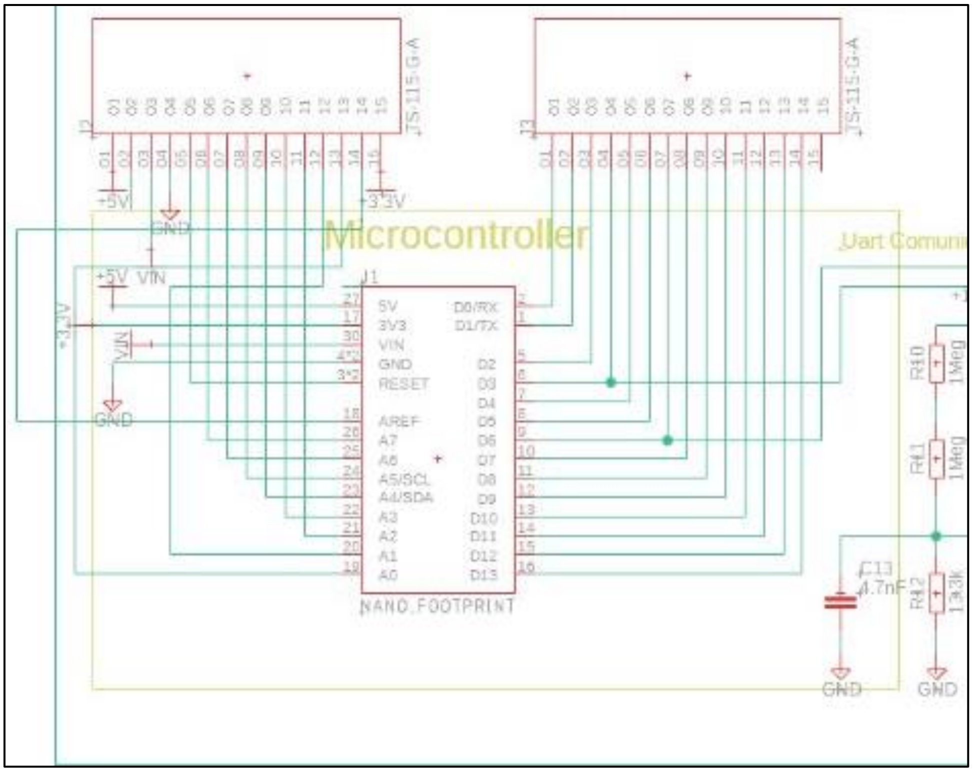


Figure 5.3.2.3.1: Master Computer Communication System Circuit

5.3.2.4 Power Circuits

The power circuits are protected by two fuses, one is rated for 1 Amp and the other 2 Amp. The 2 Amp fuse is for the 120VAC to 120VDC Circuit, and the 1 Amp fuse is for the 120VAC to 24VDC. Furthermore, all power circuits have decoupling capacitors to hold voltage at the proper level at input and output pins. Also, the 120VAC to 120VDC Circuit has a passive electromagnetic interference ("EMI") filter where the ground protection capacitors are.

Since the motor is only going to pull 0.15A and the microcontroller is going to pull 200 mA max, the fuses were properly chosen. Furthermore, all components voltage ratings were chosen based on the input and output voltages of the power circuits.

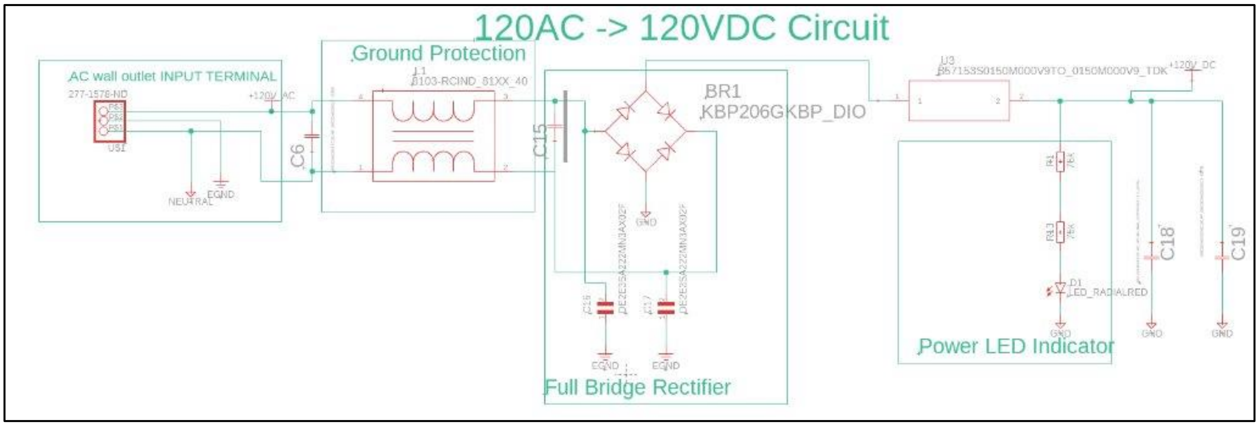


Figure 5.3.2.4.1: 120 VAC to 120 VDC Circuit

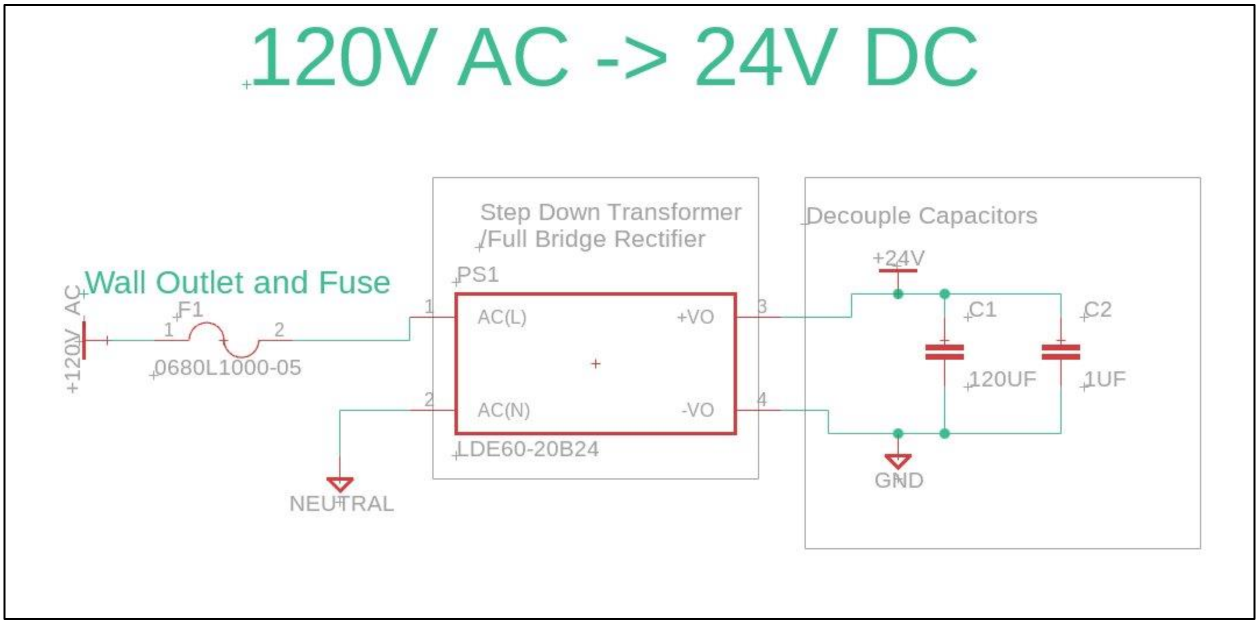


Figure 5.3.2.4.2: 120 VAC to 24 VDC Circuit

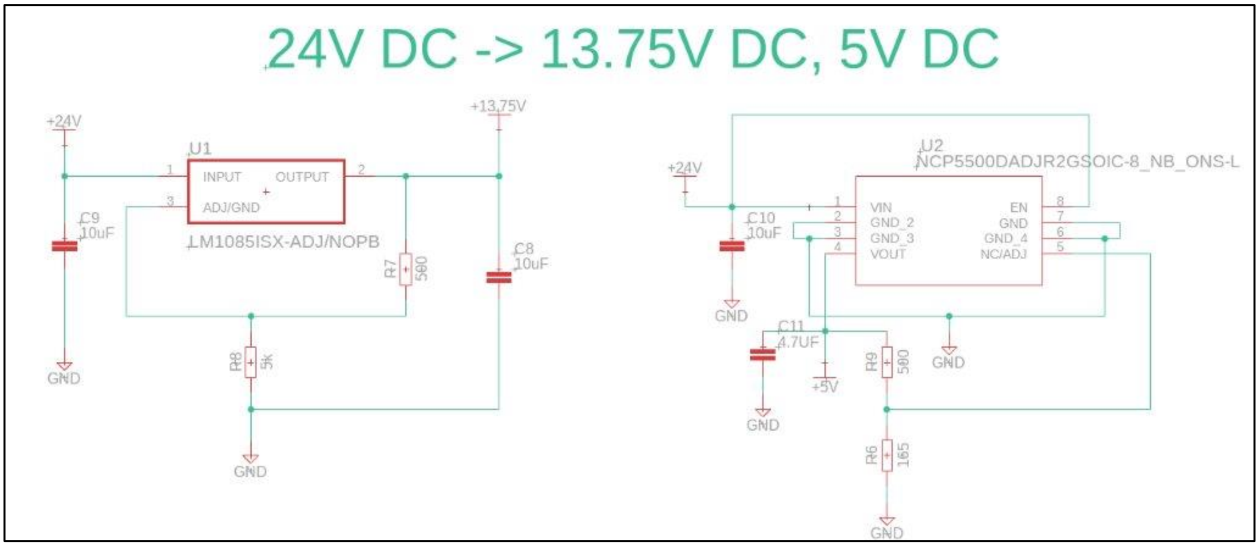


Figure 5.3.2.4.3: 120 VAC to 13.75, 5VDC Circuit

5.4. Robotic Arm Subsystem Final Design

Most of the Robotic Arm design was discussed in Section 4: System Concept Generation. A simulation was created using the Octopuz offline robotic simulation program based on the design. The program allows for the simulation of robotic arms and for the code to be exported to physical robots, making the process faster and easier. Since the scoop was identified as the most common utensil, the main goal of the Robotic Arm subsystem was to simulate the robotic arm scooping food and dropping it onto a specific predetermined location on the plate. While other utensils may be simulated in the future, the team chose to focus on the scoop. The spoon, utensil holder, and conveyor belt have already been modeled by the team and imported into the simulation. These CAD models working with the robotic arm in simulation are shown in ***Figure 5.4.1*** and ***Figure 5.4.2***.

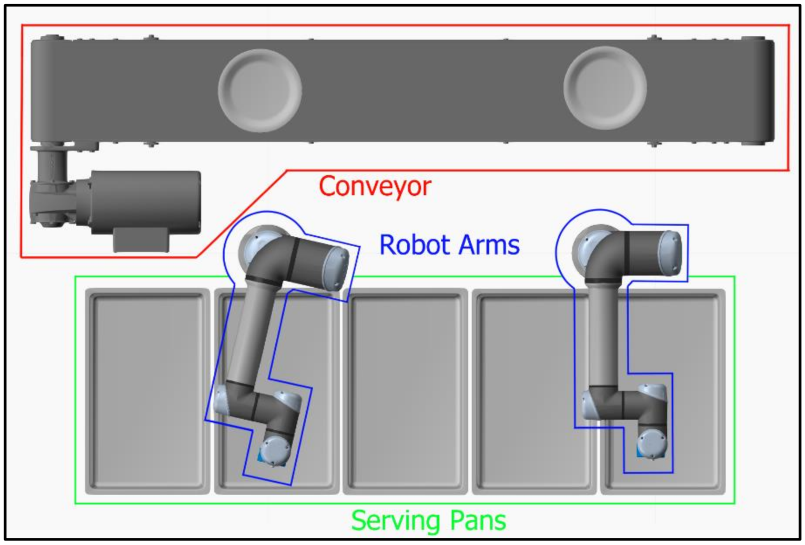


Figure 5.4. 1: Layout of Robot

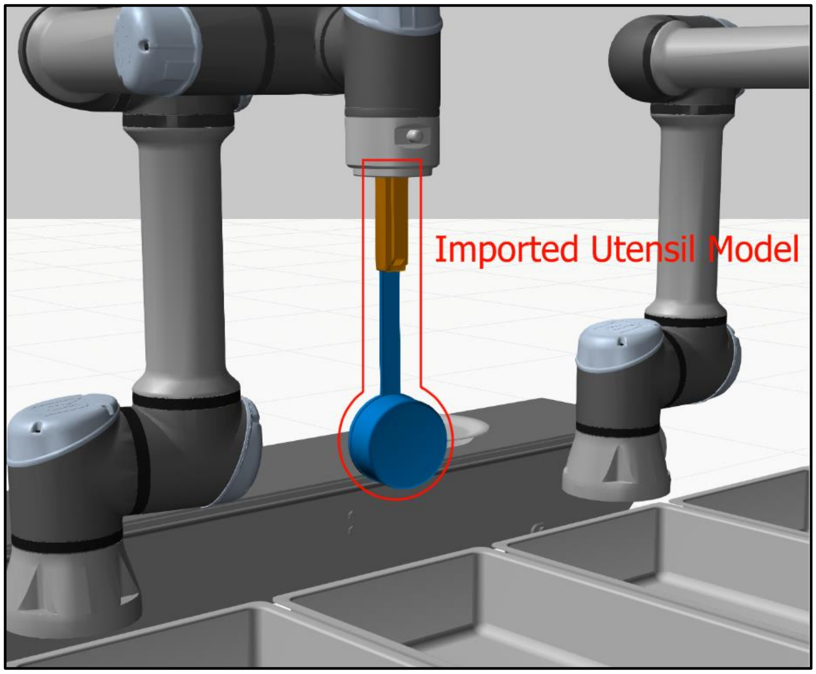


Figure 5.4.2: Utensil of Robot

When a signal is sent to the robot it makes predetermined movements to scoop and serve the food onto plate that rides on conveyor. Every time it serves from a pan, which it has multiple of, it keeps count of how many scoops were served from that specific serving pan. This data collection allows it to increment to next location so fresh food can be scooped and served. This indexing can be seen in ***Figure 5.4.3***, where the left image shows the 1st scooping position while the right image shows the 8th position.

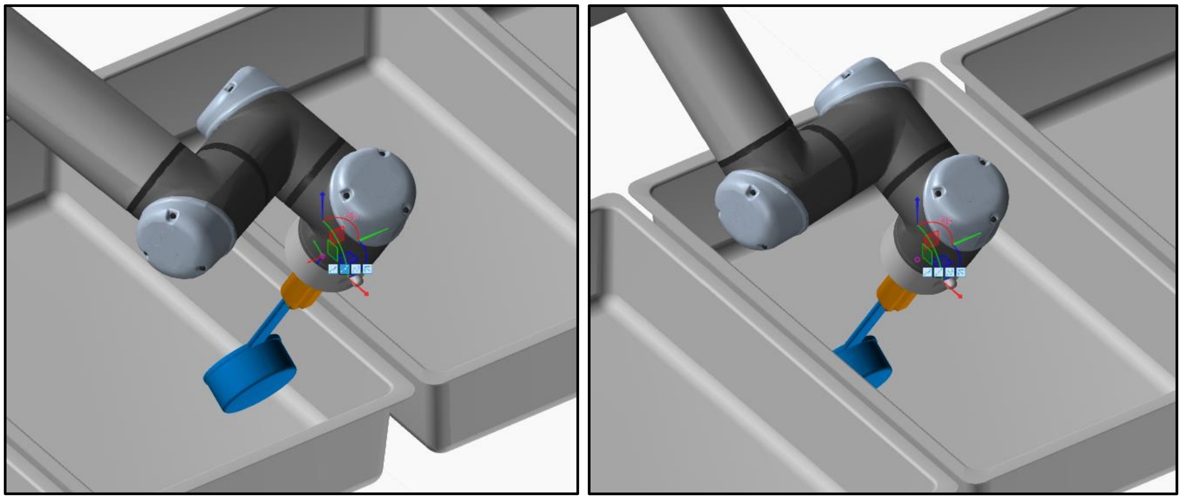


Figure 5.4.3: Left: 1st scoop; Right: 8th scoop.

This also allows the robot to keep track of whether the robot has served all the food from the tray so when the tray is empty, it knows to send a signal to alert the workers. In the case of this simulation, it sends out print statement.

5.5. Utensil Design Subsystem Final Design

The client stated a need to automate serving individual plates. Straying away from the idea of having a proportional amount of robots to dishes due to unnecessary expense, a revised requirement made it that one robot would need to serve a maximum of 3 dishes. With this configuration, using one utensil for all three dishes would lead to food contamination. With respect to this project, contamination means the mixing of food, not the introduction of a toxic substance or other contaminant. Thus, three separate serving utensils would need to be used. The robot arm must be able to pick up the corresponding utensil for each food item, serve the food item, and put back the utensil, and move on to the next dish, where it would repeat the cycle. Additionally, the client expressed preferability to reuse existing utensils to save costs, leading to a smaller subsystem of attaching existing utensils into the larger system. ***Table H.2*** presents Spring Semester 2024 data on a week of meals that would be served using specific utensils. This data led the team to decide on prototyping utensil systems that are most used and applicable. These led to the decision to prototype the most frequently used utensil systems: the serving spoon and the serving tong.

Figure 5.5.11 displays an example serving spoon in blue, placed in the orange key. The key is an object which allows utensils to be attached to the robot. As per the request from the client, the type of spoon is interchangeable, as long as it fits the ***Table D.4*** specifications listed under “Spoon.” Additionally, the spoon must undergo modifications including two drilled holes through the handle. The serving spoon is placed within the key, where the key is manually screwed to it through the holes on the top.

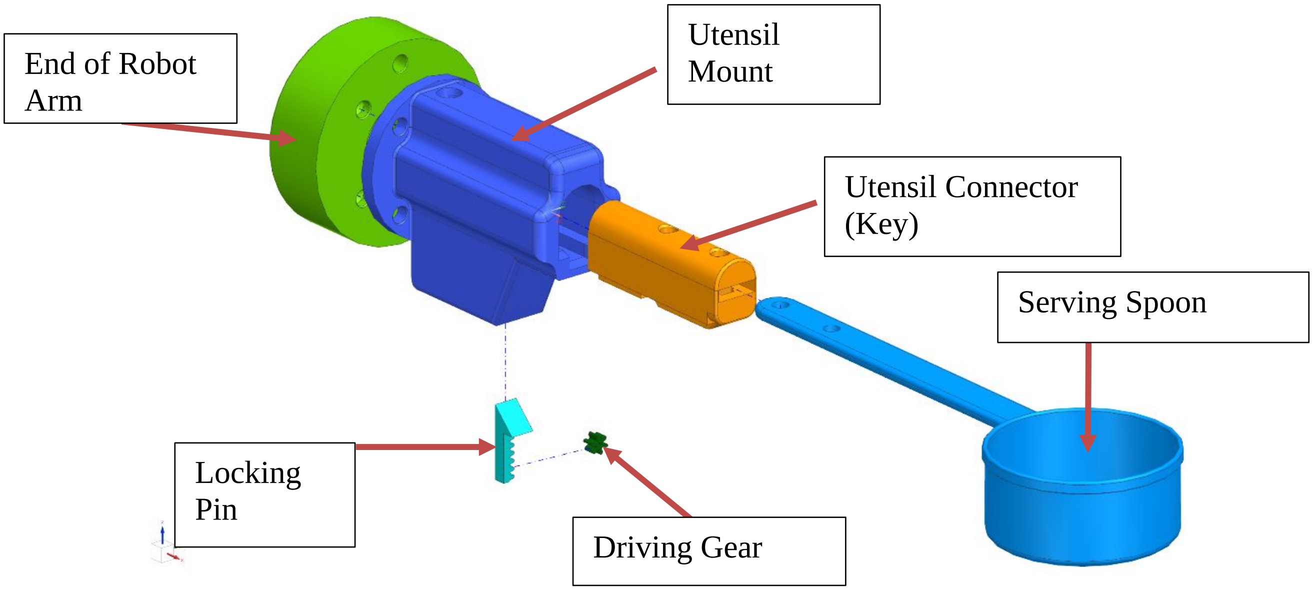


Figure 5.5.11: Exploded view of serving spoon assembly.

