Final Report

Developing an Automated Sandwich Assembly Robot

A Major Qualifying Project (MQP) Submitted to the Faculty of
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Abstract

The objective of this project was to design and prototype a fully automated robotic kiosk for serving fresh, made-to-order meals. The team researched the various mechanical, electrical, and software components necessary to apply assembly line technology from large-scale food-processing plants to a small-footprint kiosk to automate the role of a traditional sandwich shop. The constructed prototype demonstrates the viability of automating sandwich assembly at the point of sale. This project also investigated the additional capability needed to scale the concept to a production-ready product which meets food safety standards as well as the needs of franchise owners. The team believes this prototype attempted to address the current demands of the restaurant industry by reducing labor costs and combating foodborne illness by reducing human contact with food.

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Chapter 1. Introduction

1.1 Market Analysis

Fast food restaurants, also known as Quick Service Restaurants (QSR), represent 50% of the restaurant industry's total sales (Sena, 2017). The Fast Food industry will be referred to as the QSR industry for the remainder of this paper due to the growth of Fast Casual restaurants, which tend to offer better quality food at a higher price point, within the Fast Food industry. This $570 billion industry all started in 1921 in Wichita, Kansas, with the first White Castle restaurant selling miniature sized hamburgers.

1.1.1 Origins of the Fast Food Industry

White Castle is widely regarded as the nation's first QSR restaurant (Hogan, 1997). The restaurant chain, founded in 1921 in Wichita, Kansas, changed America's perception of hamburgers by offering a high quality product in its distinctively branded restaurants. White Castle was one of the earliest pioneers of standardized food production and replaceable works, which helped to propel the success of this fast food pioneer.

In the 1940's and 1950's, White Castle restaurants, which have always remained privately owned, faced significant competition from other fast food restaurants (Hogan, 1997) which relied on franchise models, as well as innovative business practices to capture larger portions of the market. McDonald's, which was founded in 1940, was the epitome of these restaurants. In 1954, Ray Kroc, a commercial mixer salesmen, discovered the McDonald's brothers restaurant and founded the McDonald's System Incorporated the next year. Under Kroc's leadership, McDonald's created an efficient system around a limited menu, focusing on high quality and consistent products. Over the next decades, McDonald's, (along with the QSR industry as a whole) experienced incredible growth, rising from its first family-run location in San Bernardino, California to over 36,000 locations worldwide, as of 2017 (McDonald's, 2017).

1.1.2 Big Players in the Fast Food Industry

As of 2017, the three major players in the QSR industry are McDonald's Corp, Yum! Brands Inc, and Subway, each with a market share of 15.2%, 8.4%, and 4.6% in 2017, respectively (Alvarez, 2017b). These firms primarily rely on a franchise-centric business model, in which independent business owners purchase a right to run a business and pay royalties based off sales to rent. Every Subway store is franchised and the other two companies franchise at least 80% of their locations with plans to increase the percentage to over 90% due to stagnant revenues. This allows these firms to insulate themselves from location-specific losses while expanding. The franchise-centric business model shift can be seen throughout the chain restaurant operators in the QSR industry for both publicly traded and privately held companies. Changes in customer desires has forced these major players to adapt their marketing and menus to protect their market share and revenue, specifically with the desire for better quality, healthier options that Fast Casual restaurants like Panera and Chipotle offer (Alvarez, 2017b).

1.1.3 Current Trends of Fast Food Industry

Customers increasingly desire healthy fresh foods along with information about nutrition content and how eating habits affect weight and other long term health issues. The desire can be seen in the growth of Fast Casual restaurants, major players adding healthy options to their menus, and the increase in the Healthy Eating Index (Alvarez, 2017a). Fast Casual is the fastest growing segment of the restaurant industry, seizing market share from the traditional Fast Food industry due to the perceived healthier options and diversified menus that these restaurants offer (Sena, 2017).

Convenience and speed were traditionally seen as fast food's advantages over Fast Casual, but increasingly Fast Casual restaurants have added drive-throughs and online ordering to close the gap. Panera was one of the first Fast Casual restaurants to have success with their drive throughs and others have now followed suit (QSR Magazine, 2017). The QSR industry is beginning to integrate technology such as online ordering and self-ordering kiosks that assist with order accuracy and minimizing food waste.

1.1.4 Present Challenges of the Fast Food Industry

Some challenges that have cropped up in the QSR sector include perception of unhealthy menus, poor working conditions, low wages. One of the most challenging aspects to overcome for traditional fast food restaurants has certainly been their unhealthy perception. Decades of menu reconstruction, transparent calorie advertising, ingredient changes, and healthy substitution options have all played a role in curbing the stigma. Yet most fast food is still high in sugar, fat, and salt which can lead to health conditions such as cardiovascular disease (Franchise Help, 2017), the leading cause of death in the U.S. for both men and women (Nichols, 2017). And with the average American diet consisting of 11% fast food (Ervin, R. B., & Fryer, C. D., 2013), the unhealthy perception is also a significant factor why individuals are gravitating to fast casual over the traditional fast food counterpart.

The QSR industry is heavily reliant on low wage workers, and in fact the restaurant industry employs most near-minimum wage workers of any industry, commonly in the roles of cooks and cashiers (Alvarez, 2017a). Due to the large staffing requirements and quick turnover in these workplaces, there are substantial costs for human resources to staff chefs, busboys, and cashiers with wage costs representing 24.9% of total revenues (Alvarez, 2017a)(Franchise Help, 2017). This heavy reliance on low-wage workers poses a threat to the QSR industry in the face of rising minimum wages. Even if staffing requirements remain stable, wage costs are projected to significantly rise as 19 states entered 2017 with higher minimum wages than the previous year. A number of those states will continue to increase the minimum wage with some states implementing increases of nearly 50% over the next 5 years. This has the potential to shrink or even eliminate the 5.3% profit margin in the QSR segment due to the vast number of employees affected (Alvarez, 2017a). As a result, QSRs including McDonald's, Wendy's and Panera Bread are already looking into automation of human roles as a potential solution to rising labor costs (Alvarez, 2017a).

1.2 Automation in the Fast Food Industry

1.2.1 Automation in Food Processing

The seasonal and perishable nature of food products, often combined with low profit margins, makes the food industry a particularly difficult industry to automate. The industry is diverse and utilizes many different types of systems depending on the food types. Overall, there is a general lag in automation based on the variety of food types. According to food processing experts and robotics engineers at the Italian Institute of Technology and Sheffield University, the number of people willing to work for low wage food processing jobs will decline substantially over the next 3 to 10 years (Caldwell, Davis, Moreno Masey, & Gray, 2009). As a result, food processing companies are attempting to to automate many industrial processes to improve production, reduce waste, enhance hygiene standards, and improve quality. For example, in the dairy industry, the use of robotic milkers have increased milk production, lowered labor costs and even increased the health of the cow (Nayik, Muzaffar, & Gull, 2015).

End-of-line processing is currently one of the most developed areas of automation in the industry. Technology development in weigh stations, labeling machines and palletizing systems have emerged as few of the most efficient technologies in the food supply chain process. Examples of robots that are currently being used today include the Bosch Sigpack Delta robots, the FANUC LR Mate 200iB food robot, Gerhard Schubert's TLM-F4, and the ABB IRB 340 FlexPicker, which is one of the most common robotic systems in high-speed pick-and-place applications and well suited to handling wrapped food products (Caldwell, Davis, Moreno Masey, & Gray, 2009). The integration of these robotic systems have greatly increased efficiency and reduced the need for undesirable low wage jobs.

The design of end effectors, the manipulators at the end of robotic arms, is another critical developing area of automation. Since food can become damaged easily if not handled correctly, there is a real need for dexterous grippers to manipulate food delicately enough to prevent damage. While it is sometimes possible to solve such problems using a more intelligent or dexterous general purpose system, oftentimes a simple tool designed specifically for the given task is a successful method for automating complex food processing tasks. These systems are often cheaper and easier to manufacture. For example, Moreno Masey, a robotic engineer at the University of Salford, Manchester, investigated the possibility of automating microwave-ready lasagna meals and developed a custom method based on the simple rolling action common in pasta making. The machine is sufficiently simple and low cost that nine identical machines could be used to produce microwave-ready meals at a typical production rate of 60 per minute (Caldwell, Davis, Moreno Masey, & Gray, 2009).

Lastly, many automation systems utilize some form of a controller. Industrial and manufacturing machines generally rely on the use of an industry standard programmable logic controller (PLC) to control basic process functions. Sensors, drivers, and vision systems are all controlled in these machines by the PLC. Many of these machines also have a Human Machine Interface (HMI) touch screen which is used to operate the machine and give feedback on certain systems if maintenance is needed.

1.2.2 Modern Attempts at Automation in QSRs

In 2013, a study by the University of Oxford attempted to forecast the landscape of future employment by predicting automation potential for over 700 job categories. The study estimates that the category of "Combined Food Preparation and Serving Workers, Including Fast Food" faces a 92% chance of becoming fully automated in the next few decades (Frey & Osborne, 2017). For "waiters and waitresses" (94% chance of automation), and "cashiers" (97% chance of automation), automation is already well underway. In February 2017, *The LA Times* reported that Wendy's would automate cashier positions in 1,000 of its restaurant locations by the end of the year using touchscreen self-ordering kiosks (Shan Li, 2017). McDonald's and Panera Bread have announced similar initiatives. This new focus on automation has also led to the rise of startup QSRs designed around semi-automated processes.

Eatsa, a San Francisco-based restaurant chain, is one such startup–a semi-automated restaurant that allows customers to order quinoa bowls through touchscreen kiosks and then pick up their food at automated lockers. Behind the scenes, Eatsa employs human workers to prepare the food, but is looking to employ an increasing amount of automated food-prep, as the company grows. Eatsa is seen by some as the modern day revival of the *automats* of the early 20th century. Automats are a now defunct restaurant concept in which simple food is served by vending machines (Schlossberg, 2015).

Zume Pizza is a Silicon Valley pizza restaurant that employs industrial robots alongside human workers to automate repetitive and dangerous tasks and deliver pizza more efficiently and precisely. The company delivers their pizzas to the Silicon Valley area using delivery vans with onboard ovens to automatically reheat pizzas before arrival (Zume Pizza).

With point-of-sale automation nearing maturity, the QSR industry is now shifting towards automating food preparation positions. Several startup companies have attempted to capitalize on modern advances in robotics to create restaurants which are almost completely automated. These startups are beginning to receive media attention and investment, but have yet to reach significant market penetration.

CafeX is a San Francisco-based fully-automated coffee shop kiosk that uses an industrial robotic arm to brew and serve high quality coffee, for a cheaper price than comparable shops like Starbucks, and in a much smaller footprint (Cafe X: robotic café in san francisco.).

Spyce is another automated QSR startup, which was founded by a group of MIT students in 2015. Spyce built an automated fast food kiosk that serves complete meals by incorporating rotating heated drums which cook the food to order. The company focuses its menu around dishes which do not require robotic dexterity, such as bowls of pasta and grilled meats and vegetables. The kiosks can produce roughly half as much food as an average fast food restaurant in a small floor plan, using fresh ingredients (Tietjen, 2016). While the startup has received $2.5 million in investment, they have yet to deliver production-ready kiosks to any locations, outside of a short pilot program at MIT.

BistroBot was a startup focused on automated sandwich assembly, founded by two Silicon Valley engineers. The company's robotic assembly line could produce simple peanut butter and jelly sandwiches, with the goal of later producing more complex sandwiches (Lucas Matney, 2016). The startup received a $150,000 investment but shut down in 2016 (Bistrobot.).

Chapter 2. Relevant Art

2.1 Automation Potential in the Sandwich Industry

The growing fast food market is in need of healthy fast food options. In the U.S. the second largest fast food restaurant is Subway and they have been at the forefront of advertising towards the health-conscious demographic (Alvarez, 2016). Subway has recently faced lackluster demand for its menu and overall presentation resulting in slower global expansion (Alvarez, 2017b). As a result, new competitors have entered the market and developed rapidly. According to IBISWorld's report on national sandwich and sub store franchises, "Smaller chains, such as Jimmy John's, Firehouse Subs and Jersey Mike's, have proven that Subway is not the only sub store franchise that can grow quickly. All three have undergone rapid growth and increased their market share over the past five years by chasing a defined segment of the market (Alvarez, 2016)." Now that the economy is bouncing back from the recession there remains a need for for customers to find franchises with healthy, tasty, and quality sandwiches.

The sandwich and sub franchise industry has reached a mature point in market growth but is forecasted to grow 1.6% annually (Alvarez, 2016). A more underdeveloped area of growth can be seen in the technology changes within the industry. Advancing technology has the potential to improve order-processing systems, cooking equipment and food preparation within the industry but has not been fully taken advantage of. Since sandwiches consist of many ready-to-eat ingredients, that do not require cooking, the assembly required for creation can be simple and provide a prospective process for automation. As we progress through our project we will have to make sure to keep our components simple and even look at other sandwich assembly components that were successful to develop our own system.

2.2 Existing Strategies for Automating Sandwich Assembly

When it comes to automating sandwich assembly, simple human tasks such as slicing bread, placing ingredients, and adding sauces and spreads require robotic systems to integrate advanced motion control in order to fully automate the process. However, examples of such systems do exist in industrial environments. British food manufacturer, Uniq plc, uses industrial robots to automate the entire process from buttering to packing sandwiches but operates most successfully for products with paste fillings, like chicken salad (Davis, King, Casson, Gray, & Caldwell, 2007). Also, a study on Automated Handling, Assembly and Packaging of Sandwiches from IEEE's International Conference on Robotics and Automation found through observation of sandwich assembly lines and discussions with operators that it was apparent that the most difficult sandwiches to construct were those consisting of many discrete components (Davis, King, Casson, Gray, & Caldwell, 2007).

Pick and place applications in sandwich assembly have historically been difficult to automate due to the non-rigid and varying sizes of a majority of food products. For example, in a United Kingdom sandwich factory, cucumbers and tomato slices are put into bins and manually placed on sandwich bread by an operator because of the difficulties robotic end effectors have with these types of ingredients (Davis, Gray, & Caldwell, 2008). One solution for soft materials is to implement an end effector that utilizes the Bernoulli effect of suction to grip materials like fruits and vegetables. The University of Salford designed an industrial robot arm and vision system with a suction end effector, which placed vegetable slices on the sandwich in the correct position regardless of their original position on the conveyer (Davis, Gray, & Caldwell, 2008). As a result, a pick and place system was successfully implemented without damaging non-rigid ingredients.

Vision systems can also be used to improve the hygiene of robotic handling by monitoring food contact surfaces for food residue. These systems, which use portable fluorescence image detection, have been found to be particularly useful in maintaining cleanliness in industrial deli slicers. The study conducted by the University of Maryland concluded that it was even impossible to fully clean deli slicers without the assistance of the imaging device to direct cleaning efforts (Beck, Lefcourt, Lo, & Kim, 2015).

In the pre-packaged sandwich segment, companies have seen success with automating nearly the entire assembly process–from buttering bread and adding toppings to cutting the sandwich and packaging the sandwich into boxes. The company Lieder, in collaboration with university researchers, published a frequently cited paper on their industrial assembly line process for pre-packaged sandwiches. Lieder saw success in automating many of the components that go into the assembly (Davis, King, Casson, Gray, & Caldwell, 2007). The mechanism went through in depth studies for every component including toppings, optimum cutting alignment, clapping (packaging) and cooking the sandwiches in skillets. The benefits of this system for manufacturers include reduced labor costs, and improved product quality and hygiene (Davis, King, Casson, Gray, & Caldwell, 2007).

Outside of pre-packaged sandwich automation, as seen in Lieder's machine, there are few examples of automating the entire sandwich assembly process. Furthermore, automating the assembly process for restaurant-grade sandwiches is a field that has remained largely untouched.

2.3 What can be Improved

One potential obstacle to fully automated restaurants laws and regulations on health and safety of the machines. In the United States the Food and Drug Administration (FDA) set standards for food processing while other agencies like NSF International provide actual certification that food industry equipment meets public health and safety standards (NSF International, 2017). Additionally, food serving establishments must also meet public health and safety standards. Organizations like ServSafe help educate food handlers and certify their knowledge of food safety practices (ServSafe, 2017). Most of these food safety standards were designed with human workers in mind, and as a result, fully automated systems do not have a precedent to follow. Many of the food safety certifications are regulated at the state and county level. Some states, including Massachusetts require that a certified food safety manager be onsite during business hours, while in others states, such as New York, regulate food safety certifications at the county level. In the vast majority of New York counties, food safety certification is voluntary (ServSafe, 2017).

Another issue, is that many complex automated systems face difficulties with cleaning. Since sandwich automation has many different components, the cleaning and sanitation aspect to the system is intensive. According to the FDA, deli slicing equipment should be cleaned and sanitized at least every 4 hours to prevent disease-causing pathogens (U.S. Food and Drug Administration, 2017). Despite the FDA's recommendation, inspections have shown that very few food serving establishments clean their deli slicers to the standard (Poitz, 2009). So while this constraint poses a challenge, it is also a potential area where automated systems with integrated cleaning could outperform human workers.