Figure 5.5.22 and ***Figure 5.5.33*** shows tongs in the closed and open position in the whole assembly. The tongs, like the serving spoon, also are interchangeable, following the ***Table D4*** specifications under "Tongs." The tongs must additionally go through modifications of four total drilled holes located on the handle.

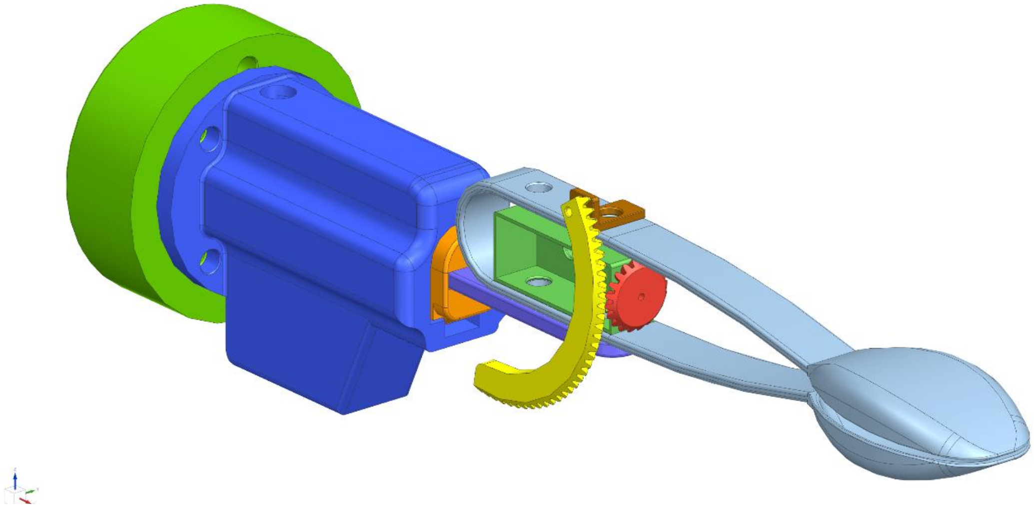


Figure 5.5.22: View of complete closed tong assembly.

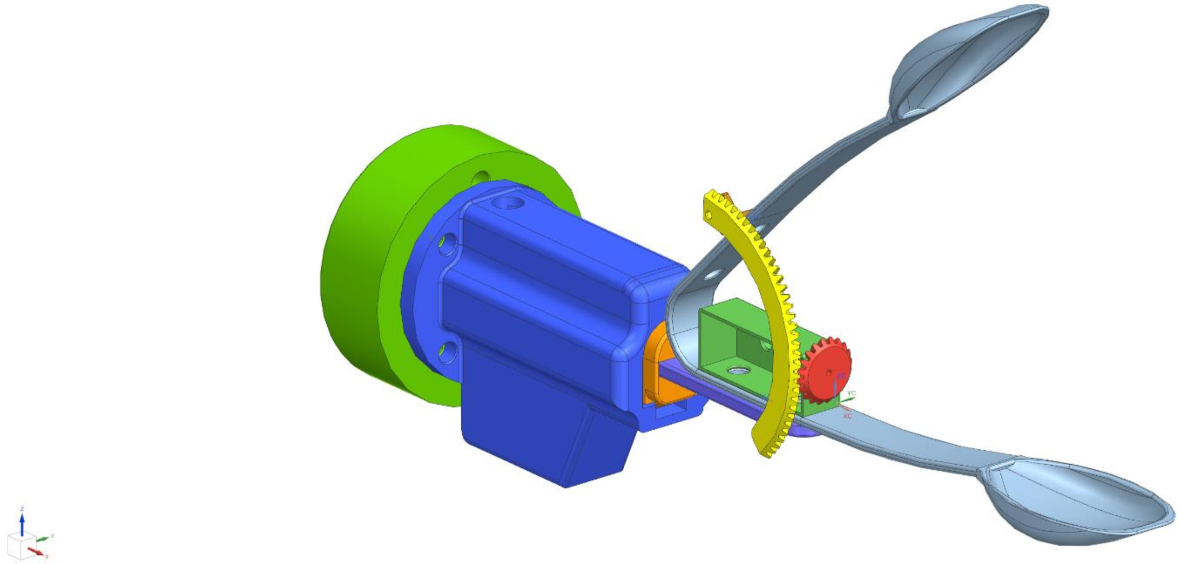
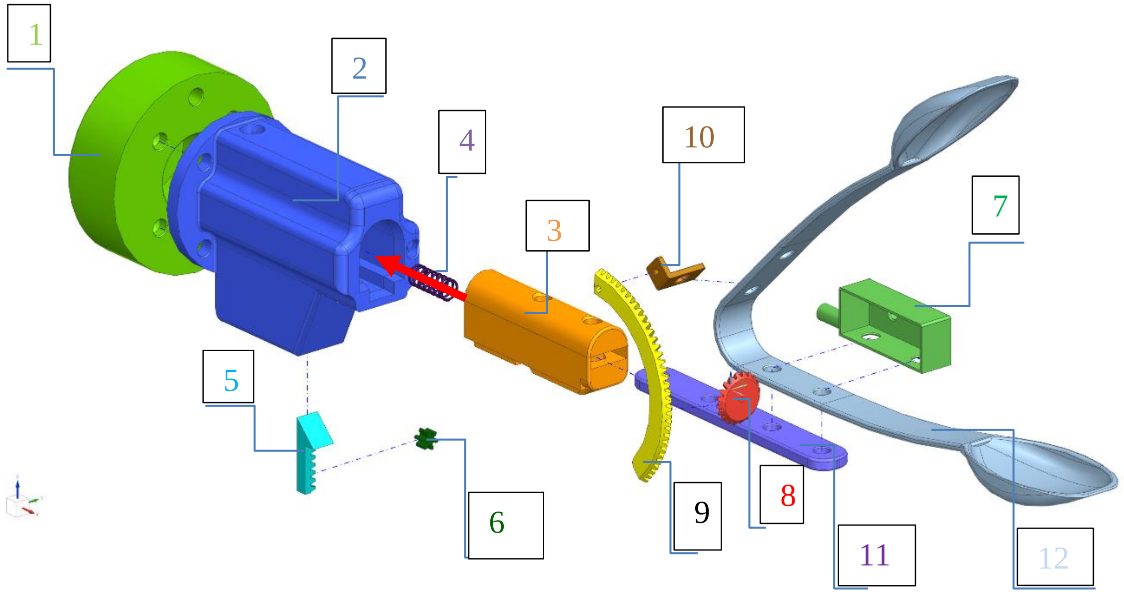


Figure 5.5.33: View of complete open tong assembly.

The tong assembly featured in ***Figure 5.5.4*** includes the 1-6 parts that will be used for all of the utensils, including the spoon. Starting with 7, this is a motor box that will contain the motor to provide the extra degree of freedom needed to open and close the tongs. It will turn the gear (8) which will drive gear 9. Gear 9 is firmly screwed into the L-bracket (10) which is screwed into one side of the tong handle (12). Thus, when voltage is introduced to the motor, it will close and open the tongs vertically. The tongs (12) are attached to a bracket on one part of the handle which is in turn inserted into the key (utensil connector 3). Then like the spoon, it works with the rest of the system similarly to the spoon in ***Figure 5.5.1***.



Component Number	Component Name	Component Number	Component Name
1	End of Robot Arm	7	Motor Box
2	Utensil Mount	8	Tong Driving Gear
3	Utensil Connector	9	Tong Driven Gear
4	Spring	10	Gear Bracket
5	Locking Pin	11	Tong Bracket
6	Driving Gear	12	Open Tong

Figure 5.5.44: Annotated, exploded view of complete open tong assembly.

6. System Evaluation

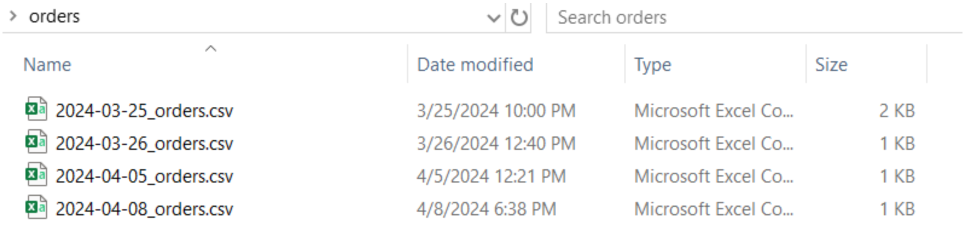
6.1. Kiosk Subsystem Evaluation

There are a few key records and functionality that can be tested without the physical implementation of the Kiosk. One test is the logging of a packet which represents an order. This packet is interpreted by the Master Computer which then decides which food will be served on the current plate it is working on. This packet (shown in ***Figure 6.1.1***) contains five binary bits, where a 0 represents that the customer did not select that menu item while a 1 represents that the customer selected that menu item.

```
b'11100\n'
```

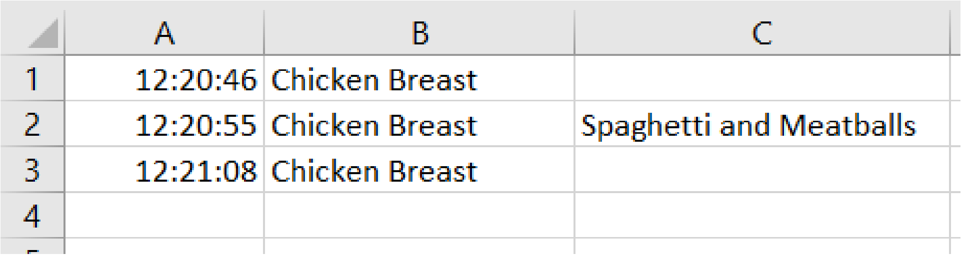
Figure 6.1.1: Customer's Order Represented as a Byte Packet (1st, 2nd, 3rd items selected. 4th and 5th items are not selected, which is working correctly in this instance).

Upon clicking the "ORDER" button on the customer's version of the Kiosk, not only is the byte packet (shown in ***Figure 6.1.2*** and ***Figure 6.1.3***) sent to the master computer, but the order is recorded and saved on the hardware in a timestamped .csv file (example shown in ***Figure 6.1.2***), which can be retrieved later by the worker and used for inventory management and customer preferences.



Name	Date modified	Type	Size
2024-03-25_orders.csv	3/25/2024 10:00 PM	Microsoft Excel Co...	2 KB
2024-03-26_orders.csv	3/26/2024 12:40 PM	Microsoft Excel Co...	1 KB
2024-04-05_orders.csv	4/5/2024 12:21 PM	Microsoft Excel Co...	1 KB
2024-04-08_orders.csv	4/8/2024 6:38 PM	Microsoft Excel Co...	1 KB

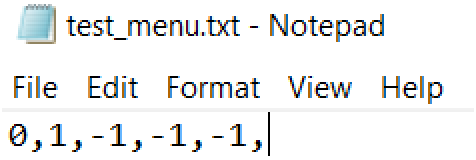
Figure 6.1.2: Example of Folder Directory Containing .csv Files Recorded



	A	B	C
1	12:20:46	Chicken Breast	
2	12:20:55	Chicken Breast	Spaghetti and Meatballs
3	12:21:08	Chicken Breast	
4			

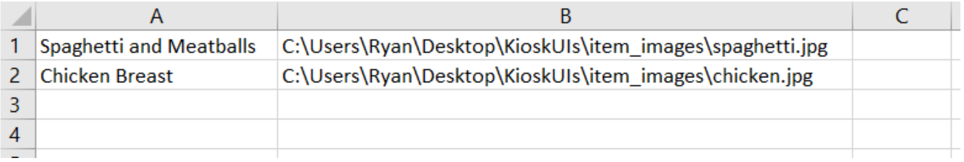
Figure 6.1.3: Examples of Order Capturing in a File Titled 2024-04-05_orders.csv (column A is the local time, and subsequent columns are for the menu items selected at that time)

The final (and temporary solution) to test functionality is the transfer of database information from the worker's computer to the Kiosk. This is done to make sure that the Kiosk can correctly read the information being sent and display it to the customer. This is done temporarily by storing this information as a .txt file (seen in ***Figure 6.1.4***) which is then parsed by the Kiosk utilizing the .csv database (shown in ***Figure 6.1.5***) of menu item names and images which needs to be manually entered by a worker but can be used in the future without reentering data.



```
0,1,-1,-1,-1,
```

Figure 6.1.4: Example of a Menu used to Communicate the Current Menu to the Kiosk (0 represents first database option, 1 represents second database option, -1 represents no database option)



	A	B	C
1	Spaghetti and Meatballs	C:\Users\Ryan\Desktop\KioskUIs\item_images\spaghetti.jpg	
2	Chicken Breast	C:\Users\Ryan\Desktop\KioskUIs\item_images\chicken.jpg	
3			
4			

Figure 6.1.5: Example of a Database Containing Two Menu Options with the Names (in column A) and the Corresponding Image Directory (in column B)

6.2. Plate Placement Subsystem Evaluation

6.2.1. Plate Placement Subsystem – Conveyor Belt Entrance

Without a physical model, there are not many ways the plate placement system can be evaluated; however, initial design calculations were used to validate the spring chosen for this subsystem. This subsystem was modeled as shown in ***Figure 6.2.1.1*** below.

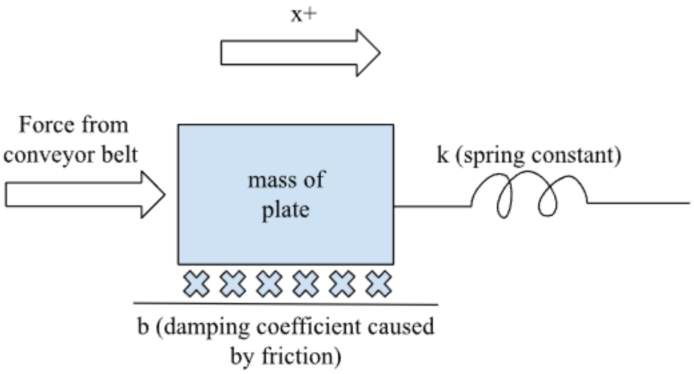


Figure 6.2.1.1: Model of the Plate Placement Subsystem Entrance

This model provided the necessary equations to determine the spring needed for the plate placement system. The following assumptions were made to determine the spring needed for this subsystem:

- When the conveyor belt is in "go," it does not accelerate, but instead moves at a constant unknown velocity.
- The plate moves about 1 foot (12 in) when it moves between each station.
- The conveyor belt is made of polypropylene plastic, and its coefficient of friction is 0.35.
- The plates are ceramic, likely porcelain, whose coefficient of friction is 0.11. [1]
- Each plate weighs about 1lb (≈ 0.45 kg).

From these assumptions, it was determined that the spring used for the system would need to have a spring constant of about 0.00511 N/mm. The full calculations, in detail, done to determine this are included in Appendix G.

6.2.2. Plate Placement Subsystem – Conveyor Belt Exit

Initial design calculations were used to validate the inclined plane for this subsystem. The inclined plane was modeled as shown in ***Figure 6.2.2.1*** below.

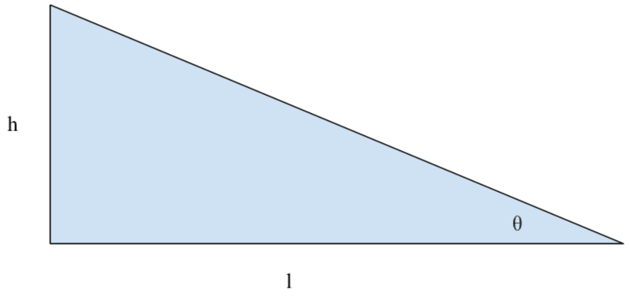


Figure 6.2.2.1: Inclined Plane Model

The following constraints were used to determine the proper length of the inclined plane:

- The inclined plane should not have an angle greater than 10°.
- The inclined plane cannot be longer than 1500 mm.
- The inclined plane needed a maximum height of 138mm

From these assumptions, it was determined that the inclined plane as shown in ***Figure 6.2.2.1*** was the best option because it fit within the available space on the counter, matched the height of the conveyor belt, and did not exceed the maximum angle. These constraints were determined based on measurements taken of the serving area at the Chef's Table Station. The full supporting calculations, in detail, are included in Appendix G.

6.3. Conveyor Belt Subsystem Evaluation

6.3.1 Overview

The conveyor belt system design for this semester was in the electrical design for AC motor control, since the physical conveyor belt system design was provided by the manufacturer, Donor, based on the dimensions of the Chef's Table station at commons.

6.3.2 Motor Control Circuit

Evaluating the electrical design was quite the challenging task because part of it must be manufactured to be fully tested, such as the speed reference voltage in pin 3 needed to move the conveyor at a safe speed (***Figure 5.3.2.2.1: Motor Controller and Master Computer Communication System Circuit***). However, most of the design has been verified by the manufacturing company of the IM111T microchip, Infineon, which is what controls the speed and direction of the 3 phase AC motor. Using the schematics, bill of materials and circuit block diagrams provided by Infineon for the Evaluation Board EVAL-IMI111T-026, in ***Figure 6.3.2.1*** and ***6.3.2.2***, the motor control circuit of the conveyor belt PCB is verified. Also using the resources previously stated, the power circuits for the IM111T chip such as the 120 VAC to 120 VDC, 24 VDC to 13.75VDC, and 24VDC to 5VDC are selected because they are needed to power the IM111T chip. The evaluation board reference schematic used can be found in the Repository ("REPO") under Electrical Schematics, 3D PCBs, and PCBs Gerbers\Conveyor Electrical System V2\Reference Schematic. To view that schematic use an online viewer such as Altium Viewer.

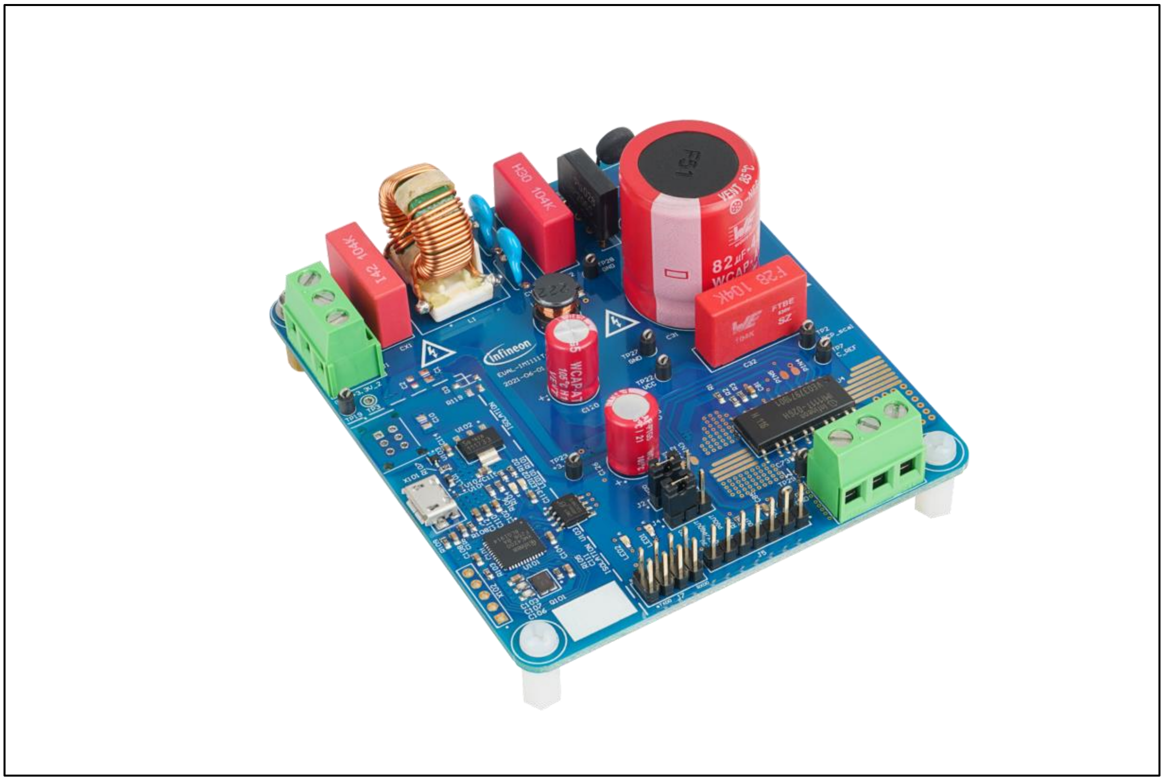


Figure 6.3.2.1: EVAL-IMI111T-026 Board

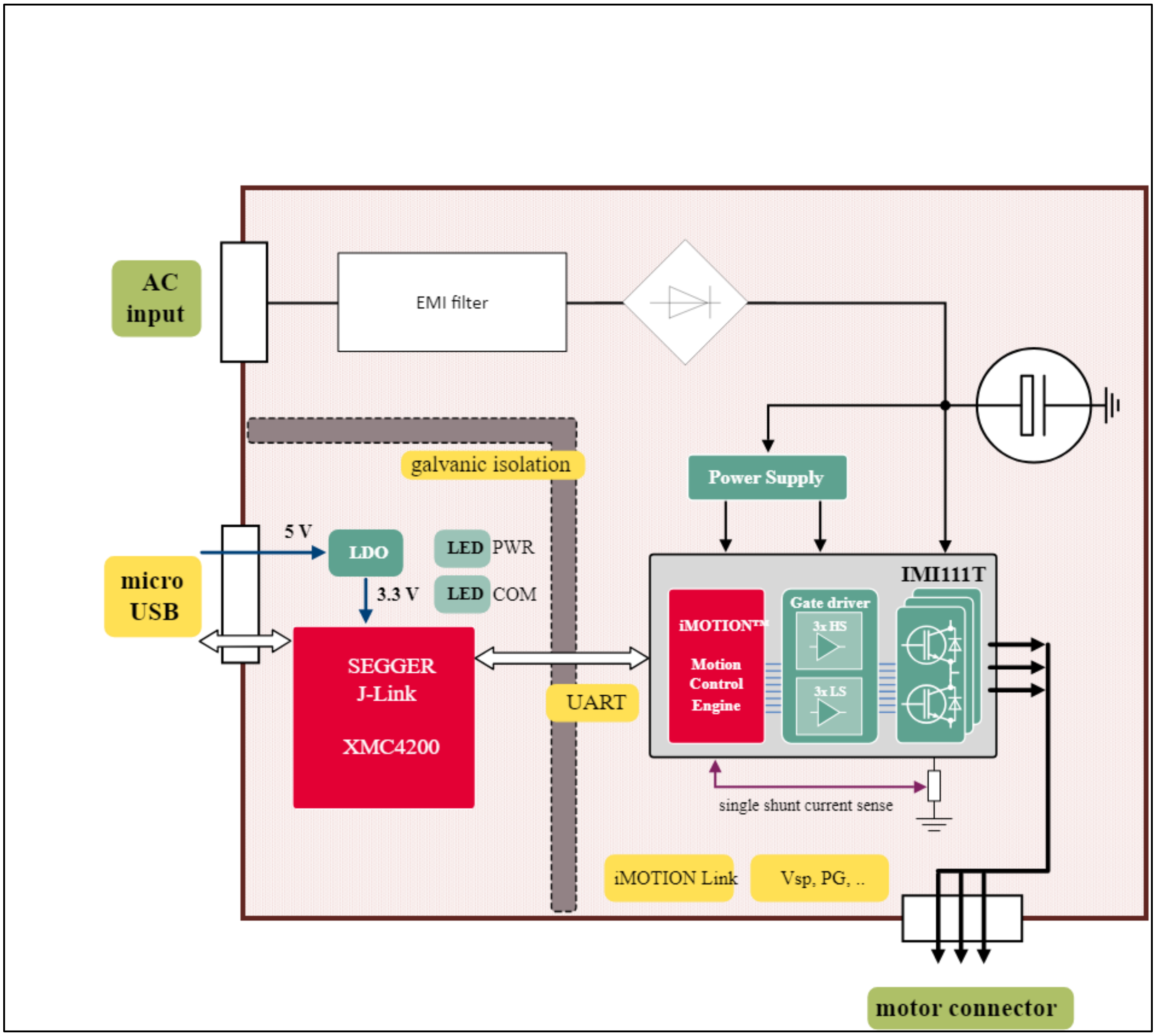


Figure 6.3.2.2: EVAL-IMI111T-026 Circuit Block Diagram

6.3.3 Power Circuits

The power circuit designs were made using reference designs in the data sheets for the main components that step down the voltage in the individual power circuits. These components consist of the linear dropout regulators (“LDOs”) such as the NCP5500 and LM1085, and the LDE60 transformer/rectifier module. The datasheets of these components provided the ratings of the required decoupling capacitors and formulas to calculate the resistors needed to get the desired output voltage for the LDOs. To find the data sheets of the components refer to the bill of materials section where each component has their corresponding link to their data sheet.

6.3.4 Communication Circuit

Next, verifying the communication circuit of the PCB was done using the Arduino website’s reference schematics. Since the IM111T chip uses the UART protocol to receive commands and messages, the PCB connects two general purpose input-output (“GIPO”) pins that can start a second serial line to send UART commands to the IM111T chip. The commands needed to control the IM111T chip can be found in the *How to Use UART Interface on IMM101T and IMI111T v1.0* provided in the REPO under the Electrical Schematics, 3D PCBs, and PCBs Gerbers Folder.

The Arduino is also being used as the method to communicate to the Master Computer ROS (Robot Operating System) System through UART. This is easy to implement since there are several open-source libraries such as the Rosserial Arduino Library that implement ROS in the Arduino nano. This system has not been fully verified since it must be manufactured to be fully tested. However, the hardware layout is verifiable since UART communication just uses two GIPO pins which can be accessed through terminals J2 and J3 to connect to the Master Computer ROS System.

6.3.5. AC 3 Phase Motor Selection

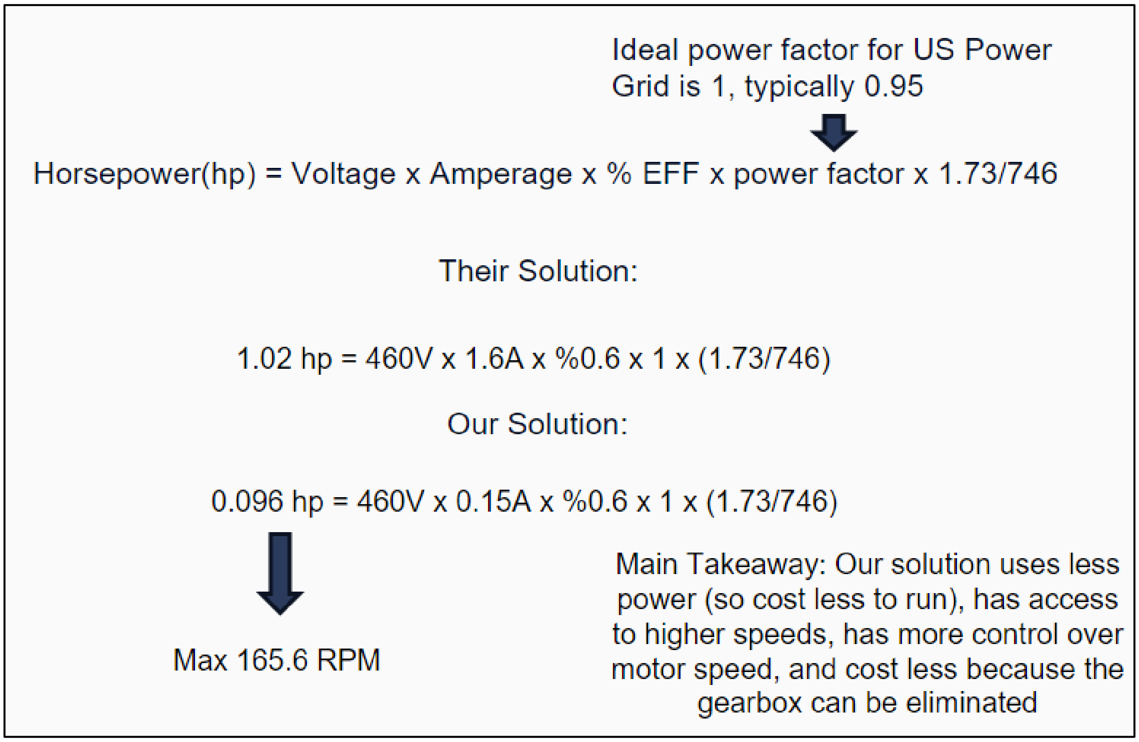
Next, evaluating the specifications needed for the motor required some calculations as seen in ***Figure 6.3.5.2: Motor Selection Calculations***. The original quote from the manufacture Donor had a 1 HP, 208-230/460 volt, 3.5-3.2/1.6 A, 3 phase motor with a 30:1 gearbox that output 58 RPM. These specifications are what is needed to move the conveyor at a safe speed according to Donor. Using the formulas in Figure 6.3.5.1: plate delivery rate calculations, this means that the conveyor can carry a plate from one extreme to another in approximately 3 seconds at max speed with the motor Donor provides because the calculation below is for two plates:

$$Belt\ Speed\ \left(\frac{inches}{minute}\right) = RPM\ x\ Pulley\ Circumference$$
$$Belt\ Speed = 58\ RPM\ x\ 12.5664\ inches$$
$$Belt\ Speed = 729\ inches\ per\ minute$$
$$Time = \frac{72\ inches}{729\,\frac{inches}{minute}}$$
$$Time \approx 0.0986\ \text{minutes} \approx 5.9\ \text{seconds}$$

Figure 6.3.5.1: Plate Delivery Rate Calculations

This means that the motor they provided complies with the customer needs (for further speed analysis refer to the process flow section). Therefore, based on those specifications, Donor's motor's true RPM can be calculated by multiplying the gearbox ratio to the output RPM which results in being around 1725 RPM. Furthermore, the conveyor belt electrical system PCB can only output 70W of power to the motor meaning that if the motor is rated 460V the max RPM the motor can reach is 165.6 RPM at full power with no gearbox, as seen in ***Figure 6.3.5.2: Motor Selection Calculations***. Which means that the team's solution uses less power because it does not need to receive more current to move the gearbox, has access to higher speeds, and has more control over motor speed because it is using a precision voltage reference instead of the potentiometer solution Donor was providing. Thus, the motor specifications are 1HP, 1725 RPM, Three Phase Motor, 230V/460V, 60Hz, and 3.8A/1.9A. A recommendation for the motor that meets these specs was added to the REPO under the BOM folder/ Electrical Design Conveyor

Belt/ Conveyor Belt BOM V3.xlsx. It can also be found in the bill of material in the appendix section.



Ideal power factor for US Power Grid is 1, typically 0.95

Horsepower(hp) = Voltage x Amperage x % EFF x power factor x 1.73/746

Their Solution:

1.02 hp = 460V x 1.6A x %0.6 x 1 x (1.73/746)

Our Solution:

0.096 hp = 460V x 0.15A x %0.6 x 1 x (1.73/746)

Max 165.6 RPM

Main Takeaway: Our solution uses less power (so cost less to run), has access to higher speeds, has more control over motor speed, and cost less because the gearbox can be eliminated

Figure 6.3.5.2: Motor Selection Calculations

6.4. Robotic Arm Subsystem Evaluation

The Robotic Arm Subsystem underwent validation using the Octopuz simulation program. Octopuz is an offline robot simulation program that enables users to simulate industrial robots and export the program. Although the Ufactory850 was unavailable in the simulation, a UR5e robot arm was used as a substitute because it has the degrees of freedom and reach as the Ufactory850.

During the selection process of the robot design, concerns arose about the robot's reach. Two robotic arms were examined, one with a reach of 600mm and the other with a reach of 850mm. Although the cost of three 600mm robot arms or two 850mm robot arms was about the same, the smaller robot arm would have fallen short of the farthest corners of the trays by 20mm. Although the distance may seem insignificant, when the robot arm approaches its limits, it loses the ability to orient itself. Therefore, the larger robot arm was identified as the better option for the project. ***Figure 6.4.1*** shows the calculations that led to this decision.

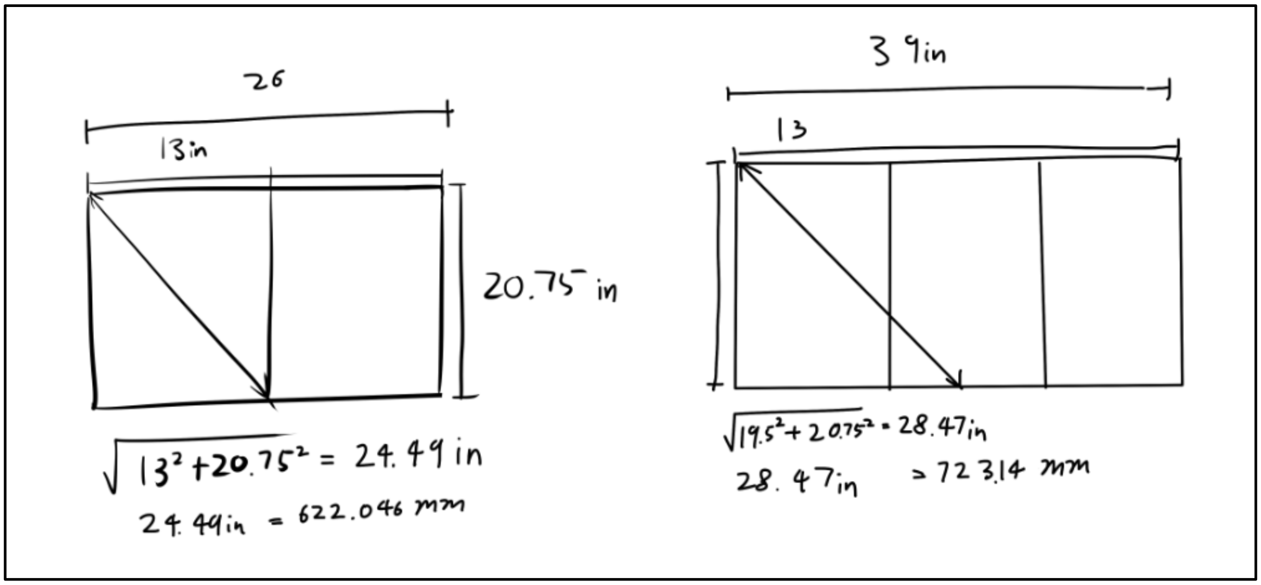


Figure 6.4.1: Calculation of Maximum reach

Through simulation, it has been verified that the robot can move appropriately to scoop and serve food from the pan. It is worth noting that fewer robots provide extra space for the arm to turn around. This freedom of motion allows the robotic arms to be placed between the conveyor belt and serving trays, making it more convenient to use. The positioning of these components is shown in ***Figure 6.4.2.***

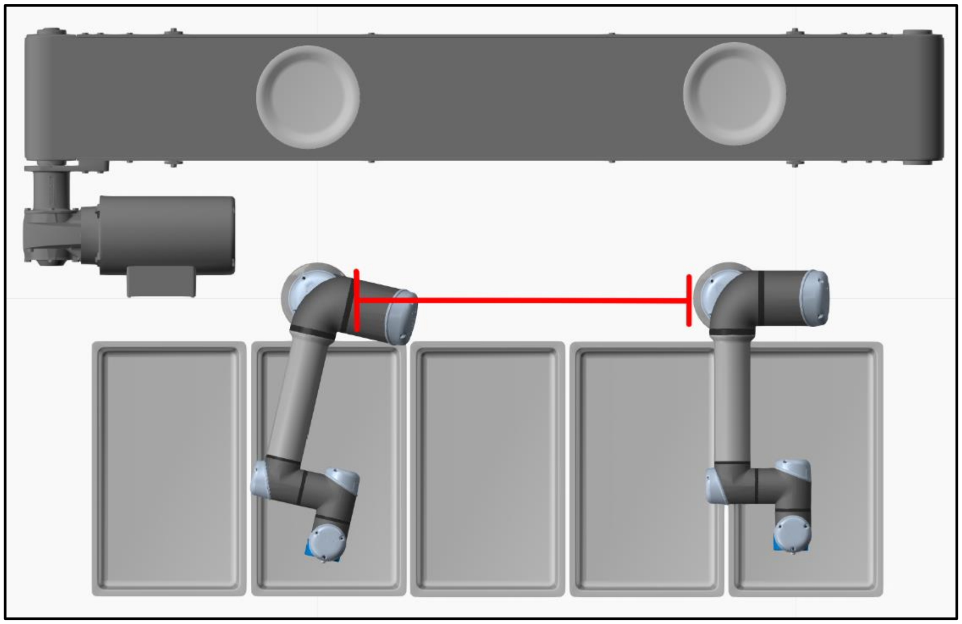


Figure 6.4.2: Robot Arm Clearance

The overall simulation also showed that robot arm can make all the necessary movements to serve food while also allowing all physical parts of the design to work in harmony without colliding with each other.

6.5. Utensil Design Subsystem Evaluation

Table 6.5.1: Percentages of a weekly (2/4/2024-2/10/2024) menu [2] that can be served per utensil.

Utensil	Number of foods that can be served with the utensil	Percentage of the menu served (%)*
Serving Spoon	33	67
Serving Tongs	16	33
Gripper hand	12	24
Skewer	7	14
Ladel	3	6

**There is some overlap between certain utensils therefore percentage does not add to 100%*

A wide variety of food is served at Commons Dining hall, so different types of utensils were researched to be used as options. Based on a weekly menu for the Chef's Table for lunch and dinner, ***Table 6.5.1***, it was found that spoons and tong are the most compatible with the menu. Therefore, this result backs the creation and design of the utensil models.

Due to the overall timeline of the project, prototyping was out of scope. For future semesters, tolerance and compatibility can be measured physically with the completion of a scale prototype. If needed, further adjustments can be made to the CAD model to enhance compatibility with the utensils currently used in Commons, and with the robot arm.

6.6. Overall System Simulation Comparison Between Current and Future Design Evaluation

6.6.1 Overview:

Running a simulation in comparison of current dining hall and future two robotic arm process simulation to compare throughput time and waiting time of both systems.

Simulation Constraints:

- Both simulations do not take restock time into account due to restocking still requiring human intervention, which is the same for current and future processes.
- Students have random probabilities of wanting food from any food tray.
- Each student can only have a maximum of one food serving size from one food tray.
- No breakdown has been considered in the simulation.
- Simulation will Run for three hours.
- Same arrival rate for both simulations.

Current Dining Hall Simulation:

- For the current dining hall, simulation is simulating a station with one worker only.
- Workers will not take a break for three hours of simulation.
- The system can only work one plate at a time.
- Assuming each type of food takes the same difficulty to serve. (same statistical distribution)

Future two Robotic Arm Simulation:

- For future process, simulation is simulating two robotic arms.
- System can process in parallel for first and second robotic arms.
- The first robotic arm will wait for the second robotic arm to complete if it complete early to simulate that they are on the same conveyor belt.