Lastly, consumer comfortability with automated food preparation is a potential area of concern. A recent customer survey conducted at the automated robotic trade show in Chicago studied consumer comfort levels with automated tasks. Around 23% of respondents said they were uncomfortable with robots preparing their food (Clinton, 2017). To put it in perspective, 65% of respondents were uncomfortable with flights being automated and 56% percent were uncomfortable with autonomous cars (Clinton, 2017). On the other hand, consumers were found to be largely comfortable with robotic vacuums (9% uncomfortable) and lawnmowers (18% uncomfortable) (Clinton, 2017). Therefore, it is important to consider the emotional and aesthetic aspects of automated food preparations systems, in order to establish trust in a market that may not be totally comfortable with these systems.

2.4 Customer Discovery

In order to better understand the potential market of food automation our team participated in the Accelerate WPI program for customer discovery. We conducted 40 interviews with potential customers and industry experts. We interviewed managers at local hotels, upper management from college dining services, NSF representatives, founders of other food automation startups, students, and many restaurant operators.

Through the Accelerate program, two of the team members had the opportunity to travel to Austin, Texas and attend the National Restaurant Association's 2017 Restaurant Innovation Summit. The 3 day conference was comprised of networking, panel discussions, presentations, and pitches on where the industry was heading. Overall the key takeaways were that the increasing minimum wage was poised to disrupt the low margin industry and companies needed to devise new strategies to survive.unique quality product, increasing efficiency of their point of sale systems, expand delivery capabilities to reach new customer bases, leverage automation of equipment to reduce the companies employee force and more.

The team directly talked with Dorothy Cudia VP of engineering for Chowbotics, pioneer of the Sally, the salad dispensing robot. Dorothy gave the team insight on the challenges with creating an automated kiosk and explained timing of implementing such a system would be the largest challenge. The company that can leverage customer excitement with comfortability of buying from their product will succeed.

We also talked with the founder of a failed startup which had attempted to build an automated sandwich kiosk. He provided insights into two key areas. He explained that the most challenging aspect of the project was not the engineering challenge, but rather finding customers and designing to meet local and federal food safety regulations.

Overall, the team leveraged the interviews to gain a better understanding of the industry, and of the complex challenges involved in implementing this type of system. In order to make the project more feasible, the team realized the need to search for simpler sub-problems to solve, which would potentially provide value and revenue before the overall system is complete.

Chapter 3. Design

3.1 System Design

3.1.1 System Design Requirements

The overall vision for this project is to develop and implement a fully automated kiosk that can assemble and sell made-to-order toasted sandwiches using fresh, high quality ingredients. This ideal model will be able to produce multiple sandwich types and include everything from meats, cheeses, vegetables, condiments, and a heating feature. The model would refrigerate all perishable ingredients and would be capable of self-cleaning all food-surfaces. The machine would ideally be able to run continuously for a normal workday without human intervention, and would be serviced once a day by a sole employee. This employee would clean any surfaces or containers which cannot be automatically cleaned and restock the ingredients. The kiosk would feature a compact footprint allowing it to be deployed to locations where traditional restaurants could not operate, such as university dormitories and office buildings, as well as high-traffic areas with the need to efficiently serve a large number of people, including mall food courts and workplace cafeterias. Finally, this ideal system would likely include other features necessary for safe autonomous operation as a restaurant, which could include ventilation, theft protection, a backup power system, and waste disposal.

Due to time and financial constraints, the team will not realistically be able to achieve our full vision for the kiosk over the course of this research project. However, the project will offer the opportunity to work toward constructing a minimal viable product (MVP), which contains the minimum feature set needed to prove the viability of the concept, begin testing, and attract the attention of further investors who can support the project through its later phases.

Our team defined our minimum viable product as a system that can produce a toasted cheese sandwich for the end customer. The team's objectives, that will guide the team through the MQP process, are as follows:

1. Develop a modular, expandable skeleton that can support the addition of features in the future
2. Develop the novel modules–solving the important pieces upon which the project depends, not reinventing the wheel
3. Develop the other modules needed to form a working minimum viable product (MVP) that demonstrates the basic operation of the overall system

We will be identifying, designing, and prototyping the core technologies of the automated food service kiosk, and possibly implementing stretch goals (goals that the team may have time for within the MQP period. Not to be confused with Phase II goals that will occur after MQP) depending on our team's success. The four core focuses can be achieved by considering the design requirements, design concepts, prototyping, and testing of four key areas of focus: System, Mechanical, Electrical, and Software. Each section will go into detail how the objectives can be satisfied and the particular approach the team seeks to implement for phase I prototype of the sandwich assembly robot.

MQP Goals

- **Expandable skeleton that can support the addition of features**
- **Develop the novel modules**

    - Slicing Mechanism
- **Develop a working minimum viable product (MVP) that demonstrates the basic operation of the overall system**
    - Must create a grilled cheese
- **Sizing**
    - The system will be limited to the size of two pallets (Two 48" x 40" areas) so that transport of the entire assembly is manageable
    - The system will also be constructed on 3 foot tall tables so that the assembly may be viewed by people in wheelchairs, children, and adults. additionally the table will allow for the space for a sanitation station below the assembly that is out of view of the customer and separate from the food.
    - The 2 tables will be built so that they can come apart without interfering the with top system setup an so that they can be locked together and not come apart when the system is setup and producing sandwiches.

If more time presents itself in the project the team will look into developing the following stretch goals. Phase II goals were also included to give a better understanding of where the team wishes to take the project after the conclusion of the project. If the team does not address the stretch goals within the time of the MQP they will be tacked onto the Phase II goals for future research.

Stretch goals

- Security System

Phase II goals

- **Food Equipment and Processing Design**
    - Verify FDA/NSF requirements
        - clean surface every 4 hours
        - Shape and Structure Design should meet safety standards where food contacts surfaces
        - Material Design should comprise of materials that are easy to clean and hygienic
    - ServSafe food safety Requirements
- Box Dispenser
- Refrigeration Unit
- Fire Suppression system
- Aesthetically pleasing redesign
- Manufacturing Analysis
- Shipment Analysis

3.1.2 System Design Mockups

Figure 1 and 2 give you a general understanding of the overall system package size we envision along with where particular subsystems are envisioned to go in such an envelope.

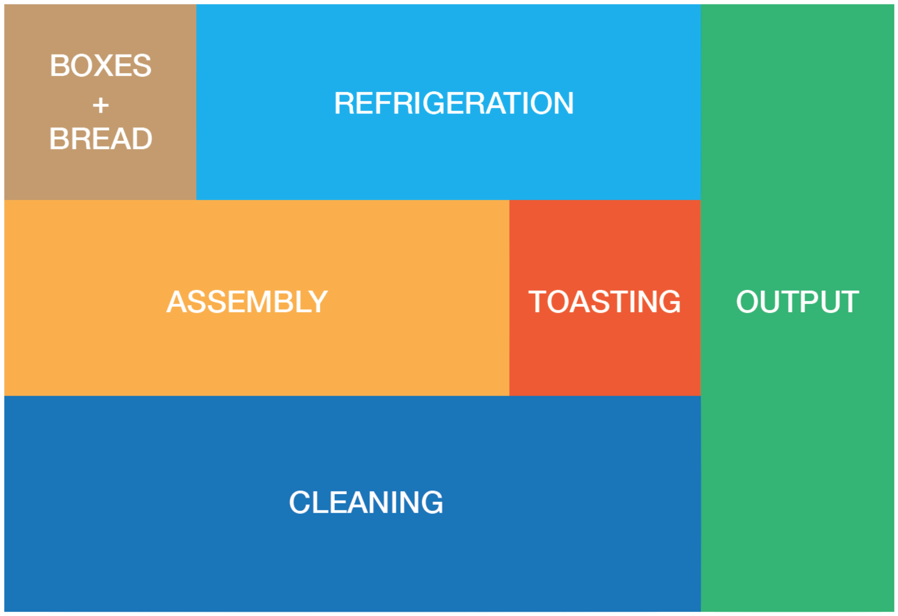


Figure 1: Initial Conceptual Sandwich Kiosk Space Distribution

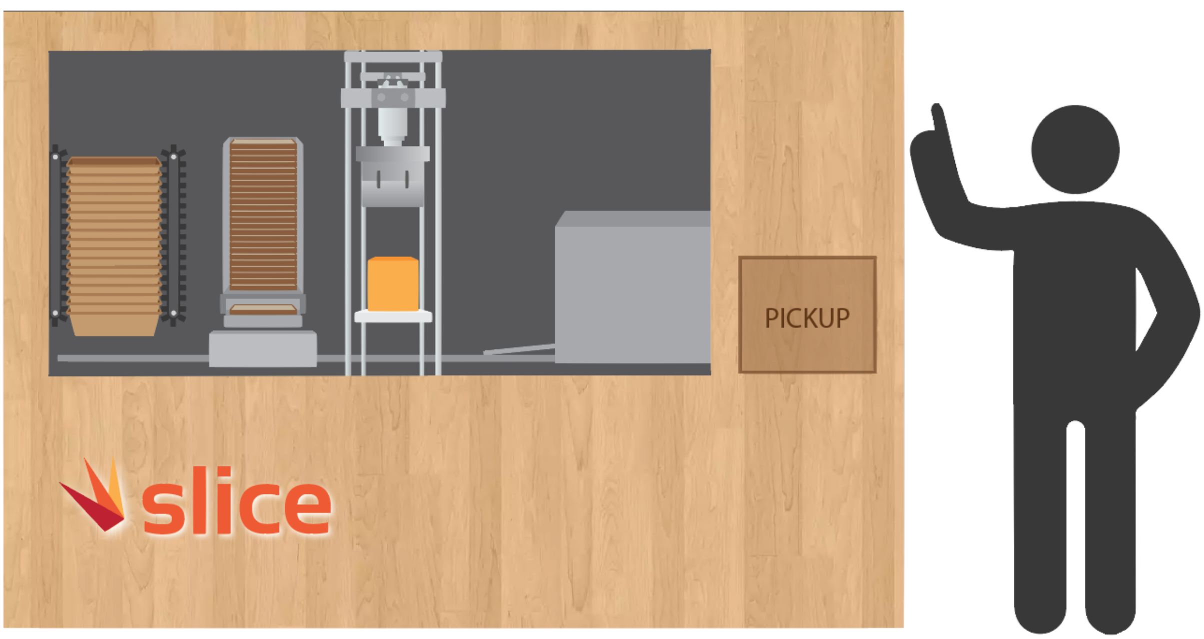


Figure 2: 1:20 Scaled Sandwich Kiosk Mockup

A combined diagram showing the interactions between the mechanical electrical and software systems can be see in *Figure 3*. The mechanical modules function as the backdrop of the picture, while an overlay of the electrical system provides a view of the wiring between the central controller, actuators, and sensors.

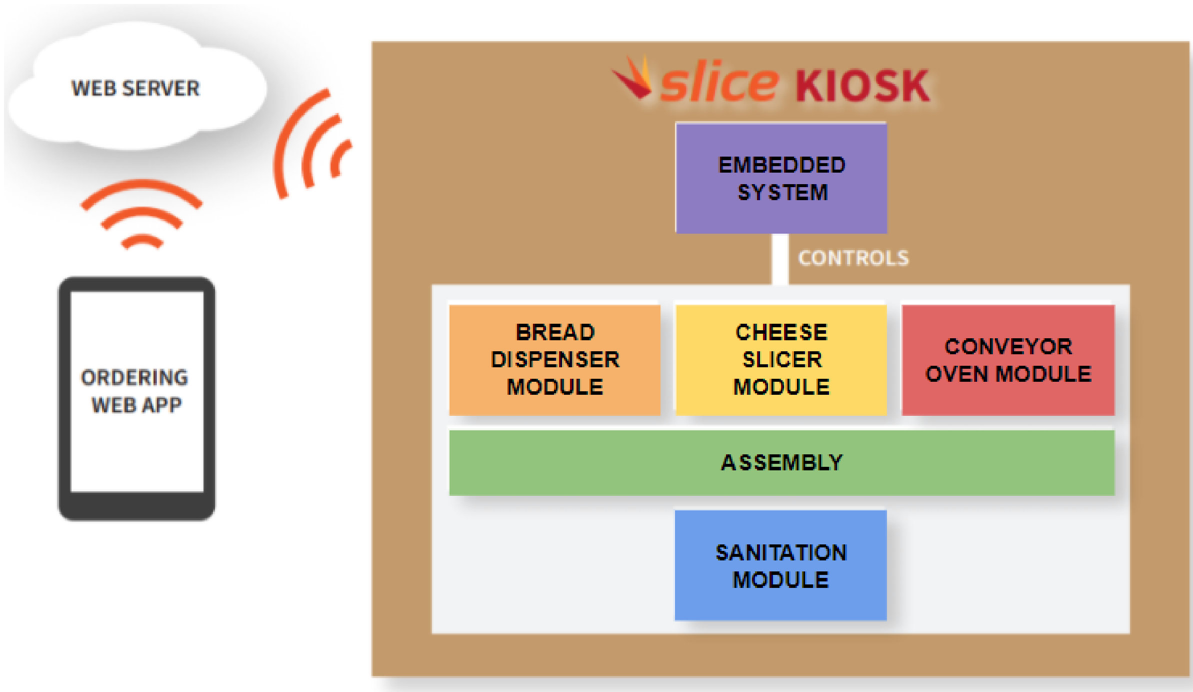


Figure 3: Final Full System Diagram

3.1.3 System Prototyping

Below is a 3D rendering if the system design using the CAD software Onshape. It's clear that the total assembly fits within the 2 pallet sizes, is elevated to the 3 foot level for optimum viewing and underneath there is a simple latching system to secure the table tops together. with that in mind all sizing requirement MQP goals are satisfied and have been adequately addressed. Therefore the final build can commence.

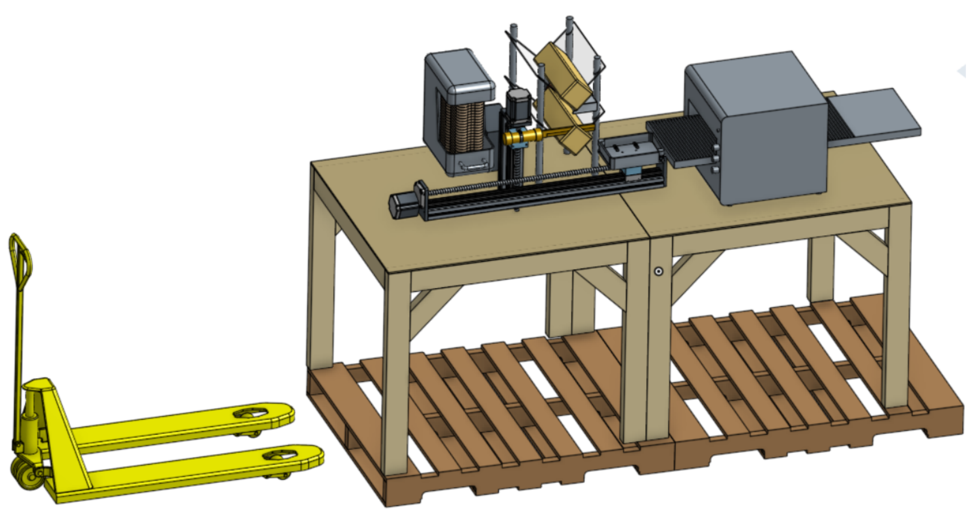


Figure 4: 3D Model of All Mechanical Systems

3.2 Mechanical Design

3.2.1 Mechanical Design Requirements

The mechanical design specifications include specs for the four key technologies and also two additional sections with stretch goals and phase II goals. If the team ends up finding extra time in the MQP project and have satisfied the four core technologies, the team will determine which reach goal to incorporate into the project next. The phase II goals include post-MQP objectives that the team wishes to pursue after MQP.