Simulation Logic:

Figure 6.6.1: Flexsim Simulation for Current Dining Hall Process

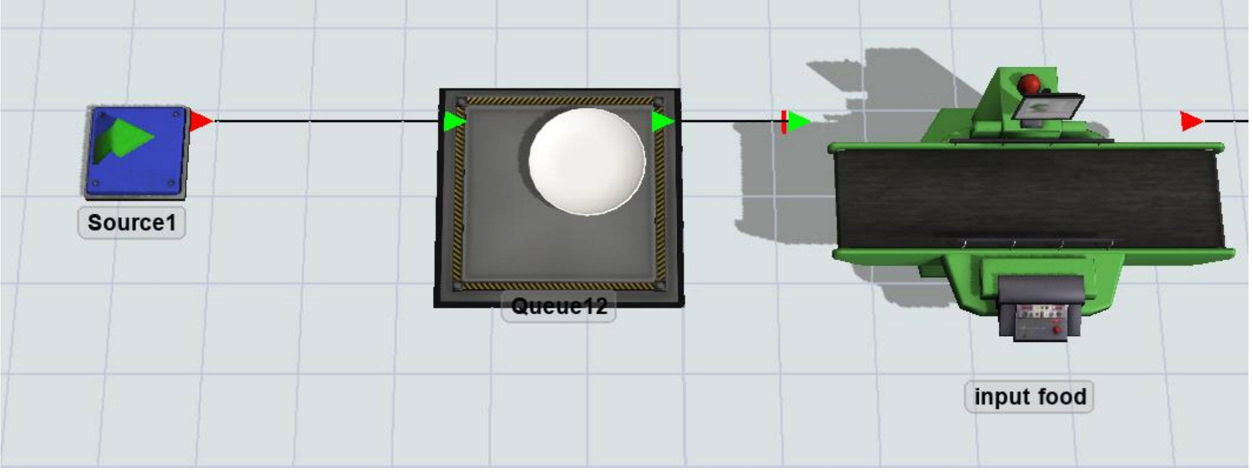
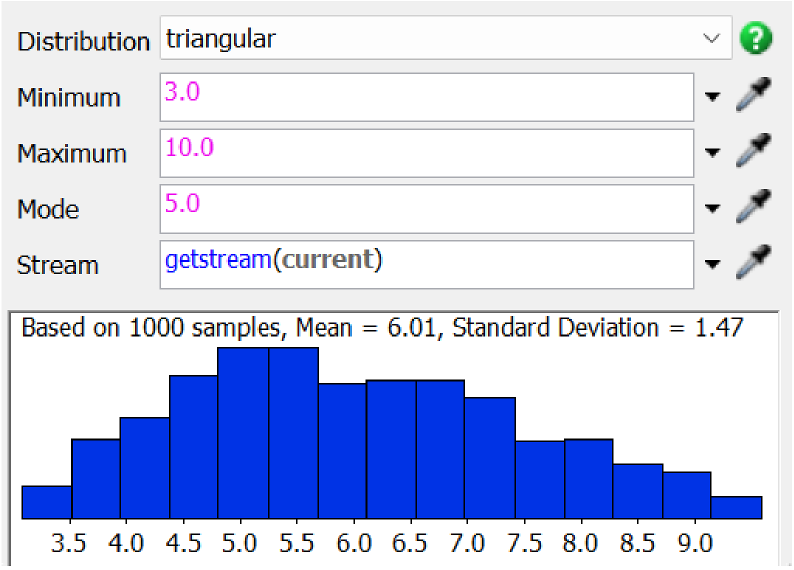


Figure 6.6.1.1: Current Process Beginning

Students will go into the system via source1, each plate representing a student.

They will go into input food processor, which has a triangular distribution to present randomness of the input with minimum of three second, maximum of ten second and a mode of five second. Figure 6.6.1.2 is the simulation of time that student speaking to the worker about the food they want.



Distribution triangular

Minimum 3.0

Maximum 10.0

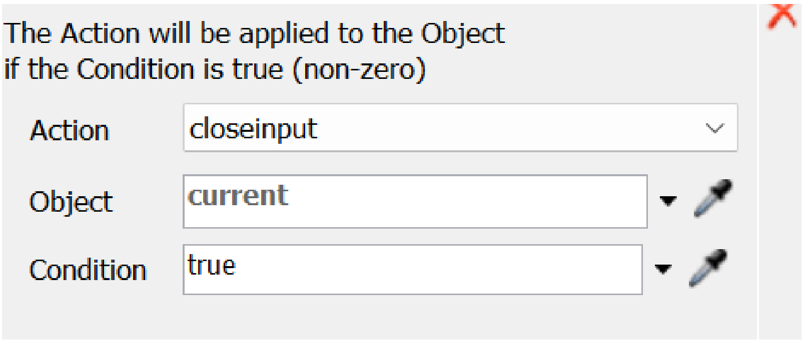
Mode 5.0

Stream getstream(current)

Based on 1000 samples, Mean = 6.01, Standard Deviation = 1.47

Figure 6.6.1.2: Current Process Beginning input triangular distribution

After the plate has exited the processor, the processor will close all input to simulate that the worker is now serving current student and that worker cannot take in more orders while serving.



The Action will be applied to the Object
if the Condition is true (non-zero)

Action closeinput

Object current

Condition true

Figure 6.6.1.3: Current Process Beginning close port when play exit the queue

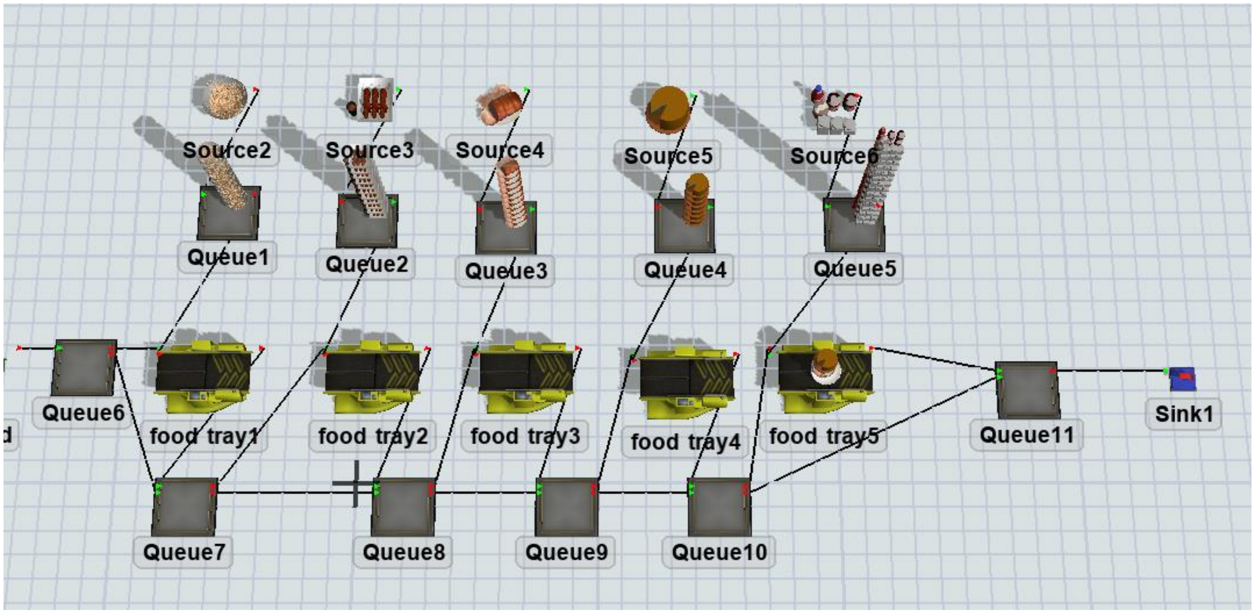
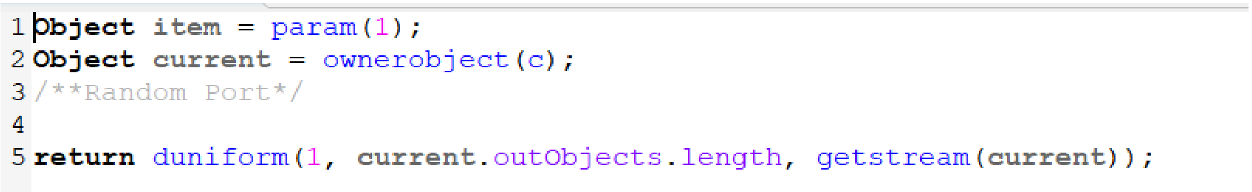


Figure 6.6.1.3: Current Process Middle and End

Source2 through Source5 represents five different types of food that can be served in the chef station.
Each food tray has a combiner that combines food with plate.
Each food tray has a queue before that randomly distributed the exit of food tray and another queue. This is to simulate the order that student wants, if it goes into food tray it represents that student have ordered that food, if it goes into another queue, it represents that student did not order that food. Repeat until all five foods have gone through.



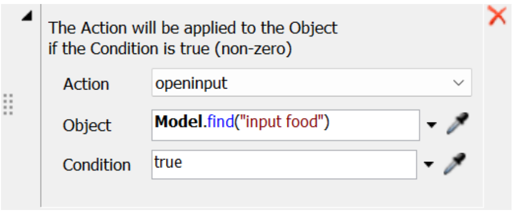
```
Object item = param(1);
Object current = ownerobject(c);
/**Random Port*/

return duniform(1, current.outObjects.length, getstream(current));
```

Figure 6.6.1.4: Current Process Random port

Flexsim Script, random port

After all process have been done, it will exit the system via queue 11 and sink1. In queue 11, it will openinput the processer “input food” after a place enter the system, this simulate that the worker is now free and its taking in an new order.



The Action will be applied to the Object
if the Condition is true (non-zero)

Action: openinput
Object: Model.find("input food")
Condition: true

Figure 6.6.1.5: Current Process Openintput to Processor “input food”

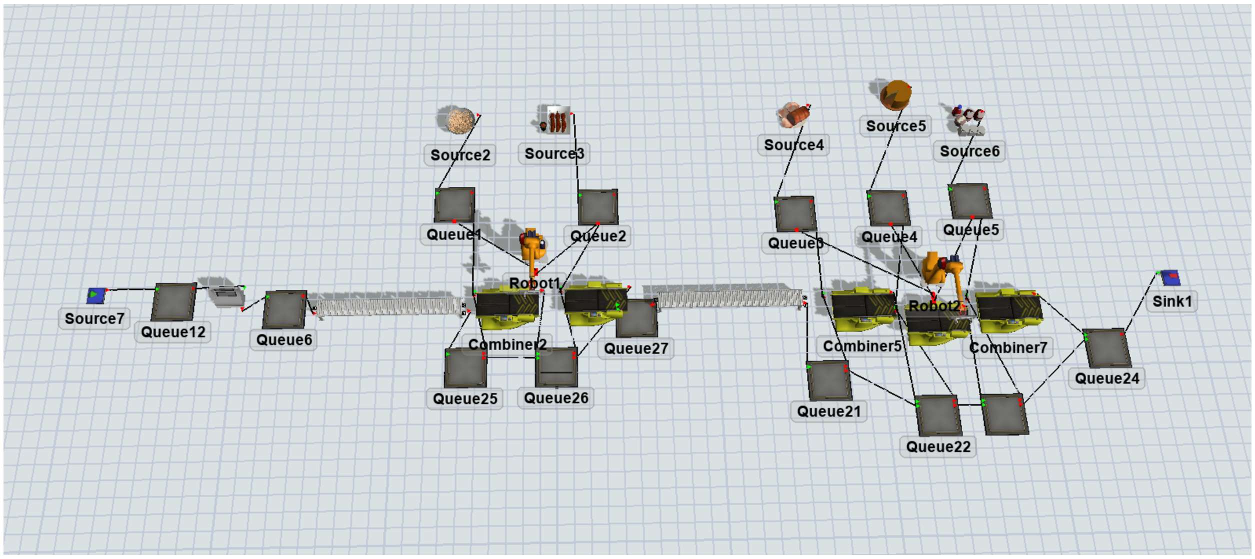


Figure 6.6.2: Flexsim Simulation for 2 Robotic Process

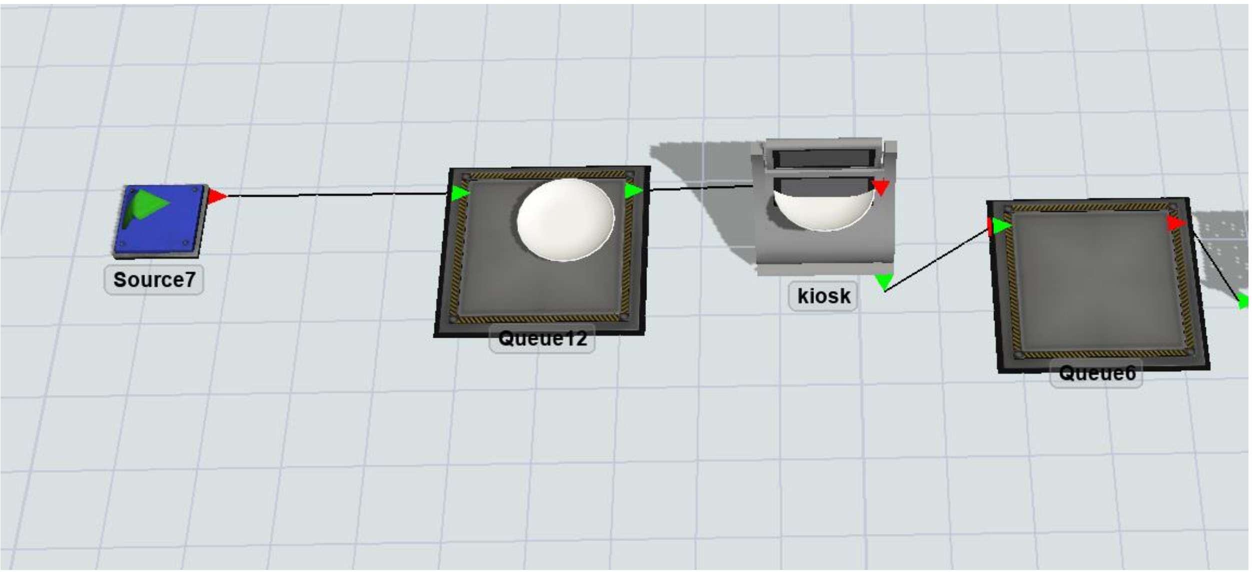
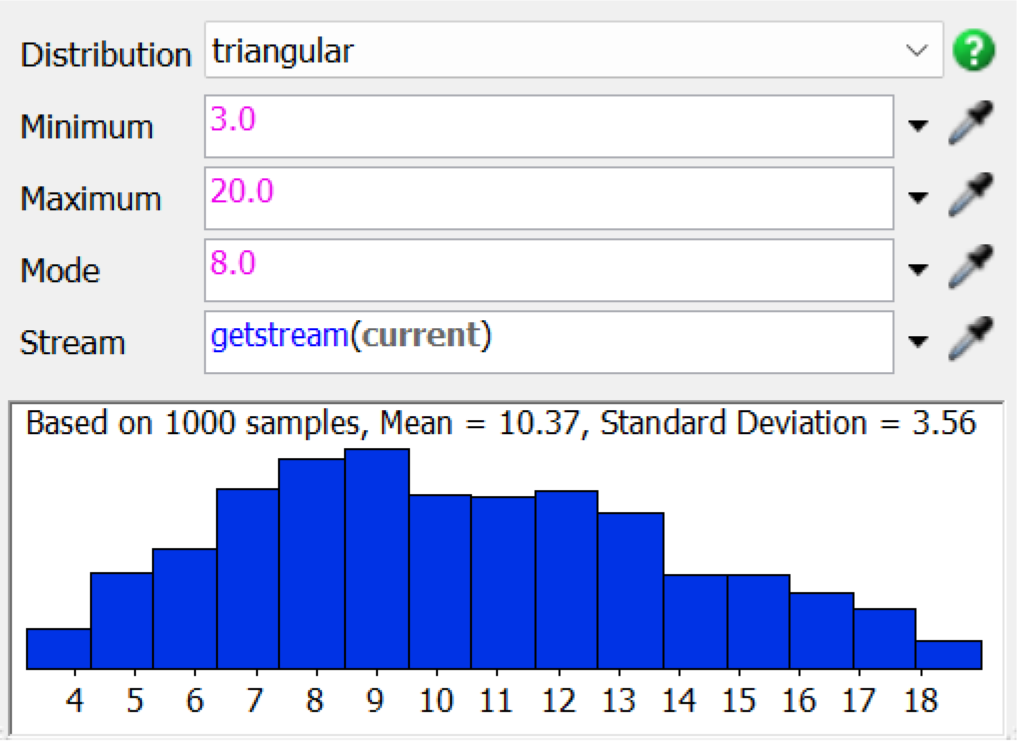


Figure 6.6.2.1: 2 Robotic Arm Process Beginning

Students enter the system via source7, and each plate represents a student in this simulation. Kiosk will follow a theoretical triangular distribution of minimum of three, maximum twenty with mode eight. A statistical representation of some students will pick the food they already want, while some students will take a longer time to pick the food with most students in the middle.



Distribution: triangular

Minimum: 3.0

Maximum: 20.0

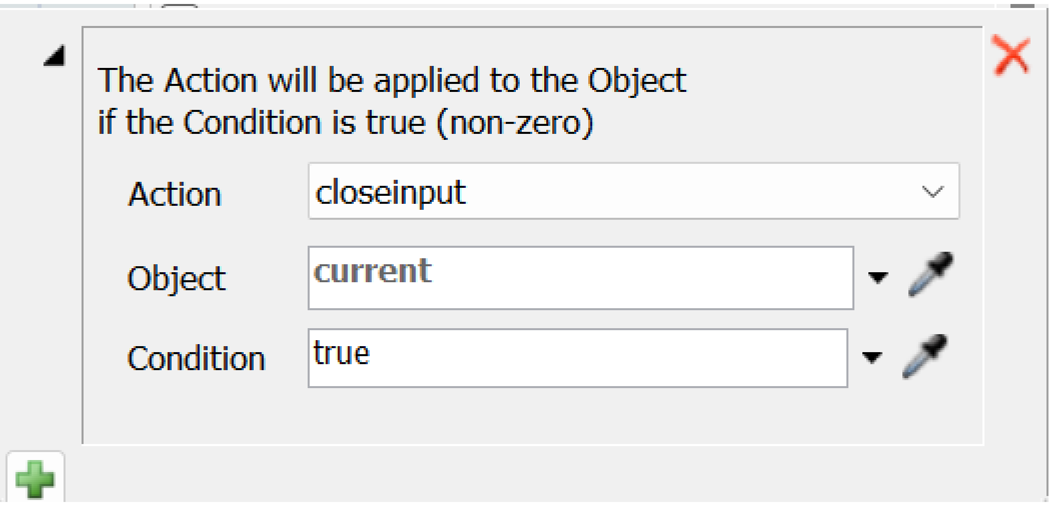
Mode: 8.0

Stream: getstream(current)

Based on 1000 samples, Mean = 10.37, Standard Deviation = 3.56

Figure 6.6.2.2: 2 Robotic Arm Process Kiosk Triangular Distribution

In queue, when a plate has left the queue, it will close the port to simulate that process is busy, no other plate can enter this time until system is free up.



The Action will be applied to the Object
if the Condition is true (non-zero)

Action: closeinput

Object: current

Condition: true

Figure 6.6.2.3: 2 Robotic Arm Process Closeinput to Kiosk after exit

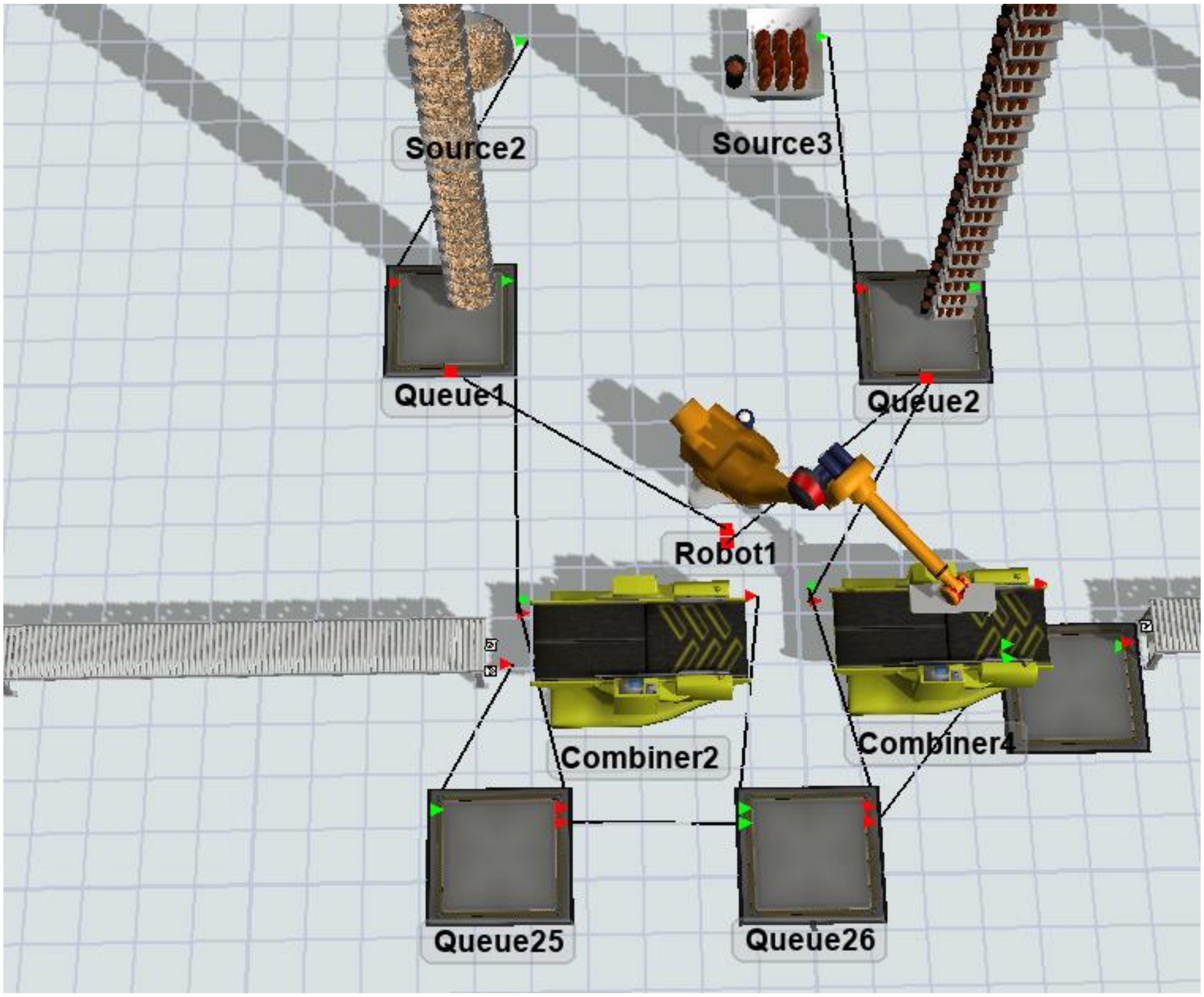
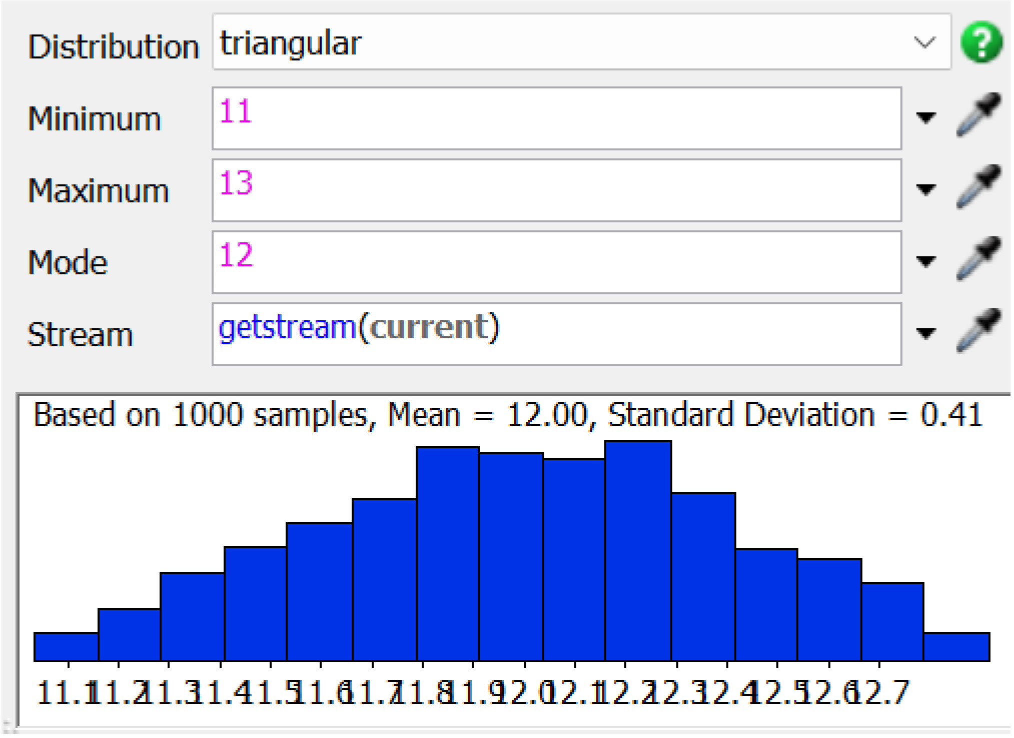


Figure 6.6.2.4: 2 Robotic Arm Process First Robotic Arm

Conveyor belt that has a three seconds of travel time from the gate to the first robotic arm location. Source2 and source3 represent food first two types of food since the first robotic arm will only serve two food trays. When plate exiting queues have a random distribution of going either into a combiner or going into another queue that mimic a student did not order that food. Based on the robotic arm calculations, it takes about twelve seconds for the robotic arm to serve one food tray. And the distribution is the same for all food trays. Using triangular distribution to represent the slight variation that the machine can have.



Distribution triangular

Minimum 11

Maximum 13

Mode 12

Stream getstream(current)

Based on 1000 samples, Mean = 12.00, Standard Deviation = 0.41

Figure 6.6.2.5: 2 Robotic Arm Process Robotic Arm Single Process Time Triangular Distribution

Once the food tray left the first robotic arm, it goes on the conveyor belt into the second robotic arm system. First robotic arm will then open the gate for the kiosk and allow a plate to go into the system. The second robotic arm system has the same logic as the first robotic arm with the only exception that it serves three food trays instead of two. When the process is complete, the second robotic arm will open the queue for the first robotic arm to allow plates to move forward on the conveyor belt. Plates will leave the system via sink1.

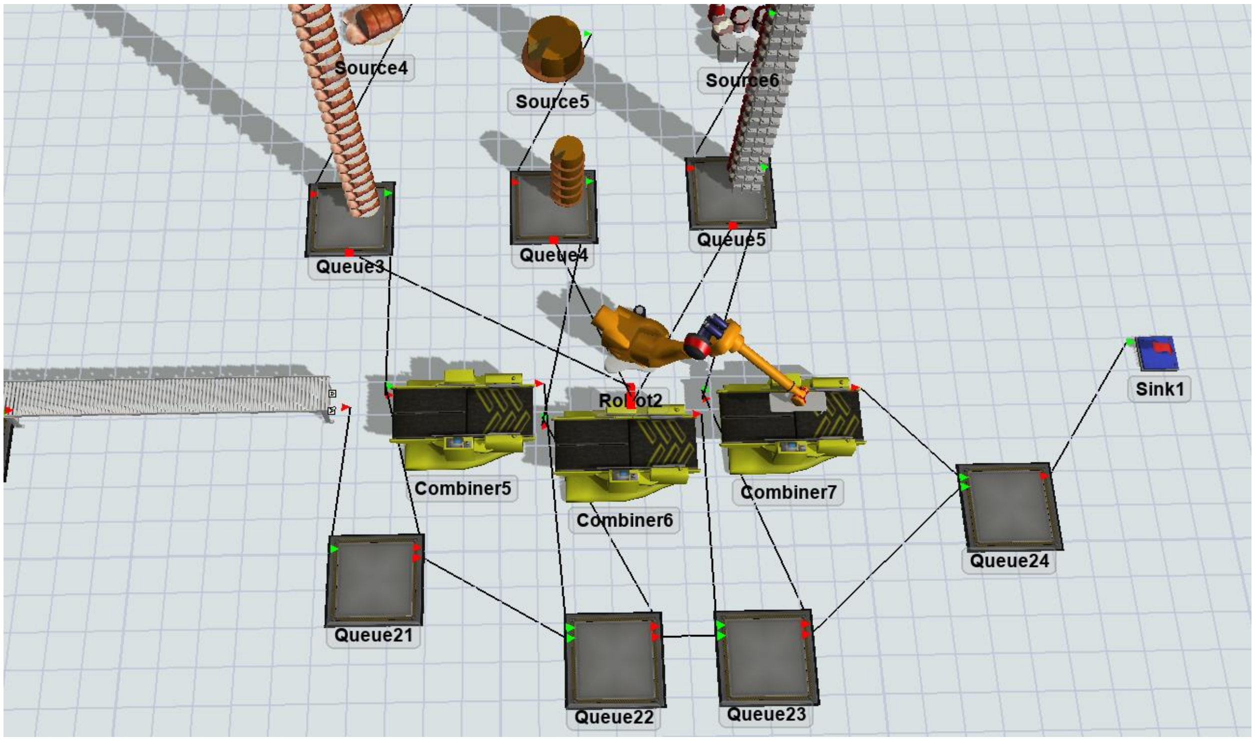


Figure 6.6.2.6: 2 Robotic Arm Process Second Robotic Arm Process

6.6.2 Data:

Data for both simulations are stored in Table G.4(Current Process) and Table G.5(Robotic Arm Process)

Based on Table G.4 and Table G.5, after Running two sample-t test in comparison of both stay time including waiting in line. Testing to see is both populations have a significant difference in mean.

Stay time including waiting in line.

WORKSHEET 1

Two-Sample T-Test and CI: current overall stay time, robot overall stay time

Method

μ_1: population mean of current overall stay time

μ_2: population mean of robot overall stay time

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
current overall stay time	178	102.1	66.9	5.0
robot overall stay time	162	107.4	46.7	3.7

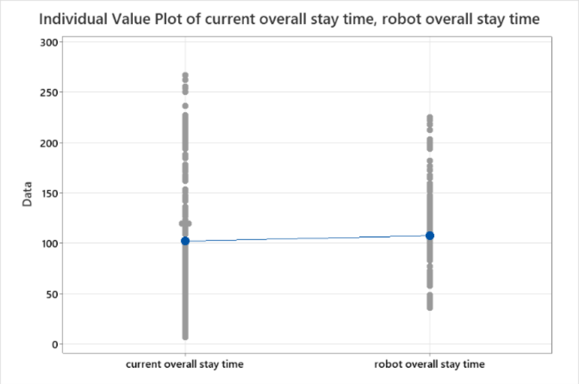
Estimation for Difference

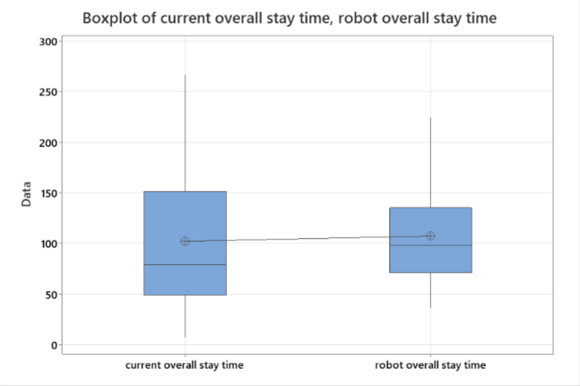
Difference	95% CI for Difference
-5.27	(-17.49, 6.95)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-0.85	317	0.397





Based on the report, the P-value is greater than 0.05, which means that they are not significantly different by the means. Therefore, fail to reject null hypothesis, reject alternative hypothesis. Both processes have the same process time overall.

Looking into individual factors, checking to see is the process time of one plate significant from one process to another.

Stay time single plate only

WORKSHEET 2

Two-Sample T-Test and CI: Current single plate time, Robot single plate time

Method

μ_1: population mean of Current single plate time

μ_2: population mean of Robot single plate time

Difference: $\mu_1 - \mu_2$

Equal variances are not assumed for this analysis.

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Current single plate time	178	41.1	16.5	1.2
Robot single plate time	162	97.8	34.6	2.7

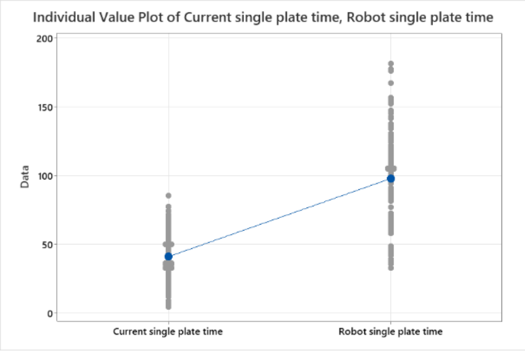
Estimation for Difference

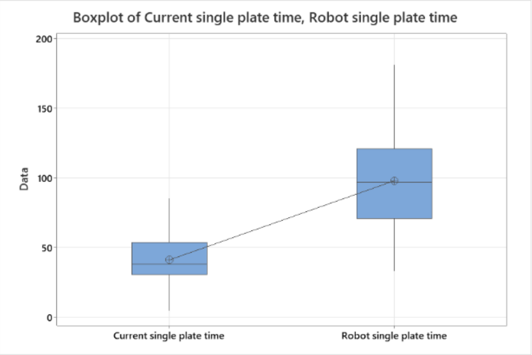
Difference	95% CI for Difference
-56.71	(-62.59, -50.83)

Test

Null hypothesis	H₀: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H₁: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-19.00	225	0.000





Based on the two sample-t tests, the conclusion is that they are significantly different from one another. It has a P-value of less than 0.05, which means reject null hypothesis, accept alternative hypothesis. Therefore, the process time of one item is significantly different from one simulation to another. In Current process have a mean of 41.1, while future robotic arm has a mean of 97.8. Current processes are faster than two robotic arms by 238%.

Looking into waiting time in line, checking to see is the waiting in line time significant from one to another.

Waiting in line time

Descriptive Statistics

Sample	N	Mean	StDev	SE Mean
Current single plate time	178	41.1	16.5	1.2
Robot single plate time	162	97.8	34.6	2.7

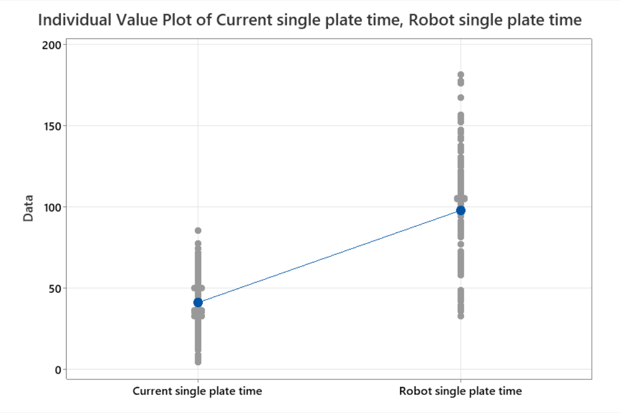
Estimation for Difference

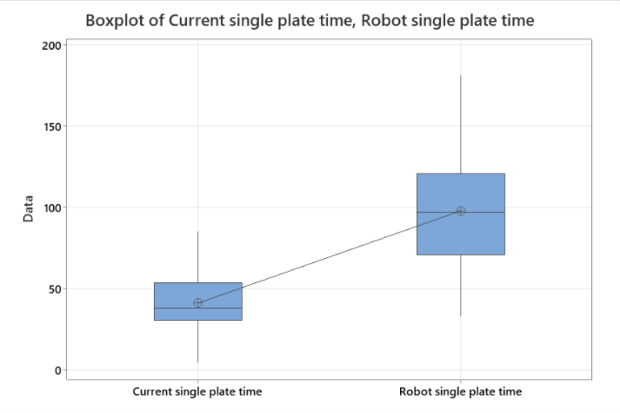
Difference	95% CI for Difference
-56.71	(-62.59, -50.83)

Test

Null hypothesis	H_0: $\mu_1 - \mu_2 = 0$
Alternative hypothesis	H_1: $\mu_1 - \mu_2 \neq 0$

T-Value	DF	P-Value
-19.00	225	0.000





Based on two sample tests, the P-value is less than 0.05. Which means they are significantly different, accept alternative hypotheses and reject null hypotheses. Therefore, they do not have the same meaning. When looking into current process and 2 robotic arms, current process has a mean waiting time of 61 seconds, while two robotic arms only have a waiting time of 9.5 seconds in the line.

6.6.3 Conclusion:

While the current process of one person serving is faster to serve one plate at a time, robotic arm can catch up when there are more people in line since two robotic arms can have two plates in the system at once. Overall based on the simulation, the student would have waited the same amount of time to get food from the current process that one worker is serving compared to two robotic arm that is serving.

7. Significant Accomplishments and Recommendations

The team made a significant amount of progress on this project over the semester, and many accomplishments have been achieved. These achievements have been described in detail and grouped by subsystem in the sections below. Additionally, to create a smoother transition from this semester to the next, the team has included recommendations for each subsystem directly following the identified accomplishments.

7.1. Kiosk Subsystem Accomplishments and Recommendations

During this semester, we accomplished the creation of both user interfaces for the worker and the customer and setup code that would test communication between the two interfaces (for transferring the menu from the worker's computer to the kiosk). We also designed a PCB with a BOM to have options for future implementations of the physical Kiosk. The following are some recommended next steps for this subsystem:

1. Implement the images/menu .csv information to be stored on a cloud service or in a database to prevent accidental deletion and the ability to recover any accidental changes.
2. Figure out what kind of Kiosk hardware will be used: whether it is an off the shelf tablet, an off the shelf Raspberry Pi with touchscreen or the custom PCB we designed over the semester. If you go with an off the shelf product like a tablet, the python code should be sufficient to be fully working or get 99% of the way there when developing the application.
3. CAD the frame and/or the mount for the Kiosk depending on the overall enclosure/structure of the automatic serving mechanism.
4. Add retrieve file button on the worker's UI to allow copying the stored order .csv files to the worker's machine for easy access.
5. Continue making the user interfaces more accessible and user-friendly.
6. Replace temporary code in both student.py and worker.py with code to transfer data between the master computer, kiosk, and worker computer (see ***Figure 7.1.1*** below). If you are continuing with Python and PyQt, I suggest using Paramiko for wireless communication.

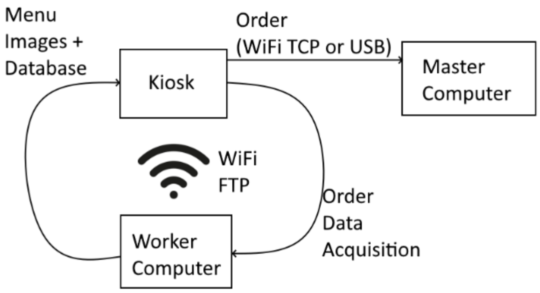


Figure 7.1.1: Flow Diagram Representing Communication Between Kiosk, Worker Computer and Master Computer

7.2. Plate Placement Subsystem Accomplishments and Recommendations

7.2.1. Plate Placement Subsystem – Conveyor Belt Entrance

The accomplishments for the Plate Placement Subsystem at the Conveyor Belt Entrance are listed below:

1. The Plate Placement Subsystem at the Conveyor Belt entrance was modeled mathematically.
2. The necessary spring constant was calculated and a spring for the flapper was chosen.
3. The Plate Placement Subsystem at the Conveyor Belt entrance was modelled in CAD.
4. The Plate Placement Subsystem at the Conveyor Belt entrance was integrated with the conveyor belt in CAD.

The following next steps are recommended for the full completion of the Plate Placement Subsystem at the Conveyor Belt entrance:

1. Create a prototype of the Plate Placement Subsystem at the Conveyor Belt entrance and run some tests with the spring chosen to ensure the system is functioning as it should.
2. Make any necessary modifications to the CAD design of the Plate Placement Subsystem at the Conveyor Belt entrance.
3. Conduct research on the implementation of an automated Plate Dispensing System to incorporate into this subsystem. Weigh the pros and cons to determine whether the addition of that automation would add value to the overall Automated System as it has been designed to this point.
4. If it is determined that the addition of an automated Plate Dispensing Subsystem would add value to the Automated System, create the necessary CAD files and perform the necessary calculations to design and integrate that subsystem to the rest of the Automated System.

7.2.2. Plate Placement Subsystem – Conveyor Belt Exit

The accomplishments for the Plate Placement Subsystem at the Conveyor Belt Exit are listed below:

1. The Plate Placement Subsystem at the Conveyor Belt exit was modeled mathematically.
2. The Plate Placement Subsystem at the Conveyor Belt exit was modelled in CAD.
3. The Plate Placement Subsystem at the Conveyor Belt exit was integrated with the conveyor belt in CAD.