MQP Goals

- **Slicer for meats and cheeses**
  - Slicer must satisfy cleaning FDA requirements (clean surface every 4 hours)
  - Must be able to run 24 hours continuously
  - Must handle irregular meat/cheese geometries
  - Clean cuts with minimal debris created
  - Easy to clean
  - Aesthetically pleasing
  - Shape and Structure Design should meet safety standards where food contacts surfaces
  - Material Design should comprise of materials that are easy to clean and hygienic
- **Develop heating system**
  - Must be capable of heating all parts of the sandwiches to 160° F to act as a last stage method for eliminating listeria and other foodborne pathogens
- **Assembly Line System**
  - Must transport sandwich and container from module to module
  - Close proximity to slicers and dispensers to limit food from falling off bread
  - Shape and Structure Design should meet safety standards where food contacts surfaces
  - Material Design should comprise of materials that are easy to clean and hygienic
- **Bread Dispenser**
  - One slice at a time
  - Can hold at least an entire loaf of bread
- **Heat-Proof Boxes**
  - Withstand heat of heating system

Stretch goals

- Sanitation System
- Box dispenser
- Vegetable Dispensers
- Refrigeration units

Phase II goals

- Heated lockers to hold sandwiches waiting for pickup
- Condiment Extruders

Mechanical Component Selection

A comprehensive table of the mechanical designs that were explored in creating the automated sandwich assembly can be found in Appendix A. The components are split up into 10 main design types: motion, packaging, refrigeration, slicers, dispensers, extruders, heating mechanisms, fixtures, guides, and sanitation. Each design includes a picture, some pros and cons that came up in discussion through preliminary design brainstorming, and materials required to incorporate the design into the full assembly. Because of the nature of the design brainstorming, the team explored all avenues of the assembly including aspects in the reach goals and phase 2 goals.

Mechanical Decision Matrix

For consistency across rating the various mechanical systems, each design was rated based on the eight categories shown below. A description, the numeric criteria, and rating factor is shown for each design. The description gives a better understanding of what the category represents, the numeric category gives the team specific values to rate particular systems to be as unbiased as possible. Additionally the team understands that some values had to be assumed since the design is not constructed, however from online research and deliberation among the team, the best value for each category was found at the time of narrowing down particular design considerations. And finally a rating factor was used to add more weight to categories the team felt were more important to the overall design of the assembly.

Table 1: Rating Criteria for Mechanical Design Rating

Categories	**Description**	**Numeric Criteria**	**Rating Factor**
Reliability	Will not jam and can land on a slice of bread repeatedly	1 = Functions for less than 12 hours without maintenance 2 = Functions for 12-24 hours without maintenance 3 = Functions for more than 24 hours without maintenance	2
Smoothness (SMO) (Slicers only)	Slice is smooth cut and meat/cheese does not come out in crumbles.	1 = Slice has noticeable crumbles and or ridges 2 = Slice may have ridges but appears smooth and does not produce any debris 3 = Slice is smooth and no noticeable debris created	1.5
Size(SIZ)	Overall size of mechanism	1 = Volume covered is over 30 X 30 X 30 inches 2 = Volume covered is 10 X 10 X 10 to 30 X 30 X 30 inches 3 = Volume covered is under 10 X 10 X 10 inches cubed	1
Aesthetic (AES)	Looks appealing for sale	1 = Customer does not think design is appealing 2 = Customer is Indifferent 3 = Customer finds design appealing	0.25
Simplicity (SIM)	Ease of building	1 = Fully design and build 2 = Utilize parts / subassemblies of other products 3 = Existing product	1.25
Cleanability (CLE)	how easy the device is to clean	1 = over 5 surfaces 2 = 3-5 surfaces 3 = 3 or less	1.75

Cost (COS)	Purchase price	1 = over $400 2 = $200-$400 3 = $200 or less	0.75
Sound(SOU)	How much noise the design produces	1 = Is noticeably noisy and disrupts normal conversation 2 = Can be heard but not annoying 3 = not noticeable	0.5

Below is the decision matrix that includes the resulting values for every design. each value is multiplied by the specific rating factor for the category and its total score is summed to the right most column labeled "Total". The decision matrix outcomes were then discussed with the team.

Table 2: Decision Matrix of Mechanical Designs

Design Type	Design	REL	SMO	SIZ	AES	SIM	CLE	COS	SOU	Total
Motion	Linear Slide	3		1	3	3	3	2	3	19.75
	Conveyor	3		1	2	3	3	1	2	18.25
Packaging	Printer Style	1		2	2	2	3	3	2	15.5
	Roll and Cut	2		2	2	2	3	3	3	18
	Box	3		2	2	1	3	3	3	18.75
	Origami Folded Container	2		2	3	1	3	3	3	17
	Plate	3		2	2	2	3	3	3	20
Refrigeration	Modular Refrigerator	3		1	3	2	2	3	3	17.5
	Entire Refrigerator	3		1	3	2	2	3	3	17.5
Slicers	Deli Slicer	1	3	2	3	2	1	1	2	15.25
	Electric knife	3	2	3	2	2	3	3	2	23.5
	Ultrasonic Food Cutter	3	3	2	2	3	3	1	3	24.25
	Wire Slicer	3	2	3	3	3	3	3	3	25.5
	Potato Slicer Table	2	3	3	3	3	2	3	3	23.25
	Spiral Potato Peeler	2	2	2	2	2	2	2	3	18.5
	Food processing blades	2	2	2	2	3	3	2	1	20.5
	Ultrasonic Vibration Band-Saw	3	3	2	2	1	3	2	2	22
Dispensers	Cereal Dispensers	3		2	3	2	3	3	3	20.25
	Bread Dispenser	3		2	3	3	3	3	3	21.5
Extruders	Spring Action Extrusion	3		3	2	1	3	3	3	19.75
	Motor Powered extrusion	3		3	2	3	3	2	2	21

	Pneumatic Extruder	3		3	2	2	3	3	3	21
	Panini Press	3		1	3	2	3	1	3	17.75
Heating Mechanism	Conveyor Oven	3		1	2	3	3	1	3	18.75
	Meat Hooks	3		3	1	3	3	3	3	22
	Tac Clamp	3		3	2	2	2	3	2	18.75
Fixtures	Suction Cup	3		2	2	2	3	3	3	20
	Funnel	3		3	2	3	3	3	3	22.25
	Pneumatic Clamps	3		2	1	2	1	2	2	15
Guides	Tube	3		3	3	3	3	3	3	22.5
	Cleaning Manual	3		3	2	1	3	3	3	19.75
	UV Light	3		2	2	2	3	2	3	19.25
	Vacuum Sealed Assembly Area	3		1	2	2	3	2	2	17.75
Sanitation	Rinsing Nozzles	3		3	2	2	3	2	1	19.25

Sensitivity Analysis

The team understands that the decision matrix is a good way to compare multiple criteria across various designs but not every aspect can be adequately captured by the matrix. Regardless of the matrix outcomes, the team had in depth discussions to validate the design we would move forward with. It so happened that most of the highest scoring designs were chosen to be the team's final decision except for the packaging and slicer design

Slicer

The team decided to move forward with the ultrasonic food cutting blade because of how consistently it can cut all deli meats, cheeses, and vegetables when compared with wire slicers. These ultrasonic food cutting systems consist of a titanium blade attached to a piezoelectric ultrasonic transducer. When the blade vibrates at a frequency between 20 kHz and 40 kHz, the coefficient of friction is reduced and the blade can cut easily through a variety of food products. These blades also exhibit a self cleaning action–they produce very little waste product and residue (Alibaba.com, 2017).

Coincidentally, ultrasonic cleaners, which are often used to clean jewelry, tools, and surgical equipment operate in a similar manner and in the identical frequency range. These cleaners usually consist of piezoelectric transducers attached to or suspended in a tub of water and detergent. Through a process called cavitation, the ultrasonic waves create small air bubbles that implode, creating a very efficient cleaning action that reaches deep into cracks and pockets on the surface of the item being cleaned (Morantz Ultrasonics, 2017). The team believes that by lowering the ultrasonic blade into a vat of water, detergent and sanitizer, and then activating the transducer, as seen below in *Figure 6*, the blade would exhibit a similar cleaning action to ultrasonic cleaners.

Packaging

The team also chose to move forward with the box packaging instead of the plate because of its ability to seal the sandwich for transport on the go. The team settled on the agreement that the bottom of the box packaging would be utilized (like the plate) and sealing/adding the cover would be added as a reach goal.

Fixtures

The thought behind using a meat hook to fixture the meat in place was to lower and raise the meet easily while reducing the contact surfaces with the deli product. To reduce rotation of the deli product and shifting left and right, the hook could not stand alone and would require side rails or guides to guide the deli product to the slicing mechanism to deliver a consistent slice everytime. With that in mind, the team decided to stray away from the hook idea and move to a flat surface with an extruding component behind the meat/cheese. since the meat hook idea would require a surface anyway, the hook never really provided any advantage over a simple table top.

Table 3: Final Mechanical Design Decisions

Design Type	Highest winning Design	Team's Final Decision
Motion	Linear Slide	Linear Slide
Packaging	Plate	Box
Refrigeration	Modular or Entire Refrigeration	Modular Refrigeration
Slicers	Wire Slicer	Sonic Vibration
Dispensers	Bread Dispenser	Bread Dispenser
Extruders	Motor, or Pneumatic Extruder	Motor Extruder
Heating Mechanism	Conveyor Oven	Conveyor Oven
Fixtures	Meat Hook	Surface
Guides	Tube	Tube
Sanitation	Cleaning Manual	Cleaning Manual

3.2.2 Preliminary Mechanical Design Mockups

After working through the design specs, and deciding which concepts to move forward with, the team generated a final assembly mockup. Below you can see the Space distribution of the Sandwich Kiosk, a 1:20 scale representation of the assembly, the Bread Dispensing mechanism, the slicing mechanism in the upper most pre-slicing position and lowermost rinsing position, a potential cheese fixture and feeder to the ultrasonic slicer, and the dual rail concept demonstrating assembly slides constructing the sandwich and the cleaning slides below bringing the rinsing reservoir to where it is needed.

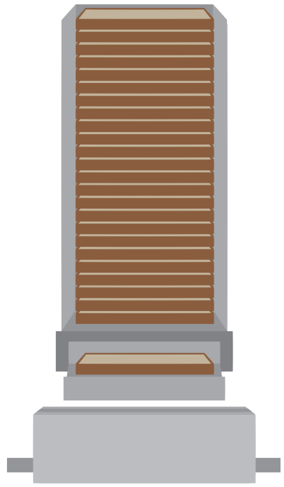


Figure 5: Bread Dispenser Mechanism

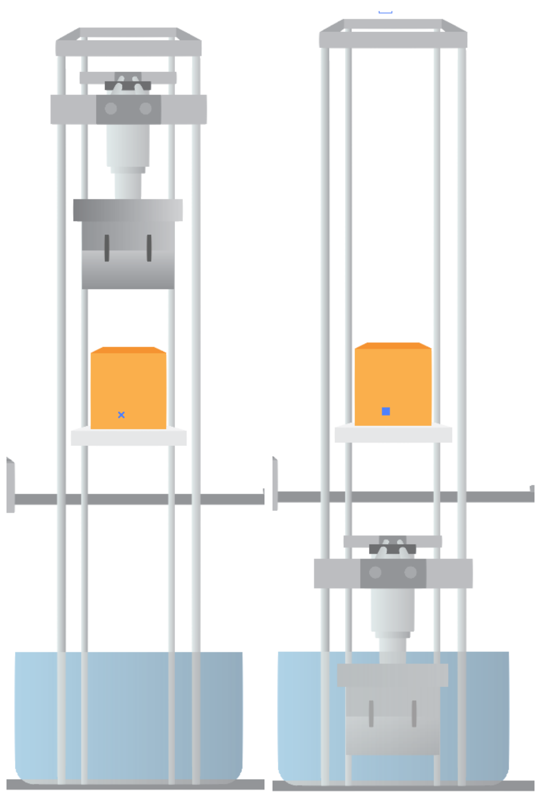


Figure 6: (Left) Pre-slicing Position of Ultrasonic Food Cutter (Right) Rinsing Cycle Position of Ultrasonic Food Cutter Below Cheese Feeding Mechanism

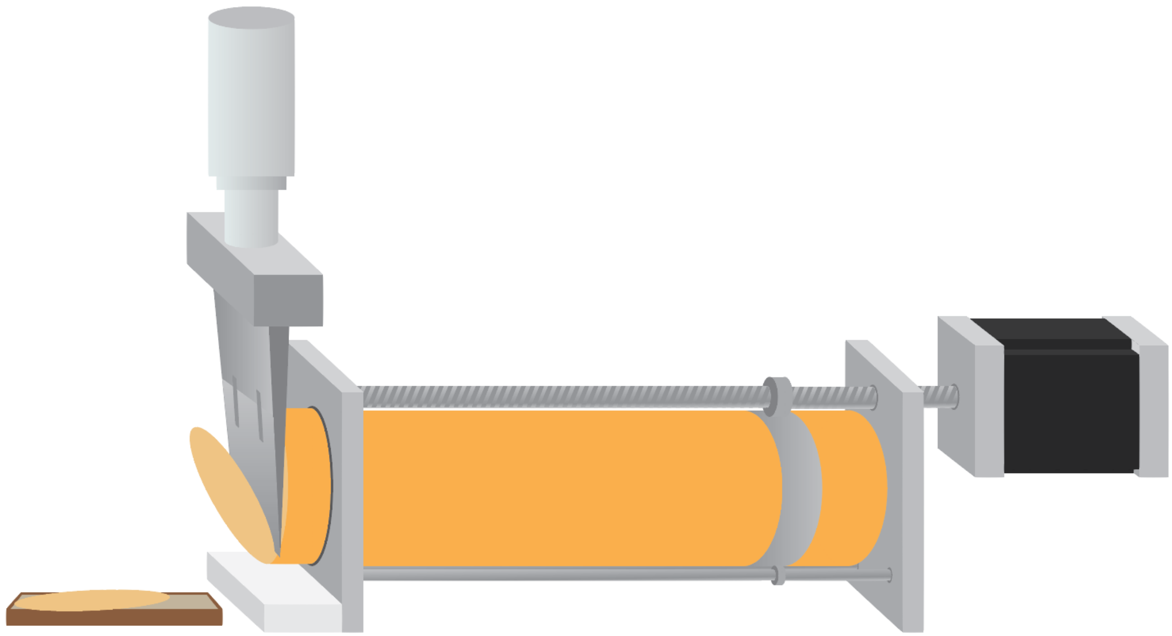


Figure 7: Potential Cheese/Meat Extrusion System

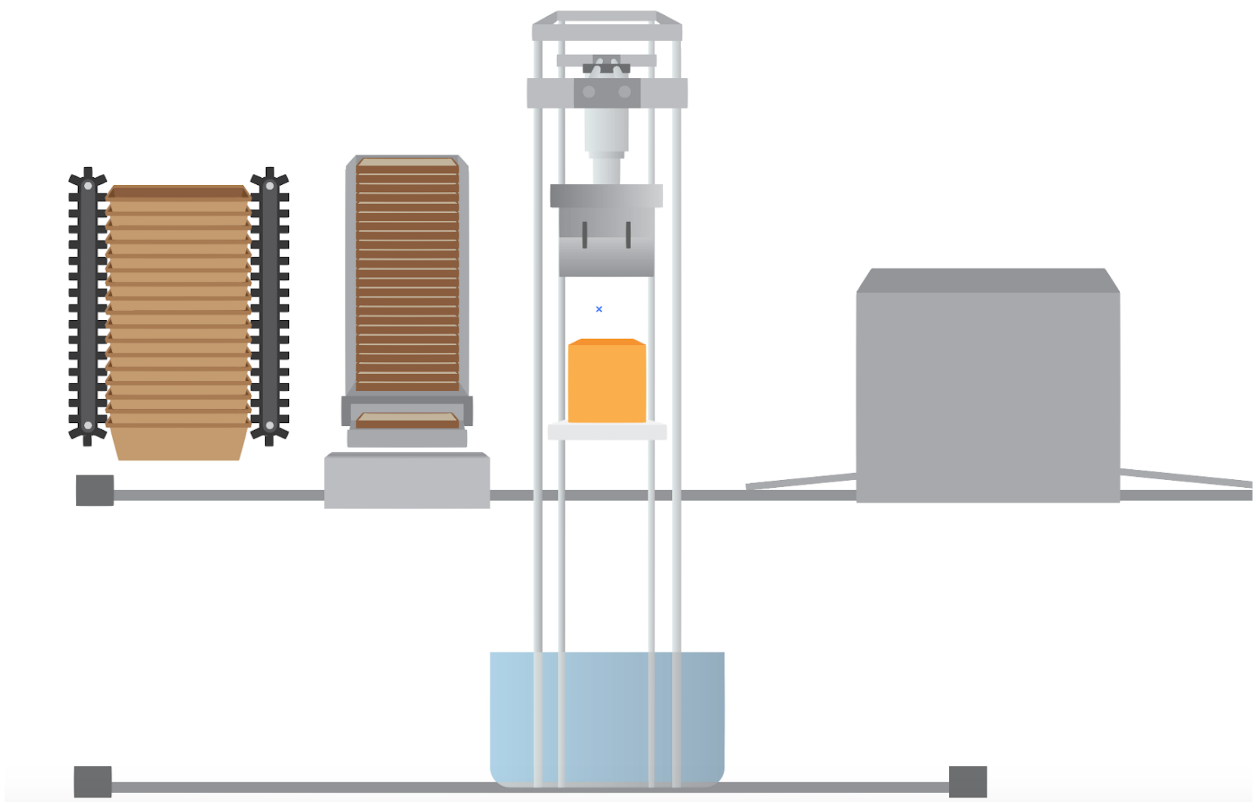


Figure 8: Dual Slide Setup with Assembly Slide Above and Rinsing Slide Below

3.2.3 Mechanical Prototyping

Linear Slide

The largest factor in deciding which linear slide to use was that it was long enough so that it could fit the prototypes bread dispenser and cheese slicing mechanism with room left over to potentially fit some of the project team's stretch goal modules such as a box dispenser. Seen in Figure 9, the team agreed 1000mm was sufficient and confirmed that the slide would move at a decent linear velocity (5.5inches a second) and could handle the sandwich payload (max load capacity is 300lbs).

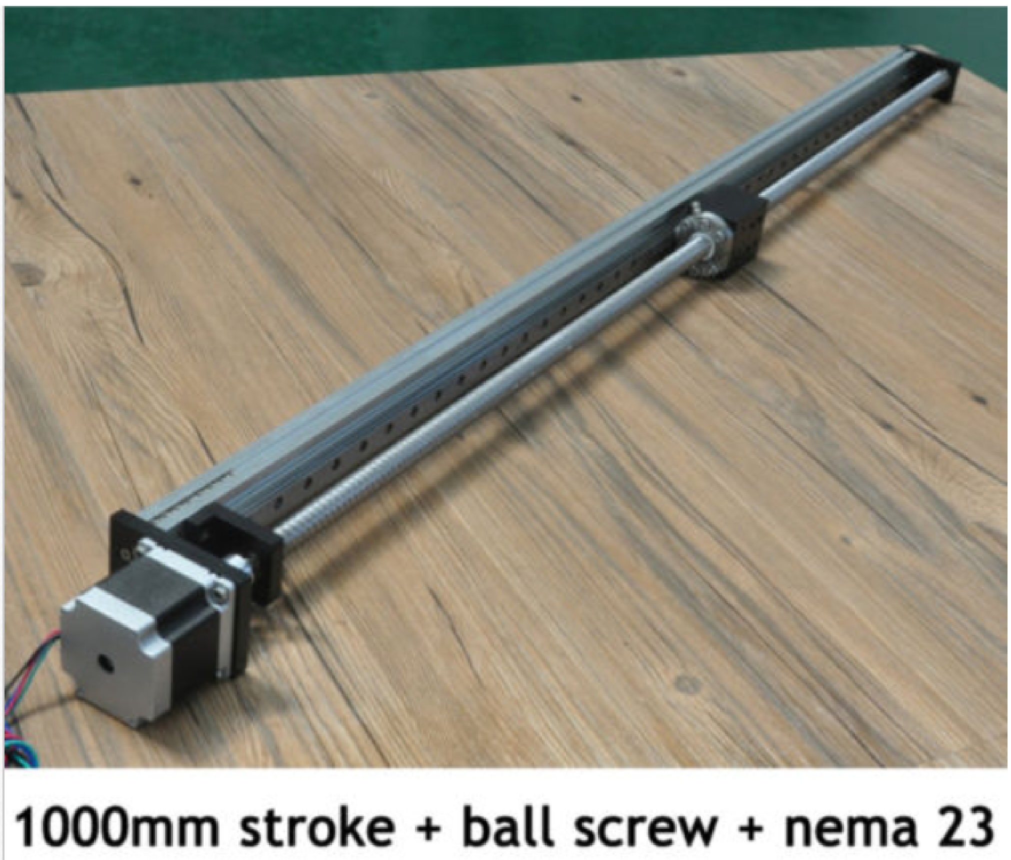


Figure 9:Product Picture of 1000mm Linear Slide

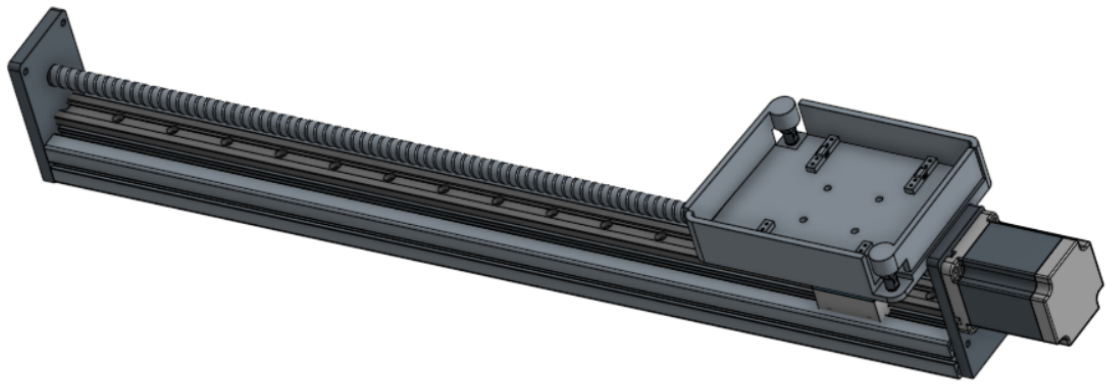


Figure 10: 3D Model of Linear Slide with Carriage

Carriage

The team decided to create the carriage that will transport the sandwich with two swinging doors controlled by servo motors to push the sandwich onto the conveyor oven at the end of the assembly. the carriage will also include 4 load cells positioned specifically on the carriage as a check to confirm the appropriate ingredients were added to the sandwich by weight confirmation. Finally, the team decided to prototype the carriage out of wood instead of metal and plastic 3D printed parts for its quick construction and ease of modifying the carriage after the initial build if the clearance on the doors are too small or if we need more/less space at the hinge for the servo motors.

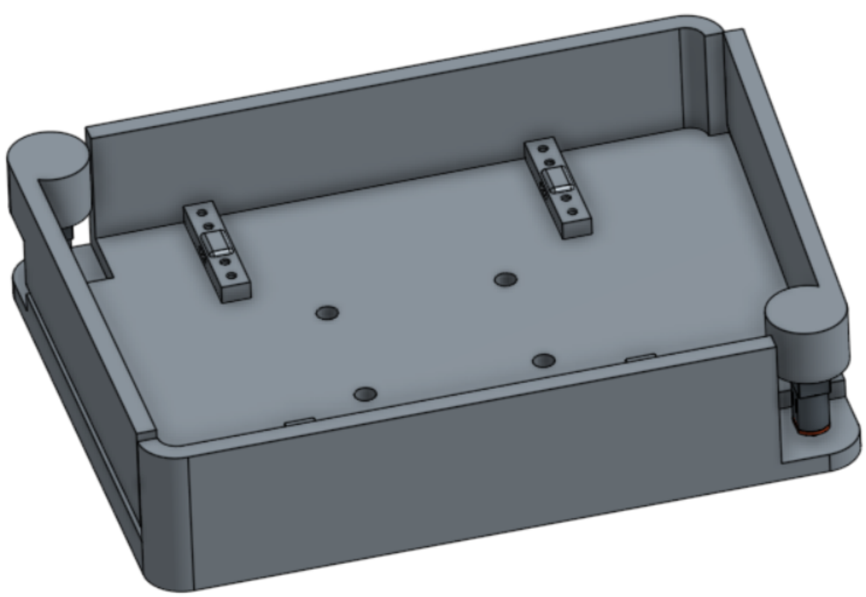


Figure 11: 3D Model of Sandwich Carriage

Box Container

The goal of the box is to catch any excess food that may drop from the original placement of the ingredients. The box will be placed in the Carriage and will be sent through the conveyor oven. As a result, the box will not exceed 3 inches which is the conveyor oven gap and also need to withstand up to

400 degrees Fahrenheit. As a result we chose a disposable cardboard pan that can be used for cooking. This product will allow the user to pick up the plate as a to go container with a lid that can be taken at the end of the assembly.

Figure 12: Disposable heat resistant packaging

Ultrasonic Knife

The ultrasonic knife is powered by an ultrasonic generator which vibrates the blade at 28kHz. The vibrating speed and titanium material makes the knife a perfect candidate for reducing residue and contamination on food contact surfaces. The knife itself prevents the buildup of food particles compared to other knives and will allow for a more easily cleanable knife. The use of the ultrasonic knife also reduces the coefficient of static friction when slicing allowing for a clean and precise cut regardless of the food hardness. These knives have been used heavily in industrial settings and could provide a promising application to our slicing composition.

Slicer Mounting

The slicer mounting bracket will utilize a 1.5 in. Galvanized Split Ring Pipe Hanger shown in Figure 13 to firmly attach to the mid-handle of the knife.

Figure 13: 1.5 in. Galvanized Split Ring Pipe Hanger

A ⅜ in. threaded rod will act as an axle attached to a geared motor using a locking collar. the motor will be attached to the side of the linear slide shuttle. Ideally The internal gearing of the motor will prevent the knife from moving backwards when itis horizontal and cutting through the deli products shown in Figure 14. However, in case the gearing is not strong enough to hold up the knife when the motor is off, a swinging fork arm controlled by a servo motor will engage itself near the front handle to restrict motion up or down.The vertical down position will be used for sanitizing, where the fork arm will first disengage itself, the knife will rotate to its vertical position once brought below the cheese/meat to prevent collision with the deli product fixture and carriage, and then the linear slide will bring the knife as far down as the 600mm slide can go where the blade will be dipped into a sanitation bath.

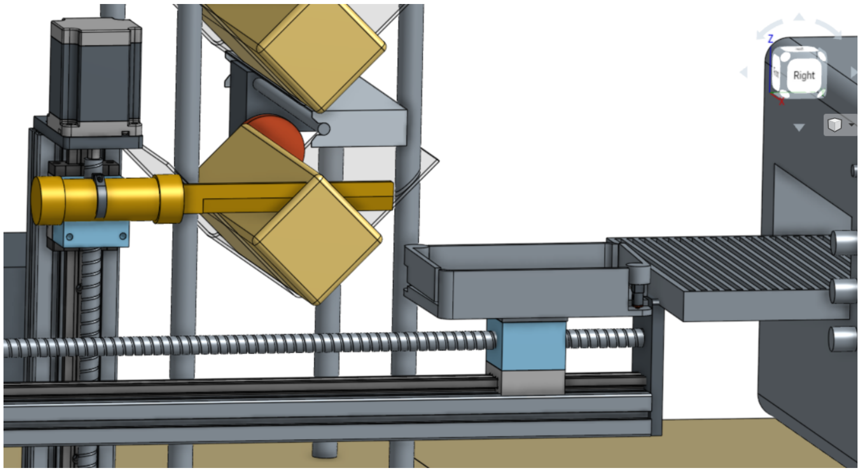


Figure 14: Slicer Mechanism with Carriage and Extruder

Cheese Extruder

To save cost, the team is utilizing components from a printer for our cheese extruder. the extruder has a large ink shuttle shown in black in the CAD model that will be modified to have a new end piece to make better contact with the but of the cheese log. the team visualizes the extruder to be above the cheese log shown in the assembly model, because it will have the least interference with other parts of the system while making greatest surface area contact to the butt of the log.

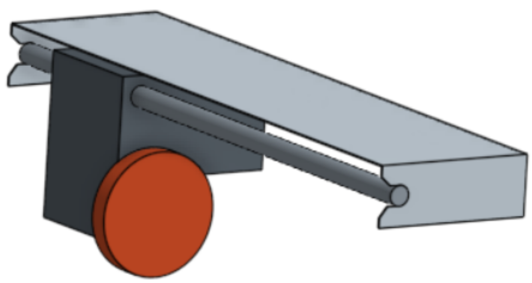


Figure 15: 3D Model of Deli Product Extruder

Conveyor Oven

The team is moving forward with the 14 1/4" Single Belt Countertop Conveyor Oven - 240V, 3.6 kW. The conveyor oven provides the team with the desired cooking temperature for a grilled cheese of about 400 degrees fahrenheit, and continuous motion perfect for assembly line operation. The equipment is already certified for food heating and cooking applications.

Figure 16: Conveyor Oven Product Picture

Deli Product Fixture

The team was initially going to make a racked system shown in Figure 17 for holding the deli products to display multiple meats and cheeses.

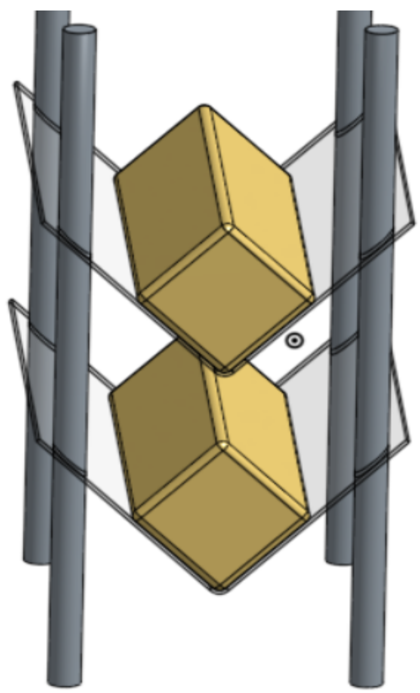


Figure 17: Racked Acrylic Deli Product Fixture

the system would maximize space and also keep the specific logs separate for sanitary, allergy, and religious restrictions that come with meat and cheese storage. However, the racked system will be reduced to one shelf since the MVP only requires cheese.

Bread Dispenser

The dispenser will slide the bread directly over the box on the carriage. The bread dispenser will be constructed from a 80/20 aluminum frame with a wood housing to hold the bread for the sandwiches. The housing can hold 2 loaves of bread. The drawer that slides the bread out will be placed on bearings to allow less friction from the shelf resting on the wooden frame. We will integrate a rack and pinion geared system with an appropriate gear train so that a Vex motor can actuate the module.

Packaging Dispenser

The dispenser that holds the packages will comprise a frame that houses the boxes and a conveyor belt that will have treads to hold the packages. The minimal viable product will be able to hold up to 10 packages at once but will need to be redesigned in the future to hold enough boxes for a day's worth of sandwiches. The dispenser will overhang the Carriage and be positioned as close as possible to ensure dropping the plate will be as accurate as possible.

Refrigeration

Cheese is a dairy product and requires refrigeration for extended periods of use. To increase the shelf life of the cheese we would like to implement a refrigeration system that can encapsulate the deli product fixture without the electrical equipment like the extruder. There will be a small sliding door to allow the cheese to be sent outside of the refrigeration area where a slice can be cut from the cheese itself. Once cut and there are no pending orders for about 2 minutes the cheese log will be moved back into the refrigeration unit where the cheese can be kept cool.

Sanitation

The sanitation area for the knife will be the approximate length of the knife at approximately 8 ¼”. The sanitation dispenser will consist of 3 containers, one for rinse water, one for sanitizer and another for rinsing the sanitizer off the blade. The containers are round plastic housings placed on a lazy susan platform constructed from wood. The actuation of the lazy susan will be controlled by a HS-645mg ultra torque servo motor. The lazy susan will rotate from 0 to 90 to 180 degrees to move the different cleaning vats into a position where the ultrasonic knife can be lowered and activated to remove any debris while sanitizing the blade’s surface

3.3 Electrical Design

3.3.1 Electrical Design Requirements

The team has defined design specifications for five sections of the electrical components in the kiosk that are within the scope of this MQP including: selecting a power supply, incorporating a microcontroller(s)/computer that meets our requirements, integrate motors for the slicer, developing heating system control, and integrating the conveyor motion with a weight sensor. Below includes a list of the specifications split between the five sections of focus.

MQP Goals

- **Selecting a Power Supply**
    - Requires AC to DC converter with multiple voltage outputs and current ranges to minimize power loss.
        - Microcontrollers usually require 3.3V or 5V DC with relatively constant power consumption
        - Motors often run off of 6-24V DC with large spikes in power consumption.
    - Oven powered by a wall outlet through its existing power supply to minimize the power constraints.
    - To minimize infrastructure installation costs, the rest of the system will be powered by a separate 120V, 60Hz wall outlet.
- **Incorporate Microcontroller(s)/Computers that meet our requirements**
    - Network enabled(using WiFi to connect to existing infrastructure)
    - Ability to interface with up to 15 PWM and 30 Digital ports
    - 6 interrupt ports
    - Real Time Operating System not required due to relatively loose timing requirements
    - Ability to be used in centralized and decentralized system (CAN Bus enabled)
- **Integrate motors for slicer**
    - Provide motors and electrical components for the slicer
    - Ensure breakout boards for potential components
- **Develop heating system control**
    - Determine best means to control the heating system
        - Control conveyor speed
        - Turn oven on and off
    - Develop a way to sense the temperature and adjust if needed
- **Integrate conveyor motion with weight sensor**
    - Ensure motor can be precise enough to develop control of sandwich motion
    - Use limit switches to calibrate positioning and prevent motion from extending past slides

Stretch goals

- Vision system
    - Ensures assembly was processed correctly at each stage
    - Quality Assurance of the equipment for hygiene purposes

- Backup Power Supply
  - Inverters and DC Batteries to keep system running during power outages
- Packaging Dispenser

Phase 2 goals

- Heated lockers to hold sandwiches
- Refrigeration container for ingredients

Electrical Component Selection

A brief table of the electrical components, we would potentially use, were explored and can be found in the table below. The components are split up into a few of the main system assemblies. Each assembly has specific components we intend to implement with their specific purpose on the overall mechanism. Many of the requirements will dictate exactly which motor or sensor we integrate into the system. More testing will need to be done in order to derive many of the higher impact items like the motors that will manipulate the slicer blade. These motors will need to be powerful enough to move the large ultrasonic knife and cut through varying meats and cheeses.