The following next steps are recommended for the full completion of the Plate Placement Subsystem at the Conveyor Belt entrance:

1. Create a prototype of the Plate Placement Subsystem at the Conveyor Belt exitand run some tests with the length chosen to ensure the system is functioning as it should.
2. Make any necessary modifications to the CAD design of the Plate Placement Subsystem at the Conveyor Belt exit.

7.4. Conveyor Belt Subsystem Accomplishments and Recommendations

7.4.1. Accomplishments

During this semester, the team accomplished the main goals of the Conveyor Belt System which are the creation of the physical 3D Model of the conveyor belt and the conveyor belt electrical system PCB. The team also created a BOM with all the components with all of them having customer references that mirror the schematic's labeling of the components for easy assembly. We also got quotes from PCB manufacturers and have an estimate of how much this system is going to cost. Also, AC motor specifications and communication protocols for the master computer and this system were defined. The following are some recommended next steps for this subsystem:

1. Design a box to hold PCB, also make sure to have holes for the 120VAC connector (DAC-11H), Arduino Headers (J2, J3), and Motor Terminal (U$10)
2. Define a connector for the master computer to the conveyor, like the 120VAC outlet and its corresponding connector DAC-11H. However, for prototyping purposes breadboarding the master computer circuit using the J2 and J3 terminals is also an option.
3. When buying the PCB, buy the stencil that comes with it because it will make it easier to solder using solder paste for the SMD components. Gerber zip is in the REPO under REPO\Electrical Schematics, 3D PCBs, and PCBs Gerbers/
4. Use the Rosserial Arduino Library to implement ROS in the Arduino Nano
5. Use the user manuals provided in the REPO to start understanding how to code the IMI111T chip using UART. The modulation Iindex control PDF will provide some code on how to code the Arduino and the iMOTION configurable UART PDF will show how to code the IM111T chip. They are in the REPO under REPO\Electrical Schematics, 3D PCBs, and PCBs Gerbers\Conveyor Electrical System V2
6. For higher quality schematic viewing use the online Altium Viewer and upload the zip in the REPO under Electrical Schematics, 3D PCBs, and PCBs Gerbers\Conveyor Electrical System V2.zip

7. When assembling the PCB, use stencil to apply solder paste first and then use precision tongs to place SMD components. Then use oven, hot-air gun, or reflow station to solder the SMD components. Then use soldering iron to do the through hole components. It will make the assembly process much easier.
8. When buying the components use Digikey to be able to automatic enter of each component by uploading the BOM excel file. Click on cart, then upload file button to do this.
9. J4 is the header used to program and upload settings and firmware to the IM111T using the debugger module. This is also the way you tune the on board PID controller for the IM111T chip.

7.4.2. Total Cost and Buying Recommendations

The total cost for one assembly of the Conveyor Belt System is $4167.38 as seen in ***Figure 7.4.2: Total Cost Breakdown***. However, the team recommends buying several assemblies of the small inexpensive SMD components of the PCB because they can get lost removing them from their package or damaged while prototyping and testing. Also, the team recommends buying corresponding debugger module for the IMI111T chip that connects through USB to a computer, it might prove to be extremely helpful.

Item	**Price**
Total Electrical Components Cost	$134.18
JLC PCB Manufacturing Cost (1 PCB and 1 Stencil)	$17.20
Estimated 3 Phase AC Motor Included Cost (1HP, 460V, 3 Phase AC motor)	$200.00
Conveyor Belt Physical System Cost	$3,766.00
Electrical System Estimated Attachment Box	$10.00
Estimated Misc (screws, wires, etc.)	$40.00
Total:	$4167.38

Table 7.4.2: Total Cost Breakdown

7.4. Robotic Arm Subsystem Accomplishments and Recommendations

The simulation and a recording of the running simulation can be found in Repository\Simulations\Robot Arm. The following are accomplishments that were made in Robotic Arm Subsystems:

1. A robotic arm was selected that fits the needs and requirements and is reasonably priced.
2. CAD files of the utensil and conveyor belt were imported into the Octopuz simulation.

3. Modifications to CAD file of the utensil were made so it could be attached to the robot arm, allowing the simulation to show how it would look in the end.
4. A working simulation of the robot arm was made in which the robot arm scooped food from different parts of the pan to better replicate the serving motion of human workers.

The following are some of the pitfalls of Octopuz simulation for this project's purpose.

1. Octopuz simulation is designed for repetitive work, thus it is hard to implement outside inputs like unique orders.
2. The simulation cannot effectively simulate food substances interacting with other objects.
3. Because of the nature of the program, it would be difficult to add a feature where the robot would change utensils.
4. While a similar robot was chosen in simulation in the place of the Ufactory850, the exact model was not present in the simulation.

Overall due to these pitfalls in the simulations it is not recommended that future teams export the code straight and try to use it exactly as it was written, Instead, they should try to get a physical robot arm, even if it is different model, for testing and improvement using the simulation as a guideline of how the code should roughly look.

7.5. Utensil Design Subsystem Accomplishments and Recommendations

The accomplishments for this subsystem this semester are listed below:

Completed CAD files of system, located in repository/working/CAD/Slowet Utensil:
The numbers follow

Component Number	**Component Name**	**Component Number**	**Component Name**
1	End of Robot Arm	7	Motor Box
2	Utensil Mount	8	Tong Driving Gear
3	Utensil Connector	9	Tong Driven Gear
4	Spring	10	Gear Bracket
5	Locking Pin	11	Tong Bracket
6	Driving Gear	12	Open Tong

*Figure 5.5.44***.**

1. End of robot arm: slowet_utensil_toolhead_1.prt

    This is just for reference.
2. Base connector to end of robot arm: slowet_utensil_connector_2.prt

    This contains "lock" system for the key with a motor lock, and power cord for the tong system motor.
3. Key: slowet_utensil_handle_connection_3.prt

This is a piece that fits into the "lock" system and allows for interchangeable utensils.

4-11. Tong system, gears, brackets:
System to open and close tongs, "plugs" into base connector

12, 13. Ideal tong: slowet_open_tong_4.c.prt , slowet_serving_tong_4.b.prt
Two tongs were created, one in an open and one in closed position. These are ideal tongs that work within the design.

14. Ideal Spoon: slowet_serving_spoon_4.a.prt
An ideal spoon that has a volume of ½ cup created for visual conception, Any spoon that fits designated constraints will work.

The following tasks are recommended for the next team to complete:

1. Verify that the gear ratios used in the CAD model are correct.
2. Create a to-scale prototype of the system and verify its compatibility with the utensils currently used in Commons Dining Hall. Make necessary modifications to the CAD model.
3. Obtain utensils from Commons Dining Hall and create accurate CAD models of those.
4. Create drawing sets of the CAD models and set tolerances.
5. Fully integrate the utensils in Octopuz.
6. Create a CAD model of a utensil "docking station."

7.6. Simulation Accomplishment and Recommendation

Accomplishments:

1. Simulation for current dining hall process is complete.
2. Simulation for two robotic arm system have is complete.
3. The layout is easily editable for different simulation scenarios.
4. Data analysis and comparison between both systems.

Recommendation:

1. Future teams can set up a global table for even easier editing to simulate scenarios.
2. Future teams should gather data on which food tray is more popular to order and see how that affects the simulation for current dining hall process and future dining hall process.
3. Future teams can edit simulation to change the simulation scenarios for better result.
4. Future teams should gather a larger sample of data for current process in common's dining hall.

8. Conclusions

This semester of Spring 24, the Sodexo sponsored team “Serving Automation for Commons Dining Hall,” achieved significant progress with respect to the design of the project. The team established project needs and requirements from what the sponsor designated as the scope of the project in addition to student-identified needs and requirements. Following this, potential concepts were brainstormed and benchmarked, to eventually lead to the final design of the project. The final design consists of six (6) subsystems, five (5) of which are ready to be prototyped in future semesters, as well as a system process flow chart. These designs will be tested physically once prototyped to account for tolerances, compatibility, overall functionality. Different aspects of each subsystem will need to be tested for these categories, and any others that future teams deem necessary. Additionally, the team developed automatic data collection embedded within the kiosk subsystem. This could be implemented into Commons Dining Hall before this automated serving system is fully complete to determine the popularity of each dish. All of the work completed this semester can be used by future teams as a starting point for the prototyping, testing, and eventual fabrication of the full Automated Serving System.

References

[1] E. Tillitson, R. G. Craig, and F. A. Peyton, “Friction and wear of restorative dental materials - E.W. Tillitson, R.G. Craig, F.A. Peyton, 1971,” Semantic Scholar, https://journals.sagepub.com/doi/10.1177/00220345710500011001 (accessed Apr. 26, 2024).

[2] Menus, https://menus.sodexomyway.com/BiteMenu/Menu?menuId=15465&locationId=76929001&whereami=http%3A%2F%2Frpi.sodexomyway.com%2Fdining-near-me%2Fcommons-dining-hall (accessed Apr. 26, 2024).

Appendix A: Engineering Tools and Methods Checklist

Table A.1: Engineering Tools and Methods Checklist

Engineering Tools and Methods	Application to project
Octopuz	Robotics/Process simulation.
SPICE	Circuit simulation.
Altium	Circuit layout/design.
NX Siemens (CAD)	Part design and stress/strain analysis.
GC Toolkit package for NX Siemens	Render gear and spring parts.
FlexSim	Process simulation.
Excel	Data gathering and statistics calculations.
R	Code assisted data manipulation.
Minitab	Data analysis.
Microsoft Access	SQL database management.
Arduino IDE	Microcontroller programming.
Analog Discovery 2	Multimeter/Oscilloscope functionality.
Free Body Diagrams	Force analysis.
Python	Coding for simulations and subsystem management.
Fusion 360	Circuit layout/design and CAD

Appendix B: Risk Assessment Checklist

Project Risks

Table B.1: Project Risks

Example	**Mitigation Strategy**
Any one of the software could crash without saving	Frequent saves will mitigate most of the problem with crashes.
There is the possibility of over budget	Speak with sponsor mentor for a confirmed budget to prevent over budget.
Getting the system FDA and OSHA approved	Look into guideline and make sure non of the system would violate the guideline

Product Risks

Table B.2: Product Risks

Example	**Mitigation Strategy**
Strength of motor used for the conveyor may be excessive	Separate people from the food conveyor with divider and make sure appropriate power is used.
Robot arm when poorly programed could flail around and damage people and property	Collaborative robot will be used which has many safety features for the purpose of working with human but proper precaution should be still made when using them.
Student touching/fiddling with robotic arm	Have a barrier/divider to prevent student to be able to touch the system other than kiosk

Technical Risks

Table B.3: Technical Risks

Example	**Mitigation Strategy**
Detecting food with camera and using that to guide robot to scoop will be very challenging	Using many libraries existing on Github and other online resources should help
Robot may malfunction when used for long time due to wear and tear	Regular maintenance would reduce the risk.
Integrating robot arms to existing layout	Talk with the workers and design so it will not impede the process flow when implemented.

Appendix C: Engineering Standards Checklist

Table C.1: Engineering Standards Checklist

Category	**Standards Applicable**	**Purpose**
Software	C++	Programing the Arduino in the Conveyor belt system and programing the master computer system.
	PEP8 - Python coding standard	GUI for Kiosk System
	Flexsim	Process simulation of current dining hall and future dining hall
	Octopuz	Simulating movement of robot arm
Electrical	UART	communication between systems and the master computer
	Serial communications baud rates	communication between systems and the master computer
	120VAC nominal at 60 hertz	Power for the Conveyor
	22 AWG Wire	Power line (120VAC) and motor wires
Materials	Polyvinyl Chloride (PVC)	Conveyor Belt Materials
	Stainless Steel 304	Utensils
	Stainless steel 316	Utensils, containers, machine parts
	Stainless steel 430	Containers, especially for corrosive foods
	HDPE (high-density polyethylene)	Bottles, food wrappers, food storage buckets
	LDPE (low-density polyethylene)	Cling wrap/film, waterproof inner container layer, six-pack connector rings
	PET (polyethylene terephthalate)	Bottles, jars, containers
	PP (polypropylene)	Yoghurt pots, disposable microwaveable containers
	Aluminum	Robot Arm
	Carbon Fiber	Robot Arm
Regulatory	Food and Drug Administration (FDA)	140°F (60°C), Hot foods are held at these temperatures to prevent bacterial growth. 40°F (4°C), Cold foods are

		held at these temperatures to prevent bacterial growth.
	OSHA 1910.212	General requirements for machine guards
	OSHA 1917.151	A power cut-off device for machinery and equipment shall be provided at the operator's working position.
	OSHA 1910.147	Work on cord and plug connected electric equipment for which exposure to the hazards of unexpected energization or start up of the equipment is controlled by the unplugging of the equipment from the energy source and by the plug being under the exclusive control of the employee performing the servicing or maintenance.

Appendix D: Bill of Materials

Table D1: Bill of Materials for Custom Kiosk PCB

Comment	Description	Designator	Footprint	LibRef	Quantity
TAJS106K002RNJ	10uF 2.5V ±10% 8Ω 1206 SMD Tantalum Capacitor	C1	FP-TAJS-MFG	CMP-04424-000459-1	1
502774-0891	Micro SD Memory Card Connector, 0.5 A, 10 V (DC), -25 to 85 degC, 8-Pin SMT, RoHS, Tape and Reel	CD1	MOLX-502774-0891_V	CMP-2000-05248-1	1
SMBJ6.0CA	TVS DIODE 6V 10.3V DO214AA	D1, D2	FP-SMBJ-MFG	CMP-08607-000029-1	2
MF-PSMF110X-2	PTC RESET FUSE 6V 1.1A 0805	F1	FP-MF-PSMF110X-2-MFG	CMP-07400-000024-1	1
694102107102	Power Barrel Connector	J1	694102107102	CMP-1502-00174-2	1
52271-2269	1.0 mm Pitch Easy-On(TM) Type FPC Connector, 3.0 mm Mated Height, Right Angle, ZIF, SMT, Bottom Contact, 22 Circuits, -40 to 85 degC, ELV and RoHS Compliant, Tape and Reel	J2	MOLX-52271-2269	CMP-1241-00257-1	1
105017-0001	Micro-USB B Receptacle, Right Angle, Bottom Mount, Surface Mount, with Solder Tabs, -30 to 85 degC, 5-Pin USB, RoHS, Tape and Reel	J3	USB-MICRO-B_V	CMP-2000-05827-1	1
CRCW06032K20FKEA	2.2k Ohm 1% Resistor	R1, R2	RESC1609X50X30NL10T20	CMP-2000-03167-1	2
CM4102008	Raspberry Pi Compute Module 4 with WiFi 2GB RAM 8GB Flash	U1	MODULE_CM4102008	CM4102008	1
DF40C-100DS-0.4V(51)	100 Position Connector Receptacle, Center Strip Contacts Surface Mount Gold	U2	MODULE_CM4102008	CM4102008	2

Table D2: Bill of Materials for Conveyor Belt Electrical Design PCB Part 1

Country of Origin may be different at time of shipment.												
The HTSUS and ECCN information shown is for informational purposes only and is not a representation or warranty as to the accuracy or reliability of these classific												
Index	Manufacturer Part Number	Manufactu	Descriptio	Availability	Stock Statu	Attrition %	Requested	Pack Quan	Pack Type	Digi-Key Pa	Unit Price	Extended
1	DAC-11H	DIT	PWR ENT,	507	In Stock		1	1	Box	4761-DAC-	0.71000	$0.71
2	2238204-3	TE Connec	FASTON 2	31,681	In Stock		1	1	Cut Tape (	17-22382	0.10000	$0.10
3	302J115J6F0701J(R)	GlobTek, I	CORD 16A	574	In Stock		1	1	Bulk	1939-189	9.06000	$9.06
4	ED1A222MP51020U	Chinsan (E	CAP ALUM	742	In Stock		1	1	Cut Tape (	4191-ED1	0.47000	$0.47
5	IMI111T046HXUMA1	Infineon T	IMOTION	997	In Stock		1	1	Cut Tape (	448-IMI11	8.18000	$8.18
6	DE2E3SA222MN3AT02F	Murata Ele	CAP CER 2	11,960	In Stock		2	2	Cut Tape (	490-16241	0.31000	$0.62
7	ECW-FD2W105K4	Panasonic	CAP FILM	2,345	In Stock		1	1	Cut Tape (	PCF1597C	0.78000	$0.78
8	1935174	Phoenix C	TERM BLK	67,075	In Stock		2	2	Box	277-1578-	0.69000	$1.38
9	0680L1000-05	Bel Fuse In	FUSE BRD	46,725	In Stock		1	1	Cut Tape (	507-0680L	0.62000	$0.62
10	LDE60-20B24	Mornsun A	AC/DC CO	323	In Stock		1	1	Tray	2725-LDE	17.04000	$17.04
11	LM1085ISX-ADJ/NOPB	Texas Instr	IC REG LIN	2,987	In Stock		1	1	Cut Tape (	LM1085IS	1.99000	$1.99
12	RT0603BRC07500RL	YAGEO	RES 500 O	9,969	In Stock		1	1	Cut Tape (	13-RT060	0.39000	$0.39
13	RT0603BRE075KL	YAGEO	RES 5K OH	17,591	In Stock		1	1	Cut Tape (	13-RT060	0.17000	$0.17
14	CWR11HH106KB	KEMET	CAP TANT	14,671	In Stock		1	1	Cut Tape (	1001-2237	4.07000	$4.07
15	293D106X0025C2TE3	Vishay Spr	CAP TANT	92,837	In Stock		2	2	Cut Tape (	718-1044-	0.53000	$1.06
16	ERJ-3EKF1650V	Panasonic	RES SMD 1	282,860	In Stock		1	1	Cut Tape (	P165HCT-	0.10000	$0.10
17	RT0603BRC07500RL	YAGEO	RES 500 O	9,969	In Stock		1	1	Cut Tape (	13-RT060	0.39000	$0.39
18	TMCP1D104MTRF	Vishay Spr	CAP TANT	3,946	In Stock		1	1	Cut Tape (	718-2500-	0.32000	$0.32
19	B58035U7155M062	EPCOS - T	CAP CER 1	345	In Stock		3	3	Cut Tape (	495-7739	17.23000	$51.69
20	CRCW08051M00FKEA	Vishay Dal	RES SMD 1	164,392	In Stock		2	2	Cut Tape (	541-1.00	0.10000	$0.20
21	CRCW060313K3FKEAC	Vishay Dal	RES 13.3K	43,059	In Stock		1	1	Cut Tape (	541-5169-	0.10000	$0.10
22	GCM188R72A472KA37D	Murata Ele	CAP CER 4	33,713	In Stock		1	1	Cut Tape (	490-4930-	0.16000	$0.16
23	TNPW060310K0BEEA	Vishay Dal	RES 10K O	337,442	In Stock		1	1	Cut Tape (	TNP10.0K	0.38000	$0.38
24	RC0603FR-07100RL	YAGEO	RES 100 O	2,363,331	In Stock		1	1	Cut Tape (	311-100H	0.10000	$0.10
25	ERJ-3EKF2001V	Panasonic	RES SMD 2	903,906	In Stock		1	1	Cut Tape (	P2.00KHC	0.10000	$0.10
26	GRM1885C1H221GA01D	Murata Ele	CAP CER 2	13,634	In Stock		1	1	Cut Tape (	490-10711	0.20000	$0.20
27	RL1206FR-070R25L	YAGEO	RES 0.25 C	12,034	In Stock		1	1	Cut Tape (	311-.25LW	0.34000	$0.34
28	KBP206G	Diodes Inc	BRIDGE 1-	29,384	In Stock		1	1	Tube	KBP206GD	0.56000	$0.56
29	8103-RC	Bourns Inc	CMC 1MH	884	In Stock		1	1	Bulk	M8898-N	5.58000	$5.58
30	890324025017CS	Würth Elek	CAP FILM (	1,239	In Stock		2	2	Bulk	732-5798-	0.43000	$0.86
31	DE2E3SA222MN3AX02F	Murata Ele	CAP CER 2	5,533	In Stock		2	2	Cut Tape (	490-16242	0.31000	$0.62
32	B57153S0150M000	EPCOS - T	ICL 15 OH	21,559	In Stock		1	1	Bulk	495-2077-	0.53000	$0.53
33	CRCW251275K0FKEG	Vishay Dal	RES SMD 7	33,213	In Stock		2	2	Cut Tape (	541-75.0K	0.34000	$0.68
34	151034RS03000	Würth Elek	LED RED C	2,395	In Stock		1	1	Bulk	732-1140	0.18000	$0.18
35	861221483002	Würth Elek	CAP ALUM	36	In Stock		1	1	Tray	732-6531-	4.62000	$4.62
36	890303425004CS	Würth Elek	CAP FILM (	1,371	In Stock		1	1	Bulk	732-11831	0.74000	$0.74
37	TS-115-G-A	Samtec In	CONN HEA	674	In Stock - Value Adde		2	2	Bulk	SAM1111-	5.13000	$10.26
38	NCP5500DADJR2G	onsemi	IC REG LIN	23,188	In Stock		1	1	Cut Tape (	NCP5500D	0.81000	$0.81
39	860020272006	Würth Elek	CAP ALUM	1,426	In Stock		1	1	Cut Tape (	732-8908-	0.12000	$0.12
40	CL31B475KAHNNNE	Samsung E	CAP CER 4	238,053	In Stock		1	1	Cut Tape (	1276-105	0.18000	$0.18
41	102010268	Seeed Tec	SEEEDUIN	2,457	In Stock		1	1	Bulk	1597-102	7.60000	$7.60
42	GRM188R72A472KA01D	Murata Ele	CAP CER 4	140,637	In Stock		1	1	Cut Tape (	490-1073	0.12000	$0.12
Motor Rec	108074-5349-1721106061	GCCSJ Sto	Electric Motor	1	In Stock		1				$199.99	

Table D3: Bill of Materials for Conveyor Belt Electrical Design PCB Part pro

se classifications. All information is provided "as is" and is subject to change without notice. Any use made of the information provided is without recou

Extended	Minimum	Customer	Requested	Lead Wee	Datashe	Reference	US Import	Note	Part Statu	RoHS Stat	Moisture	ECCN	HTSUS
$0.71	1		4761-DAC-	1	https://		N/A		Active	RoHS Com	Not Applic	EAR99	8536.69.4
$0.10	1		17-223820	17	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8536.90.4
$9.06	1		1939-1896	16	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8544.42.9
$0.47	1		4191-ED1	18	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.22.0
$8.18	1	U$3	448-IMI11	35	https://		N/A		Active	ROHS3 Co	Not Applic	EAR99	8542.39.0
$0.62	1	C16, C17	490-16241	19	https://		N/A		Active	ROHS3 Co	Not Applic	EAR99	8532.24.0
$0.78	1	C2	PCF1597C	29	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8532.25.0
$1.38	1	U$1, U$10	277-1578-	12	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8536.90.4
$0.62	1	F1	507-0680L	10	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8536.10.0
$17.04	1	PS1	2725-LDE	15	https://		May apply		Active	RoHS Com	1 (Unlimit	EAR99	8504.40.6
$1.99	1	U1	LM1085IS	6	https://		N/A		Active	ROHS3 Co	3 (168 Ho	EAR99	8542.39.0
$0.39	1	R7	13-RT0603	20	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.17	1	R8	13-RT0603	20	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$4.07	1	C8	1001-2237	16	https://connect.ke		N/A		Active	RoHS non-	1 (Unlimit	EAR99	8532.21.0
$1.06	1	C9, C10	718-1044-	14	https://www.visha		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.21.0
$0.10	1	R6	P165HCT-	21	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.39	1	R9	13-RT0603	20	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.32	1	C12	718-2500-	16	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.21.0
$51.69	1	C3, C4, C5	495-77399	11	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.24.0
$0.20	1	R10, R11	541-1.00	14	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.10	1	R12	541-5169-	18	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.16	1	C13	490-4930-	23	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.24.0
$0.38	1	R2	TNP10.0K	14	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.10	1	R4	311-100H	18	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.10	1	R3	P2.00KHC	21	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.20	1	C14	490-10711	19	https://		N/A		Not For N	ROHS3 Co	1 (Unlimit	EAR99	8532.24.0
$0.34	1	R5	311-.25LW	20	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.56	1	BR1	KBP206GD	8	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8541.10.0
$5.58	1	L1	M8898-N	20	https://		May apply		Active	ROHS3 Co	1 (Unlimit	EAR99	8548.00.0
$0.86	1	C6, C15	732-5798-	30	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8532.25.0
$0.62	1	C16, C17	490-16242	19	https://		N/A		Active	ROHS3 Co	Not Applic	EAR99	8532.24.0
$0.53	1	U3	495-2077-	20	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8533.40.8
$0.68	1	R1, R13	541-75.0K	14	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8533.21.0
$0.18	1	D1	732-11403	18	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8541.41.0
$4.62	1	C18	732-6531-	26	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8532.22.0
$0.74	1	C19	732-11831	30	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8532.25.0
$10.26	1	J2, J3	SAM1111-	2	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8536.69.4
$0.81	1	U2	NCP5500D	8	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8542.39.0
$0.12	1	C1	732-8908-	26	https://		May apply		Active	ROHS3 Co	Not Applic	EAR99	8532.22.0
$0.18	1	C11	1276-1055	22	https://		N/A		Active	ROHS3 Co	1 (Unlimit	EAR99	8532.24.0
$7.60	1	J1	1597-1020	17	https://		May apply		Active	Unknown	1 (Unlimit	EAR99	8471.50.0
$0.12	1	C7	490-10739	19	https://		N/A		Not For N	ROHS3 Co	1 (Unlimit	EAR99	8532.24.0

https://www.amazon.com/Electric-General-Purpose-Diameter-Rolled/dp/B0BTDD6XF6?source=

Table D4: Bill of materials for utensil subsystem

Item Number	Description	Type	Dimensions	Item Price	Quantity	Total Price
1	Screw	2M	5mm	$0.02	7	$0.14
2	Screw	6M	10mm	$0.02	7	$0.14
3	Motor	12 V	40mmX20mm	$30	1	$30
4	Motor	6 V	40mmX20mm	$15	1	$15
5	Utensil	Spoon	Handle width(W), 8mm<W<17.5mm	Variable	1	N/A
			Handle height(H), H<5mm			
			Length of handle(L), L>50mm			
			Total length of Spoon(S), 125mm< S< 300mm			
	Utensil	Tongs	Gap between handle of tongs when fully closed(G) G≥25mm	Variable	1	N/A
			Inside length of flat part of handle(I) I≥50mm			
			Angle of use(A), A≤45 degrees			
			Total Length of Tongs(T), 170mm<T<255mm			
					Total	$45.28

*Table D5: Bill of Materials for Plate Placement Subsystem**

Item number	**Subsystem**	**Description**	**Vendor**	**Product or Part Number**	**Item Price**	**Quantity**	**Total Price**
1	Plate Placement	Flapper system for centering plates at the entrance of the conveyor belt	Axcess Spring	PC007-234-1200-MW-0500-C-N-IN	$7.88	2	$15.76
2	Plate Placement	Rollers for Parking Lot system	Ashland Conveyor	1VAT5	$29.42	13	$382.46
							$398.22

*Does not include cost of 3D printing/fabricating flapper casing, pole, or inclined plane

Appendix E: Ethical and Professional Responsibilities

.Table E.1: Ethical and Professional Responsibilities

Issues	Impact 1 (low) - 5 (high)	Description of Impact and Related Project Decisions
Public Health, Safety, and Welfare	2	We designed our system to acknowledge potential hazards with food handling such as cross contamination, which is at a minimum due to the robotic arms using one utensil per food type. There are safety concerns with workers replacing the food trays when they run out, however, there will ideally be future implementations which will allow the machine to be turned off.
Global	1	Our system was designed to operate to Sodexo's food handling specifications, particularly preventing cross contamination and providing a sneeze guard. This will meet most national standards for food handling and will likely meet international food safety standards as well.
Cultural	1	This design doesn't have any cultural impact, since it is localized in a particular dining hall and is focused on taking orders and plating food.
Social	5	This product inherently removes any social aspect from the food ordering process, using a kiosk and a series of robot arms to plate the food. The design also removes the need for additional workers, which creates job loss.
Environmental	2	Besides an increase in energy consumption in the dining hall, there are no hazardous wastes or chemicals produced by the design.
Economic	5	This design was made to meet the customer's needs and requirements with little concern about cost. This means the product requires considerable cost resources in construction and storage and maintaining the device to be operational.

Appendix F: Calculations

F.1 Plate Placement Calculations – Entrance

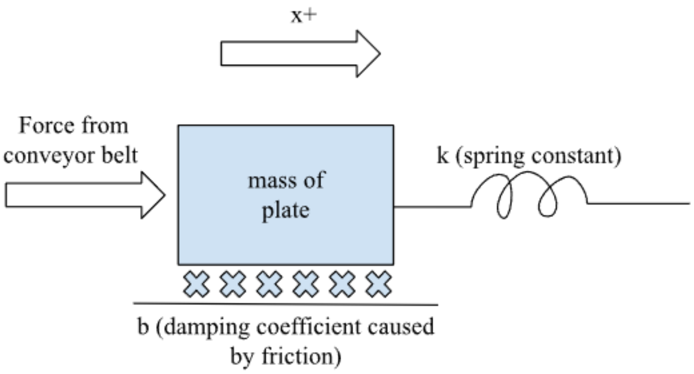


Figure G.1: Model of the Plate Placement Subsystem Entrance

Assumptions:

- When the conveyor belt is in "go," it does not accelerate, but instead moves at a constant unknown velocity.
- The plate moves about 1 foot (12 in) when it moves between each station.
- The conveyor belt is made of polypropylene plastic, and its coefficient of friction is 0.35.
- The plates are ceramic, likely porcelain, whose coefficient of friction is 0.11. [1]
- Each plate weighs about 1lb (≈ 0.45 kg).

$$F_x = m_p\ddot{x}_1 = F_c + F_k + F_f$$

$$m_p\ddot{x}_1 = F_c + k(x_2 - x_1) + b(\dot{x}_2 - \dot{x}_1)$$

$$k = \frac{m_p\ddot{x}_1 - F_c - b(\dot{x}_2 - \dot{x}_1)}{(x_2 - x_1)}$$

$$k = \frac{\mu m_p g}{(x_2 - x_1)}$$

$$k = \frac{0.35 \cdot (0.453592\ kg) \cdot (9.81\ \frac{m}{s^2})}{0.3048\ m}$$

$$k = 0.00511\ N/mm$$

F.2 Plate Placement Calculations – Exit

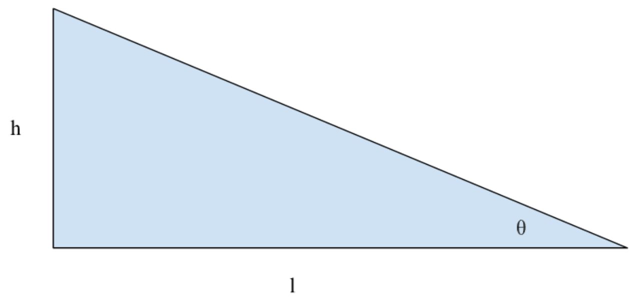


Figure G.2: Inclined Plane Model

The following constraints were used to determine the proper length of the inclined plane:

- The inclined plane should not have an angle greater than 10°.
- The inclined plane cannot be longer than 1500 mm.
- The inclined plane needed a maximum height of 138mm.

$$\tan\theta = \frac{h}{l}$$

$$l = \frac{h}{\tan\theta}$$

$$l = \frac{138\ mm}{\tan 10} = 782.6\ mm$$

Appendix G: Data Collection

Table G.1, Key for Table G.3 and percentages of each food category found on a week's menu [2].

Category	Color	Number per Category	Percentage (%)
Protein	🟧	12	24
Starch	🟦	13	27
Vegetable	🟩	17	35
Sauce	▨	3	6
Unknown		4	8
		Total= 49	

Table G.2, Key for Table G.3 and percentages of the menu that can be served per utensil [2].

Utensil	Color	Number per Category	Percentage of the menu served (%)
Serving Spoon	🟨	33	67
Tongs	🟩	16	33
Ladle	🟦	3	6
Gripper	🟥	12	24
Skewer	🟪	7	14

Table G.3, Categorization of weekly menu, color coded per utensil and category of food [2].

Day	Meal Time	Food Items	Serving Spoon	Tongs	Ladle	Gripper	Skewer
Sun	Dinner	Chicken Piccata Pasta Bowl	🟨				
		Garlic Bread		🟩		🟥	🟪
		Greek Salad	🟨	🟩			
		Steamed Broccoli	🟨				
Monday	Lunch	Sauteed Onions	🟨				
		Contry Style Kitchen Vegetables	🟨				
		traditional Poutine		🟩		🟥	
		French Fry		🟩		🟥	
		Waffle Fries Poutine		🟩		🟥	
		Texas Chili	🟨		🟦		
		Sauteed Mushrooms	🟨				
		Poutine Brown Gravy			🟦		
	Dinner	Country Style Kitchen vegetables	🟨				
		Beefy Mac Casserole	🟨				
Tuesday	Lunch	Shredded Lettuce		🟩			
		Sour Cream	🟨				
		Jalapeno Pepper	🟨				
		Chedder Cheese Sauce			🟦		
		Taco Beef Soft Taco	🟨				
		Part Skim Shredded Mozzarella Cheese	🟨				
		Jackfruit Carnitas		🟩			
		Cilantro Jasmine Rice	🟨				
		Bean and Corn Salsa	🟨				
		Refried Black beans	🟨				
		Shredded Cheddar Cheese	🟨				
	Dinner	Roasted Marinated Vegetables	🟨				
		Roast Pork Loin with Mustard Herb Crust		🟩		🟥	🟪
		Scalloped Potatoes	🟨				
Wednesday	Lunch	baked Bread Stick		🟩		🟥	🟪
		Grilled Mediterranean Chicken		🟩		🟥	🟪
		Roasted Tomato Rice Pilaf	🟨				
		Steamed Italian Vegetable Medley	🟨				
	Dinner	Corn Bread		🟩		🟥	
		Collard Greens	🟨				
		Baked Macaroni and Cheese	🟨				
		Southern Fried Chicken		🟩		🟥	🟪
Thursday	Lunch	Turkish Pickled Vegetables	🟨				
		Tumerc Basmati Pilaf	🟨				
		Shawarma Chicken Breast		🟩		🟥	🟪
	Dinner	Old Fashioned Beef Stew	🟨				
		Buttermilk Drop Biscuit		🟩		🟥	
Friday	Lunch	Chicken Jambalaya With Andouille Sausage	🟨				
		Ratatouille	🟨				
		Blackened Catfish With Ponchatrain Sauce	🟨	🟩			
	Dinner	Maple Chile Glazed Pork Loin		🟩		🟥	🟪
		Apple Braised Red Cabbage	🟨				
		Sweet Potato Casserole	🟨				
Saturday		Steamed Broccoli	🟨				
		Chicken Pot Pie With Biscuit	🟨				

Table G.4: Current process simulation data (seconds)

entry	exit	stay time(overall)	entry (Process Starts)	exit	stay time (in system)	waiting in line time
217.2	270.79	53.59	217.2	270.79	53.59	0
285.04	324.19	39.15	285.04	324.19	39.15	0
363.92	413.9	49.98	363.92	413.9	49.98	0
378.34	438.1	59.76	413.9	438.1	24.2	35.56
516.86	551.59	34.72	516.86	551.59	34.72	0
688.1	705.68	17.58	688.1	705.68	17.58	0
698.55	755.02	56.47	705.68	755.02	49.34	7.13
923.34	994.81	71.47	923.34	994.81	71.47	0
961.7	1024.63	62.93	994.81	1024.63	29.82	33.11
1010.6	1067.7	57.1	1024.63	1067.7	43.06	14.04
1088	1125.5	37.5	1088	1125.5	37.5	0
1250.45	1265.81	15.36	1250.45	1265.81	15.36	0
1260.95	1281.51	20.57	1265.81	1281.51	15.7	4.87
1355.61	1392.85	37.24	1355.61	1392.85	37.24	0
1363.9	1428.21	64.31	1392.85	1428.21	35.35	28.96
1442.44	1498.53	56.09	1442.44	1498.53	56.09	0
1481.9	1530.02	48.11	1498.53	1530.02	31.48	16.63
1567.55	1623.12	55.56	1567.55	1623.12	55.56	0
1627.17	1664.99	37.82	1627.17	1664.99	37.82	0
1668.43	1735.61	67.18	1668.43	1735.61	67.18	0
1872.82	1881.65	8.82	1872.82	1881.65	8.82	0
1878.93	1912.5	33.57	1881.65	1912.5	30.86	2.71
1911.11	1978.53	67.42	1912.5	1978.53	66.03	1.39
1930.22	2017.37	87.15	1978.53	2017.37	38.84	48.31
1995.14	2040.71	45.57	2017.37	2040.71	23.35	22.22
2121.49	2157.1	35.61	2121.49	2157.1	35.61	0
2130.07	2174.74	44.67	2157.1	2174.74	17.64	27.03
2134.21	2244.51	110.3	2174.74	2244.51	69.77	40.53
2148.79	2300.37	151.58	2244.51	2300.37	55.86	95.72
2166.38	2333.23	166.85	2300.37	2333.23	32.86	133.99
2182.62	2357.5	174.88	2333.23	2357.5	24.27	150.61
2211.5	2378.04	166.53	2357.5	2378.04	20.54	145.99
2232.76	2394.55	161.79	2378.04	2394.55	16.52	145.27
2272.33	2416.52	144.19	2394.55	2416.52	21.96	122.23
2302.1	2455.07	152.97	2416.52	2455.07	38.55	114.42
2347.35	2493.17	145.82	2455.07	2493.17	38.1	107.72
2399.12	2532.3	133.18	2493.17	2532.3	39.13	94.05
2519.86	2556.82	36.96	2532.3	2556.82	24.52	12.44
2545.53	2619.31	73.78	2556.82	2619.31	62.49	11.29

2609.94	2649.48	39.54	2619.31	2649.48	30.17	9.37
2672.98	2741.26	68.28	2672.98	2741.26	68.28	0
2779.3	2829.24	49.94	2779.3	2829.24	49.94	0
2815.08	2871.28	56.2	2829.24	2871.28	42.04	14.16
2898.66	2929.14	30.48	2898.66	2929.14	30.48	0
2938.28	3000.25	61.97	2938.28	3000.25	61.97	0
3015.3	3074.11	58.81	3015.3	3074.11	58.81	0
3017.03	3107.56	90.53	3074.11	3107.56	33.45	57.08
3081.5	3138.87	57.37	3107.56	3138.87	31.31	26.06
3101.21	3175.2	73.99	3138.87	3175.2	36.33	37.66
3145.5	3195.97	50.47	3175.2	3195.97	20.77	29.7
3172.3	3251.8	79.5	3195.97	3251.8	55.83	23.67
3215.08	3288.25	73.16	3251.8	3288.25	36.45	36.71
3253.05	3336.9	83.85	3288.25	3336.9	48.65	35.2
3349.03	3382.21	33.19	3349.03	3382.21	33.19	0
3541.98	3577.29	35.31	3541.98	3577.29	35.31	0
3560.74	3637.3	76.56	3577.29	3637.3	60.01	16.55
3605.31	3681.02	75.71	3637.3	3681.02	43.72	31.99
3622.32	3758.52	136.2	3681.02	3758.52	77.5	58.7
3702.17	3796.43	94.26	3758.52	3796.43	37.91	56.35
3897.77	3928.32	30.55	3897.77	3928.32	30.55	0
3916.32	3964.43	48.1	3928.32	3964.43	36.11	11.99
3935.53	3980.67	45.14	3964.43	3980.67	16.24	28.9
3941.97	4031.21	89.24	3980.67	4031.21	50.55	38.69
3997.86	4076.68	78.82	4031.21	4076.68	45.47	33.35
4138.32	4173.53	35.21	4138.32	4173.53	35.21	0
4213.05	4258.4	45.35	4213.05	4258.4	45.35	0
4220.39	4292.95	72.56	4258.4	4292.95	34.55	38.01
4316.69	4368.6	51.91	4316.69	4368.6	51.91	0
4342.91	4426.54	83.63	4368.6	4426.54	57.94	25.69
4346.19	4468.66	122.46	4426.54	4468.66	42.12	80.34
4361.77	4508.92	147.15	4468.66	4508.92	40.27	106.88
4401.83	4535.99	134.16	4508.92	4535.99	27.07	107.09
4416.05	4586.83	170.77	4535.99	4586.83	50.84	119.93
4475.84	4672.07	196.23	4586.83	4672.07	85.24	110.99
4582.97	4724.88	141.91	4672.07	4724.88	52.81	89.1
4656.85	4792.71	135.86	4724.88	4792.71	67.83	68.03
4852.43	4911.21	58.78	4852.43	4911.21	58.78	0
4972.75	4984.79	12.03	4972.75	4984.79	12.03	0
5023.74	5057.51	33.77	5023.74	5057.51	33.77	0
5086.21	5129.62	43.41	5086.21	5129.62	43.41	0
5252.58	5315.48	62.9	5252.58	5315.48	62.9	0
5254.18	5321.11	66.93	5315.48	5321.11	5.63	61.3