Table 4: Electrical Design Components

System	Specs	Component	QTY	PWM	Digital	Purpose	Requirements
Bread Dispenser	Required	DC Motor	1		2	Pulls bread dispenser door open for bread to drop through	Simple motor for linear motion, Low force needed
Conveyor Oven	Required	Conveyor Oven	1	1	2	Heats sandwich	Control over conveyor motion and temperature
Linear Slide	Required	Limit Switches/ Bump Sensor	2		1	Ensures sandwich carriage does not exceed the rails	Simple sensor
Linear Slide	Required	Scale	1	1	1	Used to determine if ingredients are added to the sandwich	Sensitive enough to read a change in weight as little as a few ounces
Linear Slide	Required	Stepper Driver	1	3	3	Controls the Stepper Motor	Can control the stepper motor with accuracy
Linear Slide	Required	Stepper Motor	1		4	Used to move the sandwich carriage	Must be accurate enough to move between assembly stages with precision (Least amount of spilled ingredients). Also must be able to move the average weight of a sandwich
Linear Slide	Required	DC Motor				Moves a small door on the	Simple motor for linear or rotational motion, Low force

						sandwich carriage to ensure the box does not move once in the carriage	needed
Slicer Mechanism	Required	Limit Switches/ Bump Sensor	4		1	Ensures ultrasonic blade does not cut past the ingredients	Simple Sensor
Slicer Mechanism	Required	Stepper Driver	1	3	3	Controls the Stepper Motor	Can control the stepper motor with accuracy
Slicer Mechanism	Required	Stepper Motor	2		4	Used to move the sandwich carriage	Powerful enough motor to control ultrasonic knife and cut through tough ingredients like cheese and meats
Power Supply	Required	Multi Voltage AC/DC Power Supply	1	N/A	N/A	Supplied regulated power to all components	DC power for microcontrollers and AC power for refrigeration. Power will be dictated by the size of the motors and refrigeration unit used
Vision System	Reach Goal	Camera	1	N/A	N/A	Captures assembly process and checks hygiene of blade cleanliness	For assembly color recognition and basic shape recognition would be required. Quality assurance vision system would require hyperspectral imaging ranging from 470 to 700 nm
Vision System	Reach Goal	Computer	1	N/A	N/A	Translates imaging data and processes information to determine proper assembly and hygiene of equipment	Basic computer with serial connections to allow camera to send data, enough processing power to complete image processing within time constraints
Backup Power Supply	Reach Goal	Batteries	1	N/A	N/A	Supplies power to system in case of power loss	Must be able to supply enough power to all the components or at least just the refrigeration unit to prevent spoiling of food
Total			40	15	25		

With a complex system architecture, our team compared implementing a centralized system in which one microcontroller or computer handles and executes all the required tasks to a decentralized system in which multiple microcontrollers handle individualized tasks. A decentralized system would simplify wiring costs and expansion of the system if modules are added in future generations of the product. Other traditional benefits of a decentralized system are the reduced overhead on the central controller as well as faster responses by the peripheral controllers. However, due to the loose timing requirements in our system, these benefits are not applicable to our system. A centralized system allows for faster development as it removes integration time and is cheaper than buying multiple microcontrollers. These factors led the team to move forward with a centralized system but with a processor that has the ability to integrate a CAN bus or other type of distributed bus architecture in case future development of the product requires it.

Table 5: Computer/Microcontroller Component Selection

Computer	Notes	Pros	Cons
Raspberry Pi 3 Model B	$35, 3.3V GPIO Pins	Large community support, integrated WiFi, CAN expandable	Need to integrate ADC, fewer GPIO pins for system, no onboard memory
Beaglebone Black	$45, 3.3V GPIO Pins	Integrated ADC, plenty of GPIO, I2C, PWM pins to support applications, CAN expandable	Need to integrate WiFi module, slightly smaller community support
Beaglebone Green Wireless	$50, 3.3V GPIO Pins	Integrated ADC, plenty of GPIO, I2C, PWM pins to support applications, integrated WiFi + BLE, CAN expandable	Slightly smaller community support

To minimize integrating additional modules into the controllers, the team selected the BeagleBone Green Wireless as the central controller for the system. This product meets all of our requirements as stated above and robust community and library support will allow for faster development.

3.3.2 Preliminary Electrical Design Mockup

Below is a preliminary schematic of the electrical system that focuses on data lines with the BeagleBone Green Wireless at the center of the electrical system. This was created using worst case data line requirements for each subsystem of both our essential and stretch goals.

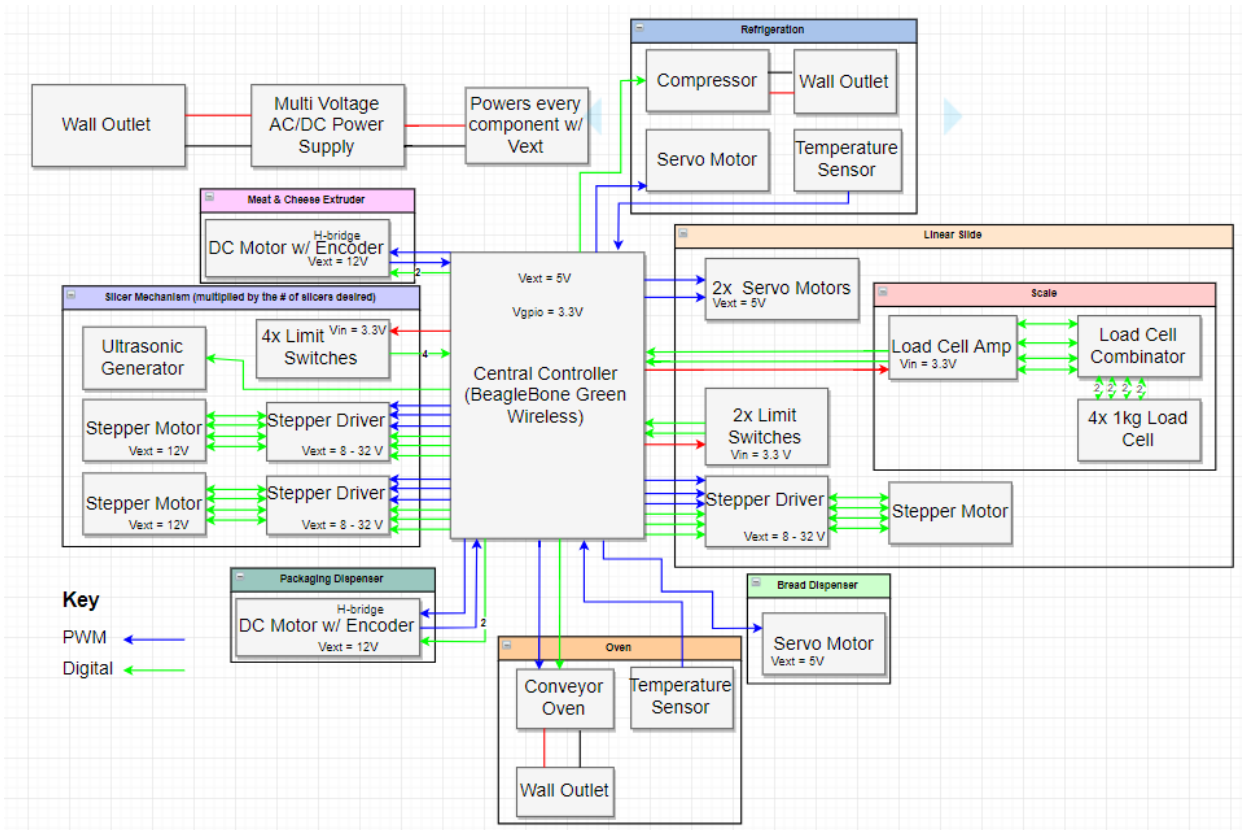


Figure 18: Electrical Design Schematic of Sandwich Assembly

3.3.3 Initial Electrical Prototyping

The team purchased components that satisfied the project requirements and conducted prototype implementation for the electrical and control system during B term, focusing on large purchases of components that are integral to the system. This included the BeagleBone Green Wireless, motor driver boards, and the linear slide for the carriage system. In this section, we will outline the project requirements that were met by the specific purchases and any initial prototyping and subsequent design changes.

Linear Slide

The linear slide for moving the sandwich along the horizontal axis was purchased due to its mechanical properties detailed in section 3.1.4.1 as well as its ease of control from the Beaglebone Green Wireless (BBGW). Another benefit is that this linear slide came with a stepper motor already integrated into the system. In conjunction with a motor driver board, the BBGW uses digital signals to control the stepper motor motion, whether in eighth quarter, half or full steps. The stepper motor's specifications state the motor can move the slide at 5.5 inches per second when pulling a current of 2.0A but this speed was not being achieved during prototyping with using the Easy Driver board due to its maximum output current of 750mA. Additionally, the motor would only turn when full stepped and produced significant noise. The team then decided to purchase a Big Easy motor driver board which is capable of an output current of 2.0A. This provided the desired results in terms of speed of the carriage and noise of the motor due to the ability to eighth step. The stepper motor also has an operating voltage range of 20-50V and will dictate the required voltage of the system, likely requiring a 24V power supply.

The next step for linear slide will be developing exact position control. In order to accomplish this, we will need to integrate limit switches or bump switches at the beginning and end of the slide. The information provided by these switches will provide exact locations of the slide to calibrate the motion control as the stepper motor has small variations in its motion control. The team acquired bump switches that may provide the necessary information.

Sandwich Carriage & Scale

A scale is implemented within the carriage of the main linear slide to monitor successful addition of ingredients to the sandwich. The scale is comprised of 4 load cells with a combinator and amplifier. The scale will be dealing with only minor degrees of weight changes from the slice of bread to cheese and will need to be precise enough to measure these values. However, the scale will also need to support the weight of the carriage, box, and sandwich, which is estimated to be roughly 1.5kg. To do this we selected (4) 0.78 Kg Micro Load Cells that are able to be read through with a HX711 Load Cell Amplifier. Since there are 4 load cells, the amplifier will require the use of a breakout board like the Sparkfun Load Sensor Combinator v1.1 to combine the 12 wires of the load cells into the standard four-wire Wheatstone bridge configuration. The amplifier will then need to communicate with the microcontroller through I^2C to relay information to the BeagleBone.

Bread Dispenser

A continuous servo motor will be used in combination with two limit switches to pull out and retract the drawer of the bread dispenser. The motor needs to be strong enough to pull out the drawer.

Cheese Extruder

The motor for the cheese extruder will need to be able to move a block of cheese roughly 5.6lbs across a wooden or teflon coated metal surface. In the instance of the wood there will be much more friction force applied to the cheese block resulting in a need for a higher torque motor. We have two options for the cheese extruder and they include a high torque motor and a stepper motor.

Heating

We have yet to purchase the conveyor oven due to lack of availability and expensive price. The team has decided to hold off on purchasing a conveyor oven until the right price and product presents itself and may elect to only build a conveyor belt to prove the concept. However, we did move forward with purchasing a Grove High Temperature Sensor from Seeed that can withstand up to 600ºC due to its use of a temperature probe. The output of this sensor is an analog signal from 0 to 3.3V corresponding to the relative temperature value, thus requiring a voltage divider to step the range down to 0 - 1.8V to satisfy the analog pin requirements of the BBGW.

Packaging

The packaging system requires precise movement of the package and the ability to hold the loaded packages in the mechanism. To do so we would like to implement a stepper motor with anti backdrive functionality so that the packages can be held in place. The step angle can be flexible because we only require the precision of the motor to be the about the distance between each held box, which can be easily changed. This is because the motor will be directly connected to the conveyor with treads to control the movement of the packages.

3.4 Software Design

3.4.1 Software Design Requirements

The team developed a comprehensive list of high-level use cases which we believe the ordering system software should be able to support. These use cases outline the basic functionality that the machine must support from the perspective of customers and employees in order the implement the MVP. This does not include lower level use cases for the embedded system, or use cases for auxiliary systems to support the operation of the machine, such as security, and waste disposal.

Table 6: High-Level use cases of Sandwich Assembler Ordering System

Actor	Action
Customer	Login
Customer	Logout
Customer	Select location
Customer	View menu
Customer	Build sandwich
Customer	Add sandwich to cart
Customer	Remove sandwich from cart
Customer	Select payment method
Customer	Add payment method
Customer	Remove payment method
Customer	Adjust pickup time
Customer	Place order
Customer	Pickup order
Customer	View order status
Customer	Cancel order
Customer	Save an order to favorites
Customer	Remove an order from favorites
Customer	Re order a favorite order
Customer	Provide feedback
Customer	Contact support
Customer	Share order with friend for pickup
Employee	Unlock machine for maintenance

Employee	Restock ingredient
Employee	Remove equipment for cleaning
Employee	Replace equipment after cleaning
Employee	Test machine after maintenance
Employee	View machine status
Employee	View sales statistics
Employee	View ingredient levels
Employee	View customer feedback submissions
Employee	View customer support messages
Employee	Submit ingredient order to suppliers
Employee	Relock machine

In order to meet these requirements, the team created a list of software features to implement during the course of the MQP, as well as stretch goals and goals for Phase 2.

MQP Goals

- Backend application
  - Configure database to store user and administrator data
  - Communication system between customer-facing application and embedded system on kiosks using an order queue
  - Basic account system and user authentication
- Customer-facing application
  - Login to account
  - Place a sandwich order (without payments)
  - Track status of order
  - Pickup order using application (no authentication)
- Embedded system
  - System to track the state of the sandwich assembly process
  - Software components to control actuators and read sensor data needed to assemble basic sandwich
    - Control positions of assembly line linear actuator
    - Control bread dispenser, oven and carriage doors
    - Control meat/cheese extruder
    - Control slicer linear actuator
    - Read weight scale and temperature sensor data
    - Test and tune values for actuator positions

Stretch Goals

- Backend application
  - Integrate an external payment service, such as Stripe
- Customer-facing application

    - Authenticated order pickups (using QR codes, passcode or similar)
- Embedded system
    - Software routine for cleaning
        - Control linear actuator and blade for cleaning operation
        - Control box dispenser
        - Scheduling algorithm for cleaning

Phase 2 goals

- Backend application
    - Consider integrating an external SMS notification service for reminding users to pick up orders
- Customer-facing application
    - Save items to favorites
    - Live out of stock status for ingredients / sandwiches
- Embedded system
    - Build system to run application on a touch screen through the onboard computer, so that customers can order without using a personal device
- Basic employee application for tracking sales, inventory, and kiosk status

Software Component Selection

After laying out the goals for each phase, the team then compared three different software approaches to an ordering platform.

Table 7: Software Component Selection

Component	Notes	Pros	Cons
In-Kiosk Touch Screen Ordering System		Customers can order without a mobile device	Ordering system would be more tightly coupled with the embedded software, Performance limits of the onboard computer, Line of people may form in front of the kiosk
Native Mobile Apps (iOS / Android) + Web App	Separate apps for each platform	Best possible performance, Web app could also run on touch screen on kiosk in the future	Entirely separate codebases, Significant duplicated work, Need proficiency in all platforms
Hybrid Web/Mobile App	Such as a React Native or Angular NativeScript App	Single codebase, Good for developing an MVP, Performance using modern frameworks is comparable to native code (source), Could also run on touch screen on kiosk in the future	Reliant on third party frameworks, Possibly less future-proof, Could be limited by the limitations of the framework

After considering all three options, we decided to use a hybrid web and mobile application for the ordering platform. This approach offers significant advantages over native apps and the in-kiosk ordering system, as it can be developed from a single unified codebase and deployed to web, Android, and iOS platforms. In the past, hybrid web apps have functioned as traditional web apps that are displayed through a web view window in a native app. These apps suffered from performance issues and often did not seamlessly integrate with the native UI. However with the advent of modern frameworks such as Facebook's React Native, or Google's Angular with NativeScript, hybrid web apps are now indistinguishable from native apps in most cases, and are the development method of choice for companies such as Facebook, Instagram, Tesla, Walmart, Airbnb and Skype (Who's using react native?). This hybrid app could also be feasibly run on a touchscreen in the kiosk by running it in a browser on the embedded computer. The team believes the

3.4.2 Preliminary Software Design Mockups

The web application backend will use a cloud-hosted database to store user data such as orders and account details. It will also store data for kiosk administrators such as purchase history, and machine status information (refrigeration and oven temperatures, cleaning status, etc.) This data could be used in the future to draw important statistics to display to Slice owners, allowing them to make informed decisions.