5333.89	5340.71	6.82	5333.89	5340.71	6.82	0
5362.67	5411.54	48.87	5362.67	5411.54	48.87	0
5388.7	5485.68	96.97	5411.54	5485.68	74.14	22.83
5433.83	5517.11	83.27	5485.68	5517.11	31.43	51.84
5536.21	5567.54	31.34	5536.21	5567.54	31.34	0
5694.91	5745.88	50.97	5694.91	5745.88	50.97	0
5882.87	5890.68	7.81	5882.87	5890.68	7.81	0
5897.54	5923.17	25.64	5897.54	5923.17	25.64	0
5898.11	5967.57	69.46	5923.17	5967.57	44.4	25.06
5911.35	6003.47	92.12	5967.57	6003.47	35.9	56.22
5927.39	6042.22	114.83	6003.47	6042.22	38.75	76.08
5989.86	6098.91	109.05	6042.22	6098.91	56.7	52.35
6016.95	6147.68	130.74	6098.91	6147.68	48.77	81.97
6057.96	6187.73	129.78	6147.68	6187.73	40.05	89.73
6093.67	6220.59	126.93	6187.73	6220.59	32.86	94.07
6181.77	6255.65	73.88	6220.59	6255.65	35.05	38.83
6187.43	6307.07	119.63	6255.65	6307.07	51.42	68.21
6242.79	6361.14	118.35	6307.07	6361.14	54.07	64.28
6335.16	6383.7	48.54	6361.14	6383.7	22.56	25.98
6376.16	6436.8	60.64	6383.7	6436.8	53.09	7.55
6516.61	6546.19	29.58	6516.61	6546.19	29.58	0
6519.41	6579.39	59.97	6546.19	6579.39	33.2	26.77
6684.88	6727.35	42.47	6684.88	6727.35	42.47	0
6700.17	6753.66	53.49	6727.35	6753.66	26.31	27.18
6728.85	6791.78	62.94	6753.66	6791.78	38.12	24.82
6919.57	6980.72	61.15	6919.57	6980.72	61.15	0
6928.92	7025.47	96.55	6980.72	7025.47	44.75	51.8
7000.08	7061.69	61.62	7025.47	7061.69	36.22	25.4
7046.65	7076.15	29.5	7061.69	7076.15	14.45	15.05
7052.32	7131.92	79.59	7076.15	7131.92	55.77	23.82
7096.57	7186.68	90.11	7131.92	7186.68	54.76	35.35
7104.83	7224.45	119.63	7186.68	7224.45	37.77	81.86
7118.68	7296.31	177.62	7224.45	7296.31	71.85	105.77
7155.54	7332.78	177.24	7296.31	7332.78	36.48	140.76
7181.86	7375.16	193.3	7332.78	7375.16	42.37	150.93
7207.76	7409.33	201.57	7375.16	7409.33	34.17	167.4
7220.61	7437.45	216.84	7409.33	7437.45	28.12	188.72
7277.2	7489.53	212.33	7437.45	7489.53	52.08	160.25
7284.55	7538.7	254.15	7489.53	7538.7	49.17	204.98
7309.75	7559.52	249.77	7538.7	7559.52	20.82	228.95
7403.01	7587.21	184.2	7559.52	7587.21	27.69	156.51
7413.91	7639.54	225.63	7587.21	7639.54	52.34	173.29
7470.36	7673.9	203.53	7639.54	7673.9	34.35	169.18

7509.48	7731.57	222.09	7673.9	7731.57	57.68	164.41
7557.11	7767.19	210.08	7731.57	7767.19	35.62	174.46
7562.2	7772.48	210.28	7767.19	7772.48	5.29	204.99
7660.43	7824.49	164.06	7772.48	7824.49	52.01	112.05
7714.14	7858.6	144.46	7824.49	7858.6	34.1	110.36
7732.33	7919.85	187.53	7858.6	7919.85	61.26	126.27
7774.01	7966.81	192.8	7919.85	7966.81	46.96	145.84
7777.73	7985.95	208.21	7966.81	7985.95	19.14	189.07
7799.71	8035.84	236.13	7985.95	8035.84	49.9	186.23
7896.3	8100.92	204.62	8035.84	8100.92	65.08	139.54
7913.28	8121.09	207.81	8100.92	8121.09	20.17	187.64
7950.44	8171.56	221.12	8121.09	8171.56	50.47	170.65
8401.5	8436.6	35.1	8401.5	8436.6	35.1	0
8402.9	8463.64	60.74	8436.6	8463.64	27.04	33.7
8420.43	8521.06	100.63	8463.64	8521.06	57.42	43.21
8433.39	8576.35	142.96	8521.06	8576.35	55.29	87.67
8679.22	8703.01	23.79	8679.22	8703.01	23.79	0
8690.01	8739.46	49.45	8703.01	8739.46	36.45	13
8878.35	8927.44	49.1	8878.35	8927.44	49.1	0
9115.62	9178.96	63.35	9115.62	9178.96	63.35	0
9125.97	9217.04	91.07	9178.96	9217.04	38.08	52.99
9144.38	9252.79	108.41	9217.04	9252.79	35.75	72.66
9240.18	9287.1	46.92	9252.79	9287.1	34.31	12.61
9293.01	9329.07	36.06	9293.01	9329.07	36.06	0
9305.36	9388.15	82.79	9329.07	9388.15	59.08	23.71
9305.92	9458.36	152.45	9388.15	9458.36	70.21	82.24
9307.2	9523.12	215.92	9458.36	9523.12	64.76	151.16
9316.38	9582.55	266.17	9523.12	9582.55	59.43	206.74
9420.5	9647	226.49	9582.55	9647	64.44	162.05
9540.21	9682.61	142.4	9647	9682.61	35.62	106.78
9604.82	9719.6	114.77	9682.61	9719.6	36.99	77.78
9714.1	9788.35	74.26	9719.6	9788.35	68.75	5.51
9731.06	9811.58	80.53	9788.35	9811.58	23.23	57.3
9744.81	9834.03	89.22	9811.58	9834.03	22.45	66.77
9781.17	9889.91	108.74	9834.03	9889.91	55.88	52.86
9809.04	9920.44	111.4	9889.91	9920.44	30.52	80.88
9810.95	9976.79	165.83	9920.44	9976.79	56.35	109.48
9847.46	9998.67	151.21	9976.79	9998.67	21.88	129.33
9848.94	10048.65	199.71	9998.67	10048.65	49.98	149.73
9924.72	10076.05	151.33	10048.65	10076.05	27.4	123.93
9936.58	10114.57	177.99	10076.05	10114.57	38.51	139.48
9937.72	10152	214.28	10114.57	10152	37.43	176.85
9938.84	10205.08	266.24	10152	10205.08	53.07	213.17

9966.46	10221.34	254.87	10205.08	10221.34	16.26	238.61
9999.33	10261	261.67	10221.34	10261	39.66	222.01
10091.93	10265.76	173.82	10261	10265.76	4.76	169.06
10110.73	10329.52	218.79	10265.76	10329.52	63.76	155.03
10285.71	10388.12	102.41	10329.52	10388.12	58.6	43.81
10394.37	10414.25	19.88	10394.37	10414.25	19.88	0
10453.88	10479.06	25.18	10453.88	10479.06	25.18	0
10484.96	10513.35	28.39	10484.96	10513.35	28.39	0
10558.49	10623.86	65.37	10558.49	10623.86	65.37	0
10727.92	10795.61	67.69	10727.92	10795.61	67.69	0

Table G.5: Two robotic arm simulation data (seconds)

time In	Time out	stay time (Overall)	Time in(Process starts)	Time out	Stay (in system)	waiting time in line
217.2	301.61	84.41	217.2	301.61	84.41	0
414.07	459.34	45.27	414.07	459.34	45.27	0
647.34	709.83	62.49	647.34	709.83	62.49	0
658.17	784.91	126.73	658.17	784.91	126.73	0
684.23	787.91	103.68	684.23	787.91	103.68	0
730.91	838.9	107.99	730.91	838.9	107.99	0
798.75	889.98	91.23	798.75	889.98	91.23	0
817.59	917.55	99.95	817.59	917.55	99.95	0
850.96	967.62	116.66	850.96	967.62	116.66	0
854.66	1019	164.34	890.64	1019	128.36	35.98
858.62	1070.96	212.33	917.55	1070.96	153.41	58.92
897.81	1122.24	224.43	968.25	1122.24	153.99	70.44
1060.66	1173.14	112.48	1070.96	1173.14	102.18	10.3
1112.07	1248.56	136.49	1112.07	1248.56	136.49	0
1202.4	1275.01	72.61	1202.4	1275.01	72.61	0
1213.85	1303.28	89.43	1213.85	1303.28	89.43	0
1216.72	1354.55	137.83	1248.56	1354.55	105.99	31.84
1231.13	1430.53	199.4	1275.49	1430.53	155.04	44.36
1310.77	1457.95	147.18	1310.77	1457.95	147.18	0
1376.36	1533.04	156.67	1376.36	1533.04	156.67	0
1496.59	1536.04	39.44	1496.59	1536.04	39.44	0
1517.39	1562.85	45.45	1517.39	1562.85	45.45	0
1716.75	1801.26	84.51	1716.75	1801.26	84.51	0
1855.27	1946.15	90.87	1855.27	1946.15	90.87	0
1900.99	2021.36	120.38	1900.99	2021.36	120.38	0
2041.94	2104.16	62.22	2041.94	2104.16	62.22	0
2068.8	2107.16	38.36	2068.8	2107.16	38.36	0
2091.08	2157.94	66.85	2091.08	2157.94	66.85	0

2152.58	2240.78	88.2	2152.58	2240.78	88.2	0
2323.82	2392.04	68.22	2323.82	2392.04	68.22	0
2428.51	2474.89	46.38	2428.51	2474.89	46.38	0
2566.68	2674.7	108.02	2566.68	2674.7	108.02	0
2589.19	2701.38	112.18	2599	2701.38	102.38	9.8
2599.6	2728.77	129.18	2616.68	2728.77	112.09	17.09
2610.04	2803.59	193.54	2674.7	2803.59	128.89	64.65
2630.69	2829.77	199.08	2701.55	2829.77	128.22	70.86
2712.54	2857.74	145.19	2728.77	2857.74	128.96	16.23
2857.9	2895.28	37.38	2857.9	2895.28	37.38	0
2943.79	3038.99	95.2	2943.79	3038.99	95.2	0
2957.83	3065.62	107.79	2959.69	3065.62	105.93	1.86
3182.63	3318.12	135.49	3182.63	3318.12	135.49	0
3451.3	3535.39	84.1	3451.3	3535.39	84.1	0
3491.35	3609.39	118.04	3491.35	3609.39	118.04	0
3643.23	3757.79	114.56	3643.23	3757.79	114.56	0
3693.54	3809.53	116	3693.54	3809.53	116	0
3765.74	3836.64	70.9	3765.74	3836.64	70.9	0
3804.1	3888.03	83.93	3804.1	3888.03	83.93	0
3881.81	3970.04	88.23	3881.81	3970.04	88.23	0
3882.32	3996.63	114.3	3893.05	3996.63	103.58	10.72
3888.98	4048.29	159.31	3919.6	4048.29	128.68	30.63
3908.69	4051.29	142.59	3970.04	4051.29	81.25	61.34
3909.52	4127.27	217.74	3997.07	4127.27	130.2	87.54
3958.42	4154.52	196.1	4048.29	4154.52	106.24	89.86
4077.85	4229.72	151.88	4077.85	4229.72	151.88	0
4240.93	4351.29	110.37	4240.93	4351.29	110.37	0
4257.89	4425.14	167.25	4257.89	4425.14	167.25	0
4295.11	4476.52	181.41	4295.11	4476.52	181.41	0
4381.84	4503.78	121.94	4381.84	4503.78	121.94	0
4459.23	4530.42	71.18	4459.23	4530.42	71.18	0
4495.14	4559.18	64.04	4495.14	4559.18	64.04	0
4539.67	4610.18	70.51	4539.67	4610.18	70.51	0
4588.09	4636.9	48.81	4588.09	4636.9	48.81	0
4678.37	4714.59	36.22	4678.37	4714.59	36.22	0
4727.67	4816.27	88.61	4727.67	4816.27	88.61	0
4890.13	4998.68	108.56	4890.13	4998.68	108.56	0
4979.1	5048.44	69.34	4979.1	5048.44	69.34	0
4994.44	5122.54	128.1	4994.44	5122.54	128.1	0
5027.98	5149.98	122	5045.44	5149.98	104.54	17.46
5215.47	5309.52	94.05	5215.47	5309.52	94.05	0
5427.42	5513.01	85.59	5427.42	5513.01	85.59	0
5437.92	5563.5	125.58	5437.92	5563.5	125.58	0

5660.97	5751.49	90.52	5660.97	5751.49	90.52	0
5815.37	5902.6	87.23	5815.37	5902.6	87.23	0
5837.8	5933.02	95.22	5837.8	5933.02	95.22	0
5899.39	6007.5	108.11	5899.39	6007.5	108.11	0
6178.61	6237.15	58.54	6178.61	6237.15	58.54	0
6320.17	6362.85	42.68	6320.17	6362.85	42.68	0
6448.43	6487.77	39.34	6448.43	6487.77	39.34	0
6603.61	6690.22	86.6	6603.61	6690.22	86.6	0
6611.9	6716.67	104.77	6612.57	6716.67	104.1	0.67
6770.01	6860.44	90.42	6770.01	6860.44	90.42	0
6861.41	6905.14	43.73	6861.41	6905.14	43.73	0
6963.25	7006.09	42.84	6963.25	7006.09	42.84	0
7041.79	7132.95	91.16	7041.79	7132.95	91.16	0
7063.99	7209.62	145.63	7063.99	7209.62	145.63	0
7127.67	7237.36	109.69	7127.67	7237.36	109.69	0
7277.03	7374.95	97.92	7277.03	7374.95	97.92	0
7330.92	7401.25	70.33	7330.92	7401.25	70.33	0
7370.38	7428.27	57.89	7370.38	7428.27	57.89	0
7385.66	7454.72	69.06	7387.1	7454.72	67.62	1.44
7410.93	7505.51	94.58	7410.93	7505.51	94.58	0
7443.14	7580.69	137.55	7443.14	7580.69	137.55	0
7560.68	7654.56	93.89	7563.97	7654.56	90.59	3.3
7646.33	7711.16	64.83	7646.33	7711.16	64.83	0
7731.42	7796.34	64.92	7731.42	7796.34	64.92	0
7769.43	7885.68	116.25	7773.91	7885.68	111.77	4.48
7811.87	7888.68	76.81	7811.87	7888.68	76.81	0
7937.05	7996.61	59.56	7937.05	7996.61	59.56	0
7996.67	8061.75	65.08	7996.67	8061.75	65.08	0
8087.46	8176.58	89.12	8087.46	8176.58	89.12	0
8168.53	8204.37	35.84	8168.53	8204.37	35.84	0
8254.2	8342.02	87.82	8254.2	8342.02	87.82	0
8386.06	8450.35	64.29	8386.06	8450.35	64.29	0
8405.47	8453.75	48.28	8405.47	8453.75	48.28	0
8446.73	8561.96	115.23	8446.73	8561.96	115.23	0
8514	8582.14	68.14	8514	8582.14	68.14	0
8535.11	8632.59	97.48	8535.11	8632.59	97.48	0
8643.89	8728.84	84.96	8643.89	8728.84	84.96	0
8688.4	8801.55	113.14	8688.4	8801.55	113.14	0
8987.84	9029.76	41.92	8987.84	9029.76	41.92	0
9042.02	9145.67	103.65	9042.02	9145.67	103.65	0
9150.42	9239.1	88.67	9150.42	9239.1	88.67	0
9295.72	9333.98	38.26	9295.72	9333.98	38.26	0
9375.13	9436.61	61.48	9375.13	9436.61	61.48	0

9381.24	9510.5	129.27	9382.76	9510.5	127.75	1.52
9521.93	9585.7	63.76	9521.93	9585.7	63.76	0
9561.3	9695.34	134.03	9561.3	9695.34	134.03	0
9564.14	9745.78	181.64	9569.93	9745.78	175.86	5.78
9649.55	9748.78	99.23	9649.55	9748.78	99.23	0
9678.38	9872.53	194.16	9695.34	9872.53	177.2	16.96
9710.55	9875.53	164.98	9745.78	9875.53	129.75	35.23
9773.41	9949.94	176.53	9796.87	9949.94	153.07	23.46
9780.21	9977.34	197.13	9872.53	9977.34	104.81	92.32
9838.5	10004.06	165.57	9879.3	10004.06	124.76	40.81
10007.65	10071.13	63.49	10007.65	10071.13	63.49	0
10059.15	10148.01	88.86	10059.15	10148.01	88.86	0
10078.26	10175.48	97.22	10078.26	10175.48	97.22	0
10100.21	10202.57	102.36	10121.04	10202.57	81.53	20.83
10116.58	10253.53	136.95	10148.19	10253.53	105.34	31.61
10136.1	10280.97	144.88	10175.48	10280.97	105.5	39.38
10167.18	10307.91	140.73	10202.57	10307.91	105.34	35.39
10279	10390.27	111.27	10279	10390.27	111.27	0
10343.92	10440.8	96.88	10343.92	10440.8	96.88	0
10466.88	10549.68	82.8	10466.88	10549.68	82.8	0
10496.41	10601.5	105.08	10496.41	10601.5	105.08	0
10527.85	10628.61	100.76	10527.85	10628.61	100.76	0
10528.11	10726.31	198.19	10573.96	10726.31	152.35	45.84
10654.46	10753.59	99.13	10654.46	10753.59	99.13	0
10707.62	10779.93	72.31	10707.62	10779.93	72.31	0
10805.87	10890.45	84.58	10805.87	10890.45	84.58	0
10952.42	10998.26	45.83	10952.42	10998.26	45.83	0
10958.78	11001.26	42.48	10968.26	11001.26	33	9.48
11022.59	11134.26	111.67	11022.59	11134.26	111.67	0
11031.18	11162.01	130.83	11031.79	11162.01	130.22	0.61
11045.63	11212.51	166.88	11058.78	11212.51	153.73	13.15
11066.91	11239.08	172.17	11134.26	11239.08	104.81	67.36
11314.15	11404.44	90.3	11314.15	11404.44	90.3	0
11343.41	11431.73	88.33	11343.41	11431.73	88.33	0
11520.03	11559.01	38.97	11520.03	11559.01	38.97	0
11524.18	11659.11	134.94	11528.51	11659.11	130.6	4.34
11566.88	11662.11	95.24	11566.88	11662.11	95.24	0
11595.69	11737.37	141.68	11595.69	11737.37	141.68	0
11613.8	11835.68	221.88	11659.11	11835.68	176.57	45.31
11669.11	11887.5	218.39	11710.02	11887.5	177.48	40.91
11806.96	11938.42	131.46	11835.68	11938.42	102.73	28.73
11835.11	11988.7	153.59	11845.98	11988.7	142.72	10.87
11840.97	12040.87	199.9	11887.5	12040.87	153.37	46.53

11879.59	12091.58	211.99	11938.42	12091.58	153.16	58.83
11915.11	12118.1	202.99	11989.29	12118.1	128.8	74.19
12057.07	12121.1	64.03	12057.07	12121.1	64.03	0
12101.35	12202.68	101.33	12118.1	12202.68	84.59	16.74
12135.35	12229.81	94.46	12135.35	12229.81	94.46	0