The backend will expose a REST API through which the front end application and embedded software can interface with the backend over HTTPS to secure sensitive data. The team plans to limit the embedded system's capability to controlling and sensing wherever possible, while storing most business logic in the cloud. This business logic will likely include pricing strategies, the payment system, the state of current inventory levels, and the order queue.

This approach offers several benefits. By delegating the responsibility of dealing with complex business decisions and data storage to the cloud, the embedded system's scope of responsibility can be limited to interacting with hardware. This allows the limited computing power on the kiosks to focus on performing the tasks they perform best -controlling and sensing. As a result, the business logic in the cloud can be updated instantaneously without having to update the firmware on the embedded systems.

The team believes this approach could be useful for:

Facilitating A/B testing - Developers can continuously update the backend and can test new strategies for pricing or ordering on different populations of users without disrupting ongoing sales operations.

Reacting to changes in market forces or ingredient levels - Prices could be quickly changed across the entire fleet or at given locations to reflect new ingredient prices from suppliers, or to feature instant deals to algorithmically limit use up surplus ingredient stocks–limiting food waste

Responding to ingredient recalls - In case of foodborne illness scares, the kiosks could be instructed in real time to stop serving certain ingredients until technicians can arrive

This approach does come with some drawbacks. By relying heavily on the cloud backend, the kiosks are also dependent on internet connectivity to operate, a dependency that most traditional restaurants do not have. However, the locations which the team initially envisions deploying the kiosks (college campuses, workplaces, and hotels) also have similar dependencies on internet connectivity. Another potential risk with tying a large portion of the functionality of the fleet of kiosks to a single backend is that software bugs have widespread impact. However, this effect could be mitigated by a well-defined software architecture which separates the critical operations from the rest of the system, as well an emphasis on thorough testing and quality assurance. As a result, the team believes that the benefits of this approach outweigh the risks. User interface mockups for this customer facing app can be found starting in Appendix B.

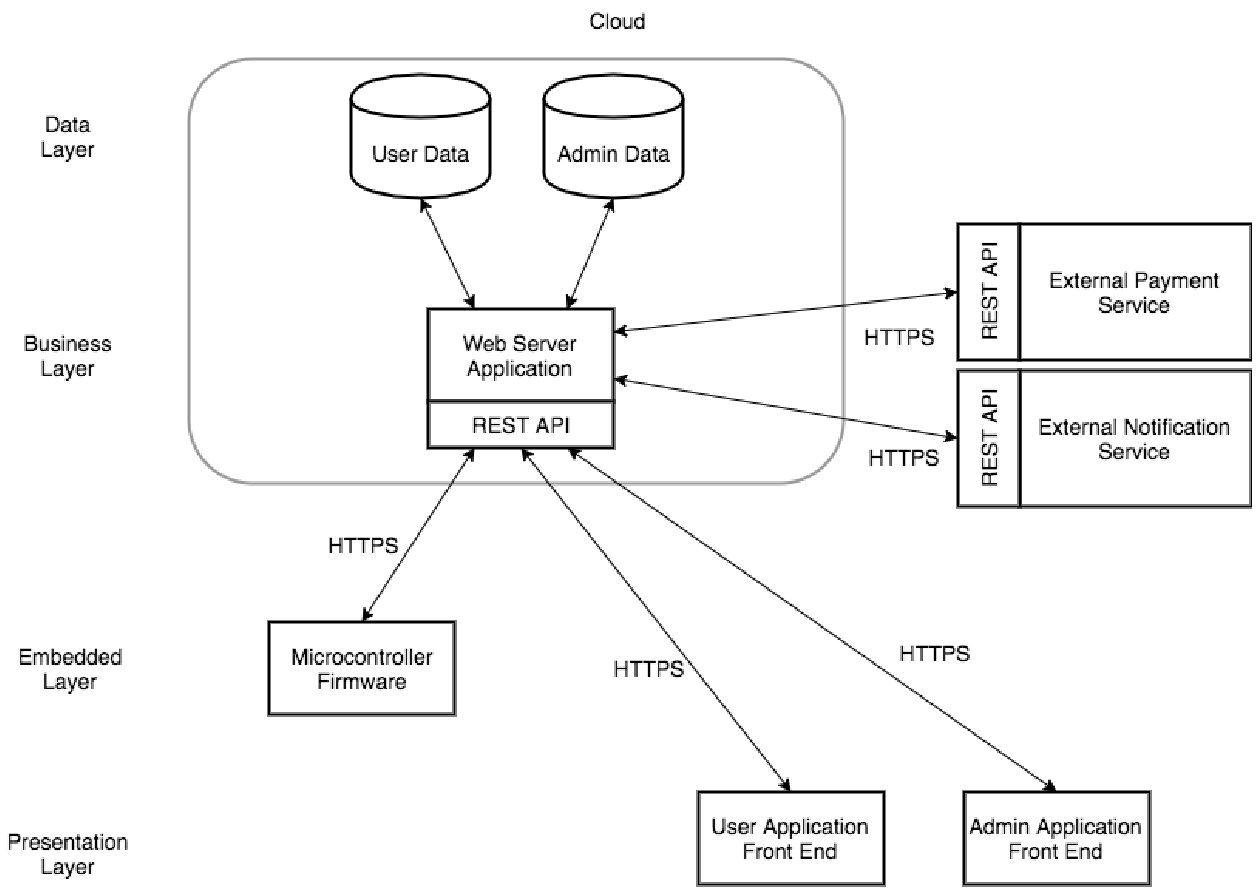


Figure 19: Overall preliminary software architecture

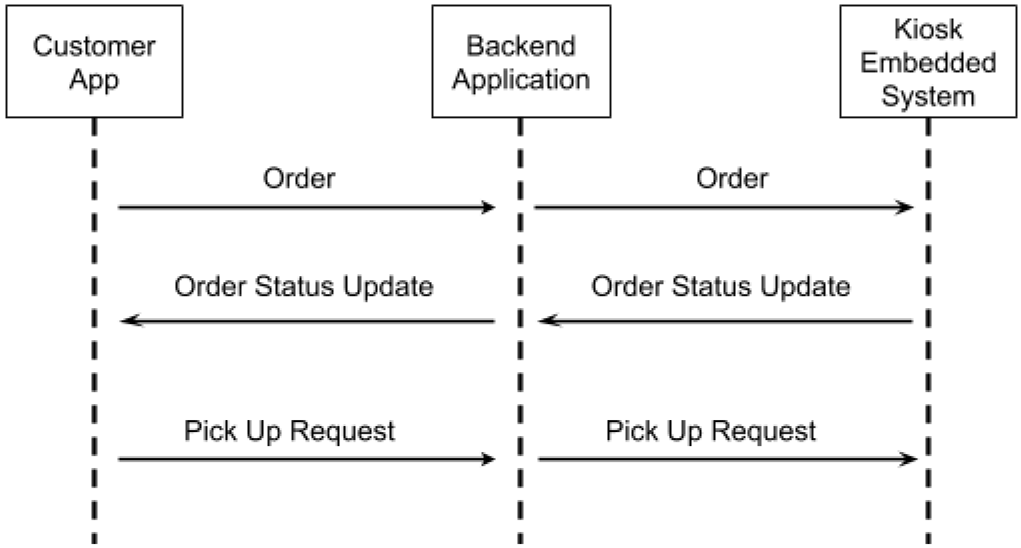


Figure 20: Basic ordering flow diagram

3.4.3 Initial Software Prototyping

Web Application Technology Stack

The web app ordering system employs what is commonly referred to as the MERN stack–an assortment of modern languages and frameworks for creating full-stack JavaScript applications. MERN consists of MongoDB, Express, React and Node.js.

Node.js is a JavaScript runtime which allows JavaScript to run as a server-side language. It is a proven technology for building scalable web applications and its package ecosystem, NPM is the largest collection of open source libraries. As a result, Node.js has a large community of developers and is predicted to be maintainable for years to come. Express is a Node.js framework for building web applications. The Express framework provides server side routing functionality and allows the team to build REST API's for the application.

React is Facebook's modern JavaScript framework for building web applications. React apps are composed of *components,* which contain JavaScript and HTML, as well as a local state, and *props,* which are data passed down from parent components. React renders the components using the state and props, and automatically rerenders the components whenever the state or props change. This model makes React ideal for building large performant web apps.

The web app front-end also makes use of the following additional JavaScript frameworks:

Redux is Facebook's predictable state container framework for JavaScript apps. The team chose to use this framework because it complements React and allows the app to maintain a global state tree called a *store* which acts as the single source of truth for the application. Redux borrows some principles from functional programming. It manages application state through *actions* and *reducer* functions. Given a previous application state and an action, the reducer functions compute the new application state. The reducers are *pure functions*–they will always produce the same result given the same inputs. This determinism allows Redux applications to be very predictable. When debugging the application, developers can use the developer tools to *time travel* between application states to quickly find errors. Our team determined this model to be a good starting point for developing a complex web application. The React Router library provides our application with client-side URL routing.

Finally, MongoDB is a robust NoSQL database that stores data in a JSON format, which makes it convenient to use in the JavaScript ecosystem. In contrast with traditional relational databases, NoSQL databases no not have a defined schema, and forgo some data consistency measures in favor of greater performance. In order to scale up a hosted NoSQL database, instead of having to purchase a more performant server, one can simply add more low cost servers to horizontally scale performance.

The team then set up a template for a Node.js app with the Express framework by cloning a boilerplate repository on GitHub, and then adding the other necessary frameworks. For prototyping, the webserver is running locally on a laptop, but will be moved to cloud hosting on Heroku. Heroku is a web app hosting provider that provides a complete suite of tools for deploying web apps (under the hood, Heroku runs on Amazon Web Services). Heroku allows developers to spend more time developing apps and less time managing infrastructure, and provides a free tier for basic use.

Initializing the Beaglebone

The team configured WiFi and SSH on the BeagleBone to remotely connect to the Beaglebone from personal laptops or web servers. This is essential to setting up communication between the web server and embedded code on the Beaglebone. Using the *requests* python library, the team was able to make basic HTTP requests between the board and the web server running on localhost, by sending dummy JSON data between the board and the server.

We have also written numerous test scripts to test the functionality of the board including its pulse width modulation, I^2C, ADC capabilities as well as take live sensor data from temperature sensors using Adafruit's BBIO libraries. These functionalities are all necessary to control the motors, read temperature and other data readings.

We also have developed an embedded code skeleton which will prove as the blueprint of code development throughout the coming terms. This code skeleton directly matches the requirements of the project and can be seen below:

```
State = 0 #Order Polling
Poll order queue from server
    If there is at least 1 order in queue
        Pull first order in queue
        State = 1
    If no orders in queue
        State = 0
State = 1 #Bread Dispensing
MoveCarriage(BreadDispenser)
DispenseBread()
If CheckWeight(FirstSlice) equals true
    State = 2
Else
    ThrowError
State = 2 #Cheese cutting
MoveCarriage(CheeseDispenser)
For number of cheese slices
    ExtrudeCheese(SetWidth)
    CutCheese()
If CheckWeight(Cheese) equals true
    State = 3
```

```
Else
    ThrowError
State = 3 #Toasting
SetConveyorSpeed(ToastLevel)
MoveCarriage(Oven)
PushSandwich(OUT)
MoveCarriage(Start)
State = 0
```

Figure 21: Simplified Embedded Code Skeleton

3.5 Next Steps

The overall MVP consists of developing a modular, expandable skeleton that can support the addition of our Reach and Phase 2 goals presented in each section. The modules we develop will be able to produce a toasted cheese sandwich for our customers. The 5 key mechanical modules to make the MVP include the linear slide system to move the sandwich from module to module, a bread dispensing system, a box dispensing system, a slicing mechanism, and the conveyor oven. The team will look closely at the previous case studies and designs to learn further and attempt to avoid any issues that previous researchers have faced. The design will attempt to stray away from the large industrial scale of producing high quantities of sandwiches and instead focus on increasing the quality of the products through as slower process, and hopefully make the system more appealing to the end user to increase their comfortability with the automation.

We believe one of the greatest obstacles that this project will face is ensuring that the system follows specifications for food equipment design and safe food serving. Especially with regards to sanitation, ensuring that the machine operates safely without human intervention will be paramount. With that in mind, the team attempted to minimize the number of food contact surfaces by isolating the food preparation to the boxes. We also believe that the ultrasonic cutting and cleaning system will help to simplify some sanitation concerns, and will hopefully even perform at a better level than traditional washing methods. Throughout the next term of the project we will work to further research the food safety requirements and address them through our final design.

In addition to sanitation, there are a number of other mechanical concerns which we will research and address as we construct a more in depth design. For example: dimensions, balance and weight according to shipping constraints, and the specific heat proof sandwiches boxes to use in the assembly process.

We will also work to identify specific actuators and sensor components for use in our design and will work to develop a bill of materials. We will also research more into the power supply requirements and identify a solution for powering and controlling the multitude of appliances and motors from a central power supply. Finally, we will identify the frameworks and languages to use in order to realize our software design, identify more in depth user requirements and edge cases, and create a more in depth software architecture specification.

While this project is a large, complex undertaking with many potential areas for issues to arise, the team is confident that we will be able to deliver an MVP which serves as a proof of concept and helps to either prove or disprove the market and technical viability of the concept.

Chapter 4: Implementation

4.1 Mechanical Implementation

Below is the mechanical implementation section for each main module. If the original design presented in Chapter 3 was modified, the module will include a table organizing the changes. The “original concept” columnis the idea generated from chapter 3 of what the design was supposed to include, the “modification” column is what was changed. the “reasoning” column was the thought process behind the change, and the “picture” column is a picture to give a visual representation of the situation.

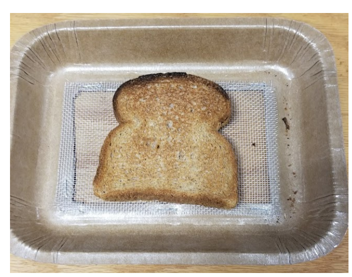
Linear Slide & Carriage

Table 8: Linear Slide and Carriage Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
4 load cells	1 load cell with rubber stoppers at the end of the top plate to keep the plate flat	Originally the team thought 4 cells were required to get an accurate reading but upon testing we found that one load cell was able to produce more accurate measurements because the load was so small split between 4 load cells that we were not getting adequate results	
2 Swinging Doors	1 Swinging door (back)	The front swinging door is not needed because we have not created a tray dispensing module and the door interferes with the conveyor oven frame	

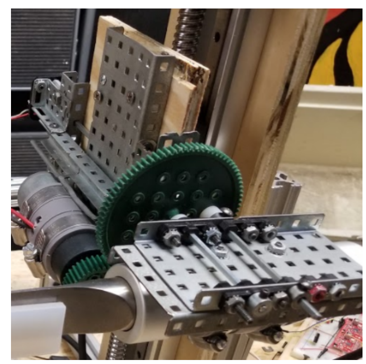
Container

Table 9: Container Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
High temperature disposable cardboard container	Cut out bottom of container and replaced with aluminum mesh	Without proper ventilation the grilled cheese would not have toasted on the bottom side. We used aluminum mesh and were able to achieve the even toasting that a grilled cheese would require	

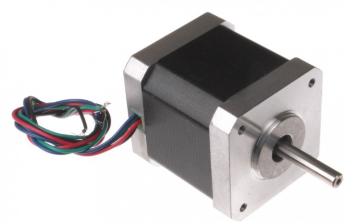
Slicer Mounting

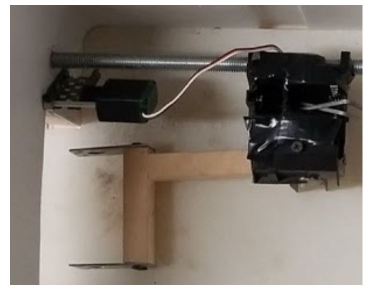
Table 10: Slicer Mounting Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
Metal Piping Clamp	Rubber pipe Clamp with vex Parts	The wooden clamp was too bulky and would interfere with the rotation of the knife when attached to the motor, So to trim down on size but keep the ability to remove the knife whenever we would like, we went with rubber pipe clamps	
Screw to linear slide	Vex parts for Motor Interaction	originally the team was going to mount the motor and knife directly to the linear slide shuttle and connect the two with gears. The team opted to move forward with vex mounts to get a more secure fixing position for both the knife and motor	
Motor stops rotation of knife	Manual Stop, with potentiometer	A manual stop and 10k potentiometer were added to the knife to limit rotation to the desired 90 degree of rotation from horizontal 180 degree position to the vertical 270 degree position so if a catastrophic failure occurred and the motor were to go haywire, we would not have $900 knife spinning frantically, damaging the system and the blade.	 

Cheese Extruder, Fixture & Refrigeration

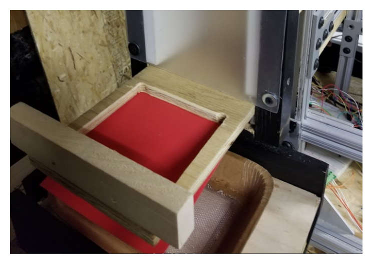
Table 11: Cheese Extruder, Fixture & Refrigeration Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
Acrylic Shelving	plastic cutting board	The moisture from cold cheese adheres to the smooth acrylic surface and makes linear extrusion along the surface extremely difficult. Plastic cutting boards seem to provide optimal movement across for the cheese.	
45 Degree Cheese offset from horizontal	No offset	The 45 degree orientation resulted in a less consistent drop so the team went back to horizontal placement	
Printer motors	Nema 17 motor	Printer motors were not strong enough to push a 9lb block of cheese	
No Refrigeration	Cooler	Extruding system could fit inside a cooler that was acquired for the project and would keep the cheese cool so that the team would not be limited to using non-refrigerated cheese for our sandwich	

Coupling attachment directly Threaded Shaft	Timing belt and pulley	The team could not manually line up the motor shaft and the threaded rod. So the team offset the motor and placed a timing belt and pulleys to connect the two as not to damage the motor from a misaligned connection	
Wooden claw fixture with metal stripe that would skewer the full width of the cheese	Wooden claw too bulky and metal stock could not fix cheese while in refrigeration unit	Wooden claw was replaced with metal arms and the metal stripe pushed through the cheese block was replaced with two square axles that could better fix the cheese and pass through the refrigeration window without any interference	

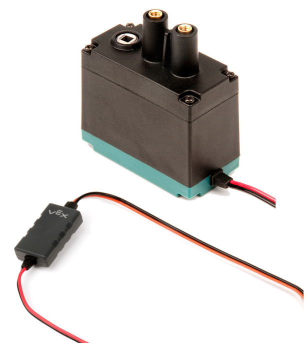
Bread Dispenser

Table 12: Bread Dispenser Mechanical Design Modifications

Original Concept	**Modification**	**Reasoning**	**Picture**
Wooden Slider Glued together	Single cut piece of wood, plastic flap	The new drawer adjusted to better fit the width of the bread and also ensured better placement onto the carriage with the plastic flap underneath	

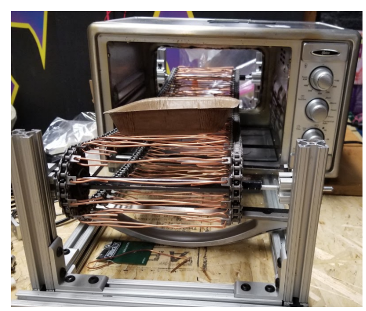
Sanitation

Table 13: Sanitation Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
HS-645mg ultra torque servo	Vex 393 Motor	The original servo could move the cleaning vat assembly but would get stuck when the vats were filled. To adjust this issue we used WD-40 to loosen the bearings but the servo still struggled. The Servo can handle 8.33in.lbs of torque so we switched to the Vex 393 motor which can handle 14.75in.lbs	

Conveyor Oven

Table 14: Conveyor Oven Mechanical Design Modifications

Original Concept	Modification	Reasoning	Picture
Conveyor oven	DIY Conveyor Oven	With financial limitations with the project and since the cheapest second hand conveyor oven the team could find was $550 dollars, the team decided to build one from scratch using 8020 aluminum, a toaster oven, chain, sprockets, and copper wire	
36T sprockets	15T and 24T sprockets	The team was able to acquire chain and sprockets and the original 36T sprockets were too large because the chain would be dragging across the toaster oven heating elements and the clearance for the sandwich and container was too small. Then we wanted to move forward with a 12T sprocket but the hex bore was not indexed with the spokes	

		and did not align the conveyor correctly so we obtained 15T sprockets we could bore ourselves with a hex broach	
Coupling attachment directly Threaded Shaft	Timing belt and pulley	The team could not manually line up the motor shaft and the threaded rod. So the team offset the motor and placed a timing belt and pulleys to connect the two as not to damage the motor from a misaligned connection	
Nothing	Velleman HC-SR05 ultrasonic Sensor	Originally there was no sensor to inform the embedded system when the tray and its contents were within the conveyor oven and to pause the conveyor for the sandwich to toast	

4.2 Electrical Implementation

Incorporate Microcontroller(s)/Computers that meet our requirements

One major deviation from our initial electrical design was using a Particle Photon as the central controller of the system instead of the BeagleBone Green Wireless. Seemingly simple development tasks proved difficult to overcome when using the BeagleBone Green Wireless for our team, specifically relating to using the PWM pins on the board. We attempted to update the firmware of the board on numerous occasions and even modify the elements of the Linux kernel to no avail. This caused our team to look at alternatives for our central controller. We elected to stay away from the other two options explored in the Electrical Design section due to the shared Linux operating system with the BeagleBone Green Wireless and the possibility of similar PWM issues. Our group member had some experience with Particle Photons and we began to explore if it satisfied our design requirements we had previously set forth.

The Photon has built-in WiFi, an 8 channel ADC with a 3.3V range, 7 PWM outputs, and an I2C controller all of which are necessary for our project. Particle also offers built-in functions to interface with web and cloud applications to simply the communication between the embedded code on the Photon and the business logic in the web application. The built-in PWM functions worked on the first attempt and with the Photon's similarity to Arduino products, there is a wide array of libraries for motor drivers, temperature sensors, and other peripheral devices. However, the Photon has fewer GPIO pins (18) as compared to the BBGW(65), which is important due to the large amount of peripheral devices in this application. This appears to be a common issue with Particle devices as SparkFun produces a Pin Expander that adds 16 GPIO ports with PWM capabilities via the I2C bus. The Photon in combination with the pin expander will provide enough I/O for our project.

Selecting a Power Supply

We elected to use multiple power supplies for our application. A 12V 5A AC to DC converter powers the stepper, and DC motors along with their motor driver boards. The max current for the system comes from the 3A stepper motor driver as only one motor will be running at a time. To get a 5V DC output for the Servo motors and VEX motors, a LM7805 voltage regulator was used to supply up to 1A. We chose to separate the 5V USB power for the Particle Photon from the 5V power for the motors due to electromagnetic effects causing variation in the DC voltage. The peripheral sensors were powered by the regulated 3.3V output pin on Photon as the sensors required little power. The Ultrasonic Knife and Toaster Oven will be powered on separate circuits in combination with relays to control the power.

Motor Integration

As set forth in Chapter 3, we purchased the Big Easy Driver from Sparkfun to control the Stepper motors for the main linear slide and the cheese extruder that were rated for 2A. These driver boards provided simple control from the Photon using the AccelStepper Library and the necessary current requirements. We needed up requiring another linear slide and stepper motor for the knife module, in which the stepper motor required a higher current rating than what the Big Easy Driver could supply. To keep the embedded development simple, we searched for another driver board that was compatible with the AccelStepper Library and had 3A current throughput. We ended up selecting a TB6560 Stepper driver board, which met those requirements at a relatively low price point. Each one of these boards require at least 2 input signals from the Photon for the timing of the step and its direction. However, only one stepper will be run at a time such that the three boards can share the step and direction pins while three individual enable pins tell which board to run. This minimizes the GPIO pin requirement to 5 from 9 pins. For the final stepper and DC motors, we repurposed an Adafruit Motor Driver board from a previous project due to the expensive nature of the project. This device required only I2C bus control, thus, minimizing the strain on the number of GPIO pins. The library that accompanied the board provided simple control of both the DC motor for the angle of the knife as well as the stepper motor for the oven conveyor. The angle of the DC motor was controlled by using a potentiometer to measure the current angle and rotate the motor in the correct direction to achieve the desired angle.

Selecting the correct parameters for the speed, acceleration, and type of step for the stepper motors required intensive testing. A ½ step proved to be acceptable for all our applications in terms of speed and relative smoothness of the stepping. This is due to our relatively lax speed and exact positioning requirements. Another important criteria was the noise level that each type of step produced. Steps less than ½ produced louder noises but a smoother movement. For some of the motors, the steps less than ½ failed to move the stepper motor due to the stepper motor driver boards being rated at the lower limit of the motor. This will be tested further during overall system testing to determine the optimal parameters for noise and speed.

Develop heating system control

The toaster oven is turned on and off by a signal from the Photon via an electrical relay. The open-air toaster oven takes a significantly long time to heat up to its maximum temperature such that it will have to be left on during operation. This time will be measured for testing purposes and to measure the initialization time for the system. A high temperature sensor will be placed within the oven to signal the Photon when the oven is ready to toast the sandwich. Additionally, the open-air design that is necessary for the conveyor belt means that the max temperature is much lower than what the toaster oven would traditionally produce. With the dial at 450 degrees, our high temperature sensor reads between 220 to 250 degrees fahrenheit for various locations in the oven above the conveyor belt. This will likely require the sandwich to left stationary in the toaster oven for a various period of time to achieve various levels of crispiness rather than varying the speed in which the belt goes through the oven. These times will have to be determined through testing and setting forth criteria for the various toast levels.

Integrate conveyor motion with scale

This module's implementation had little deviation from the initial design and prototyping in the Chapter 3 Electrical section. The stepper motor was able to provide precise control of the carriage to each sandwich location with only a single button to reset the home position of the stepper motor after each sandwich assembly.

4.3 Software Implementation

The code for the embedded system and web application can be found in the git repository at: https://github.com/dfeehrer/Slice-MQP

Ordering system back end

As described in Section 3.43, our team initially began building a Node.js and Express back end service to manage the ordering system. This server would be hosted on Heroku, and use a MongoDB database. However once we began implementing the team decided to explore a different technology stack for the back end, primarily to facilitate faster development. This stack uses Google's cloud app service, Firebase to manage the entire back end on one platform, and host the front end. Below in Table 14, is a comparison of the major differences between the two technology stacks as they relate to this project.

Table 15: Comparison of Technology Stacks

	Node.js + Express + MongoDB + Heroku	**Firebase (Firestore + Cloud Functions + Hosting)**
Authentication	Third-party module needed for authentication	Built in user authentication
Receiving order updates on front end	Poll for new changes on the server or implement websockets	Real-time database and frontend synchronization
Making new orders	Make HTTP requests to Express REST API to place orders	Insert new order objects directly into database, then Node.js cloud functions manage queue
Future code migration difficulty	Easy, because of REST API and clear separation of front and back end	Harder, because the front end will use more Firebase-specific logic
Development time	Moderate	Faster

The team ended up moving forward with the Firebase stack and built the ordering system using Firebase's realtime database, cloud functions, authentication and hosting. This decision made it much quicker to develop a working prototype to demonstrate the full operation of the MVP system without spending time implementing things like authentication.

Ordering system front end

When implementing the ordering system front-end web, the team built a modern JavaScript web application using React and Redux, and React-Router, as described in Section 3.43

The Redux "store" is a container for the global application state. In the store, the app stores information about whether the user is logged in or not, the state of UI elements, the state of orders to be placed, and the state of orders that are already placed but not yet completed. The React components render according to this global state.

To develop the front end user interface, the team used Material UI, a React component library inspired by Material Design, a design language created and used by Google. Material UI provides reusable UI building blocks like navigation bars, buttons, form elements, cards, icons and containers. In Figures 22 and 23, some of the app screens are displayed, featuring the UI the team built using Material UI components as well as custom elements. The front end consists of a welcome screen, menu screen, order status screen, and login and register screens.

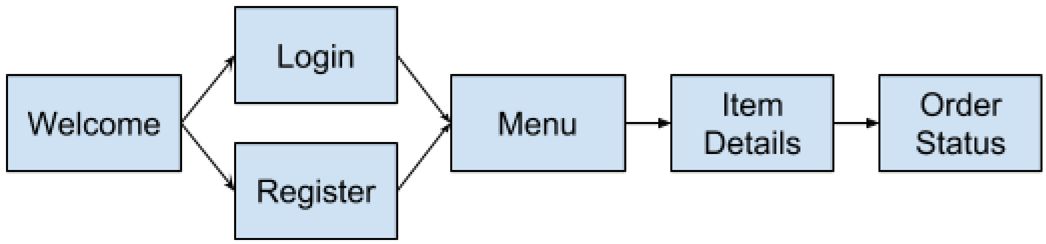


Figure 22: Ordering App UI Screen Flow

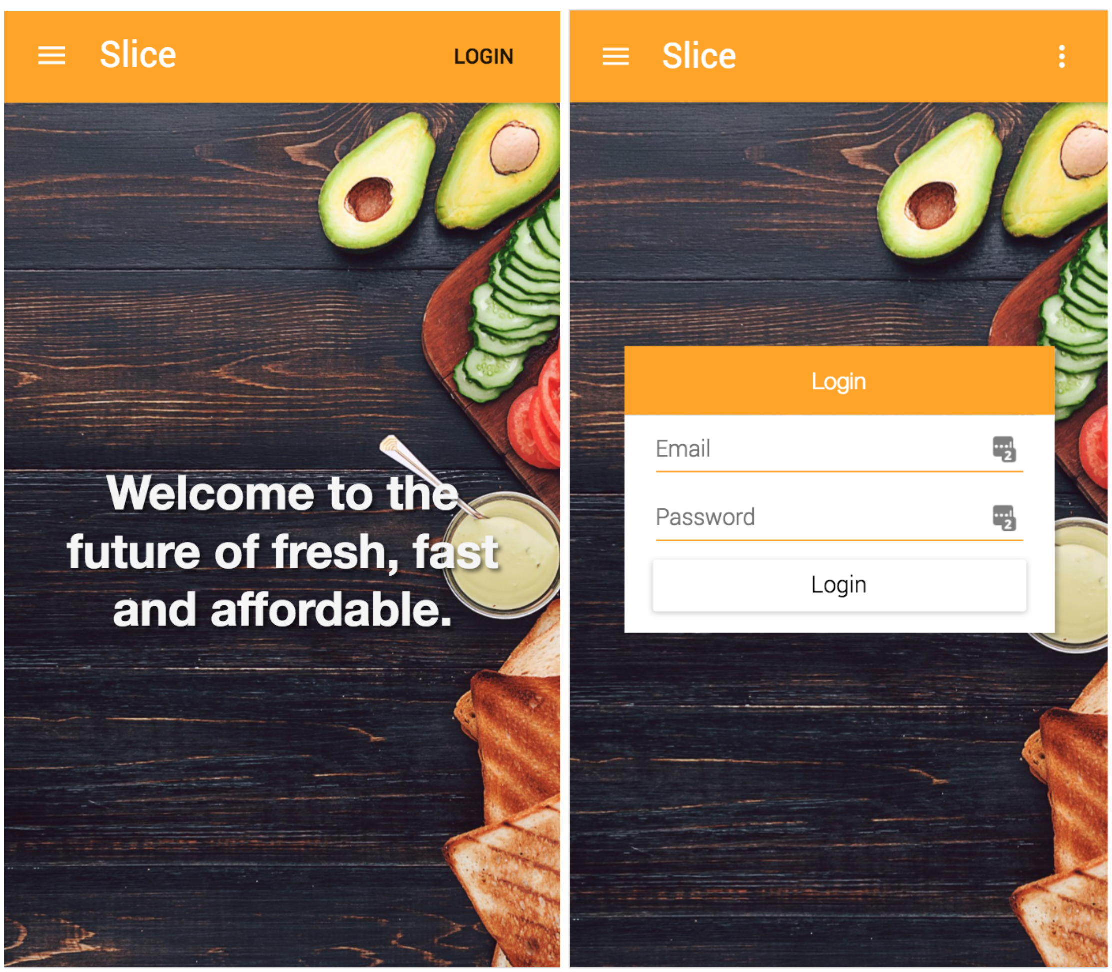


Figure 23: Welcome and Login Screens

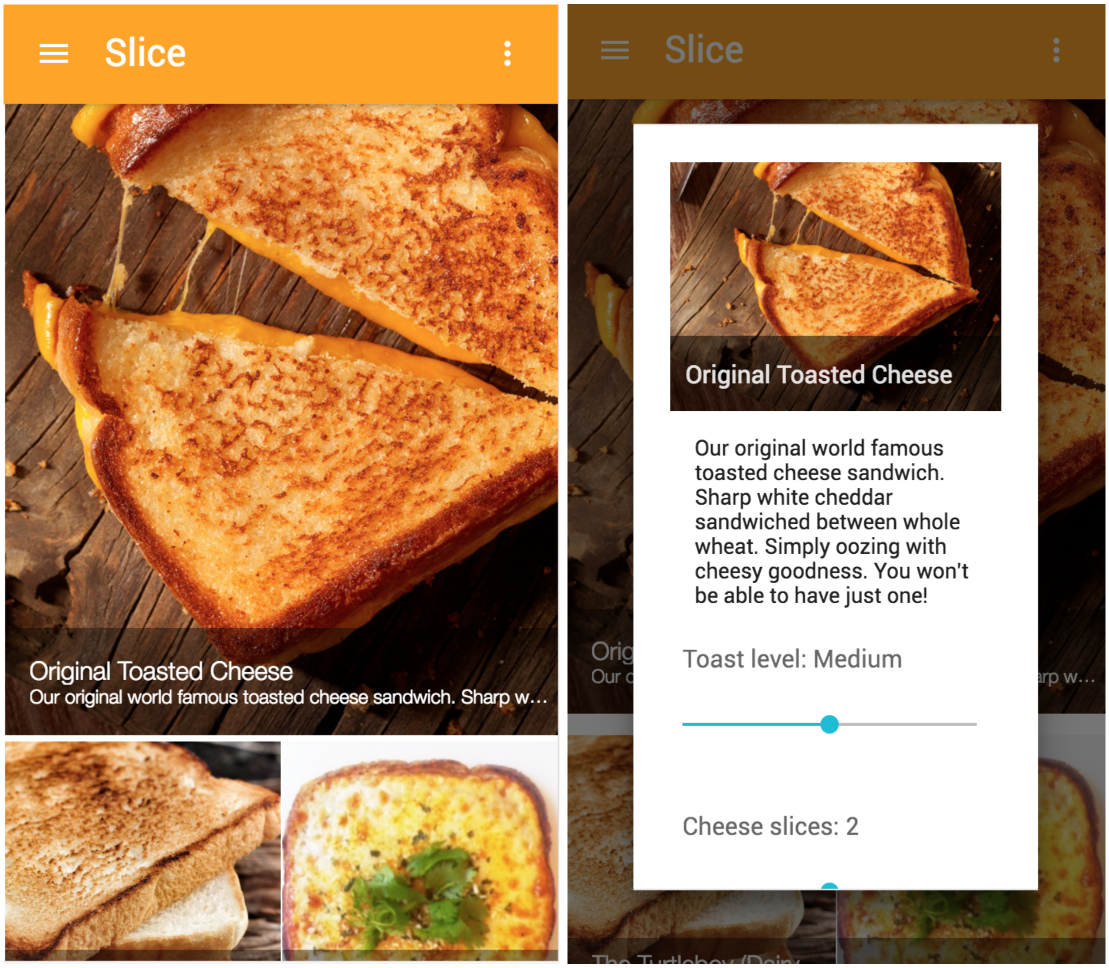


Figure 24: Menu and Item Detail View Pages

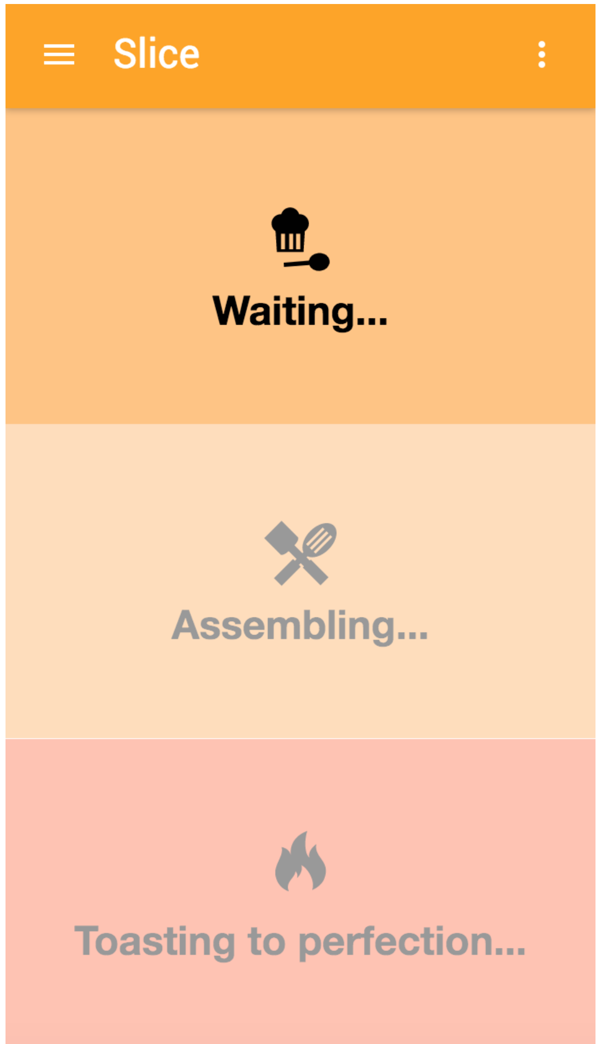


Figure 25: Order Status Page

Menu Information Database

The team used the Firebase Firestore realtime database to store the database of menu information. The "menu" collection stores information about all the items in the menu. This database collection is then retrieved by the front-end app and used to build the menu page. This allows the administrators of the system to quickly update the menu in the database without changing the front-end.

Ordering System Architecture

Figure 26 illustrates the ordering system flow. When an order is placed in the web app, the front end inserts a new order object into the Firebase "Orders" collection. This order object represents the desired preferences for the order. For the purposes of our minimum viable product, this included preference for amount of cheese, toast level, and whether or not to include chips on the side. We set up a firebase security rule to ensure that only logged in users can insert orders into the table. Once a new order is inserted, Firebase triggers our cloud functions, written in Node.js. This function validates the order and adds a reference to it in another table, called the "Order Queue." The triggered function on the queue selects the order in the queue that was added last and sends a POST request to the embedded system, which parses the request and uses the order object to set the parameters to use on the order. The embedded system also sends back several status updates during the processing of an order. These status updates are received through an Express API that is defined in the Firebase cloud functions, and is used to update the status of the order in the Orders table. The frontend then uses this status to update the order status page and inform the user on the status of their order. Once an order is set to complete, the cloud functions will select the next order in the queue and repeat the process.

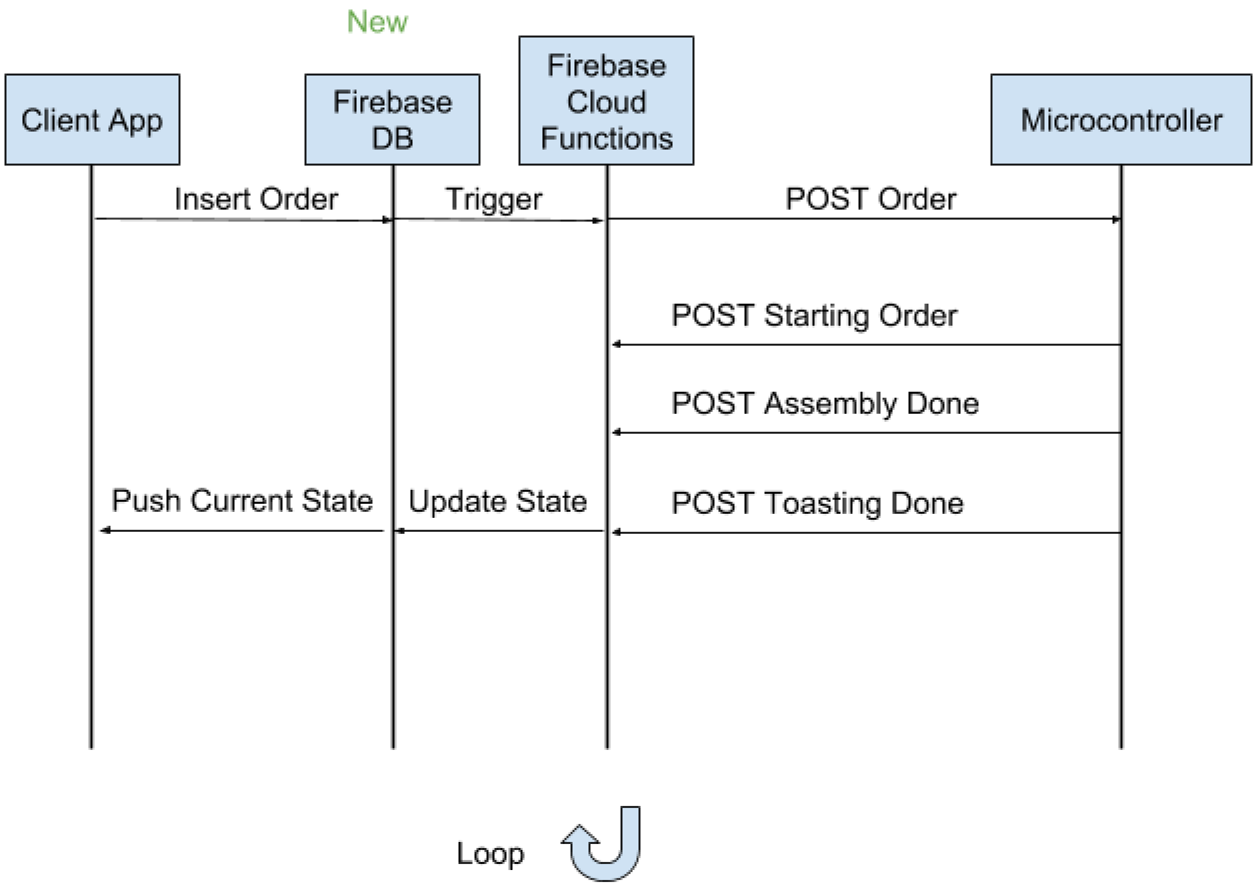


Figure 26: Ordering System Sequence Diagram

Embedded Software Control

The switch to the Particle Photon required the embedded code to shift from Python development to C++. This was not a major issue as little development had been completed when the switch occurred. Community support made embedded development rather simple once the public libraries and photon's firmware were understood fully. We faced issues with the AccelStepper library that controls the stepper motor boards initially when trying to implement the non-blocking functions. This was producing erratic motion. This would have allowed us to check inputs from limit switches on the linear slide or other locations in the body of the code. Unfortunately, we were unable to reconcile the behavior and elected to use blocking functions in combination with button driven interrupts that stop the stepper motors when necessary. This put a strain on the GPIO pins available as we were unable to offload the interrupts to the pin expander. As more sensors were added to the system, the limited amount of pins had to be addressed. We hardwired the stepping of the motor drivers to be as half stepping to remove those three pins from the Photon as well as connecting all the limit switch interrupts to the same pin and dealing with what was happening in software by knowing what module was in motion.

The embedded code is split up by module: bread, carriage, cheese, and oven module. This will serve as a template for addition of other modules in the future. The structure of the code follows encapsulation and object oriented principles. The embedded code interfaces with the ordering system back end through Particle's built in Webhook API. The ordering system back end calls a Particle function from the Cloud that starts the order and simultaneously parses an HTTP post request that contains a JSON message that represents the ingredients for a sandwich. The embedded code communicates back by publishing webhook events for when sandwich assembling has started, when toasting has started, and when the sandwich is ready for pickup.

Chapter 5: Results

5.1 System Modules

The overall system incorporated multiple modules as described in the design. The system can fit through a doorway, only spanning 29 inches wide compared to an average door at 32 inches wide. The top table holds most of the modules, while the sanitation module is below the table and under the curtain. overall, the system could produce as toasted cheese in roughly 7 minutes.

Figure 27: Full System Results

5.1.1 Bread Dispenser System Module

The bread dispenser module can hold an entire loaf of bread at the time for dispensing. In the back of the container there is room for other loaves of bread, but they must manually be placed in the dispensing position each time. The drawer them pulls a slice of bread from the stack out at a time and places the slice on the tray. The newly added plastic shield now positioned over the open slot in the wood allows for the bread slice to be positioned with ease. The bread slice can now move more easily from the stack and be placed within the tray accurately.

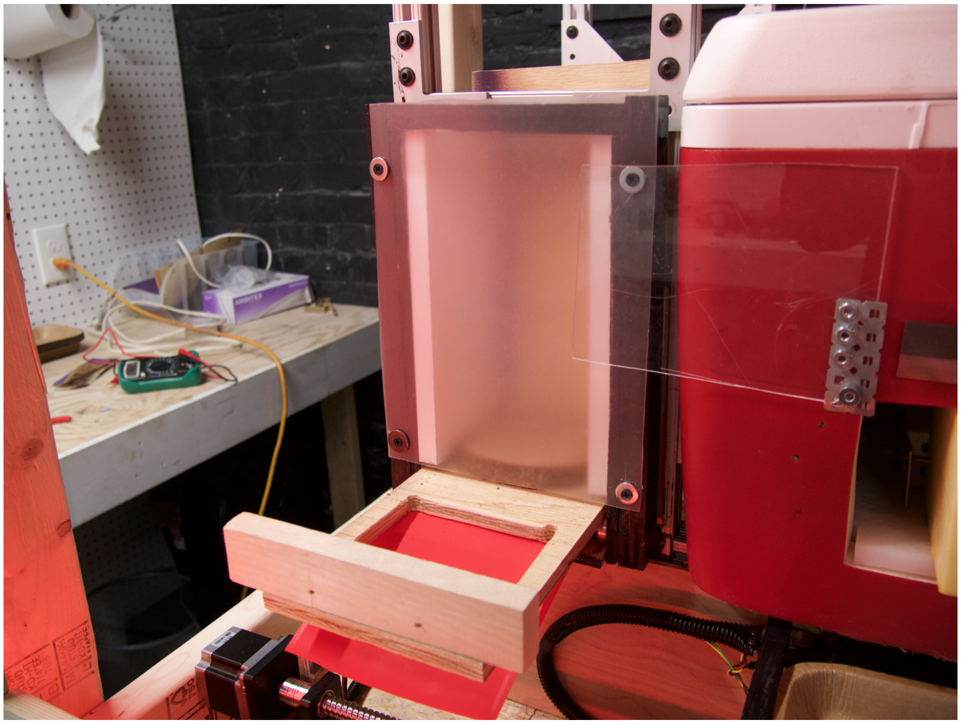


Figure 28: Bread Dispenser Module

5.1.2 Cheese Slicer Module

The cheese slicer is broken down into 2 components: the refrigeration module and the ultrasonic knife. The refrigeration unit utilizes a 48 gallon cooler, a threaded rod, a printer shuttle, a cheese fixture composed of wood and metal, and a nema 17 motor to actuate the cheese block forward. The cheese block slides on a cutting board surface for its ease in sliding in refrigeration temperatures. Additionally ice packs are place underneath the cutting board to keep the module cool while an acrylic door hooked up to a servo retains the refrigerators heat when the cheese is not being sliced.

The Ultrasonic knife is attached to an axle on the shuttle of a linear slide which is geared to a globe motor. the particular setup allows the knife to rotate and move vertically to cut cheese and lower itself into cleaning vats for its sanitation sequence.

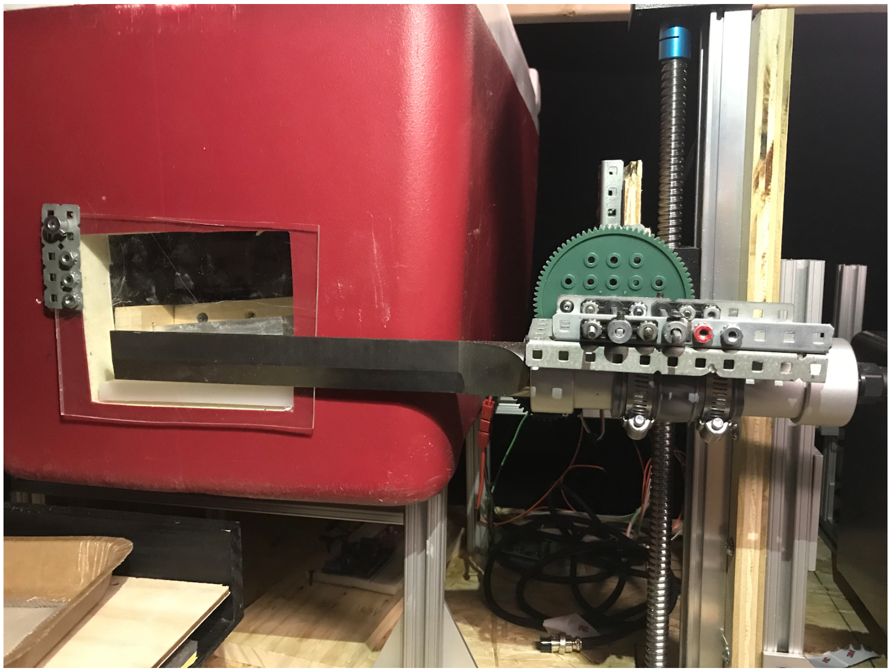


Figure 29: Cheese Slicer Module

5.1.3 Conveyor Oven Module

The Oven module is the last module of the toasted cheese process and this system toastes the toasted cheese at 250 degrees Fahrenheit. we monitor the temperature of the oven with a high temperature sensor to ensure the temperature is hot enough to toast the sandwich. Along with the high temperature sensor comes the ultrasonic proximity sensor. This sensore notifies the system when the tray passes into the conveyor along as when the try exits the conveyor. This module also composes of a custom conveyor belt drive to move the tray from position to position within the module.

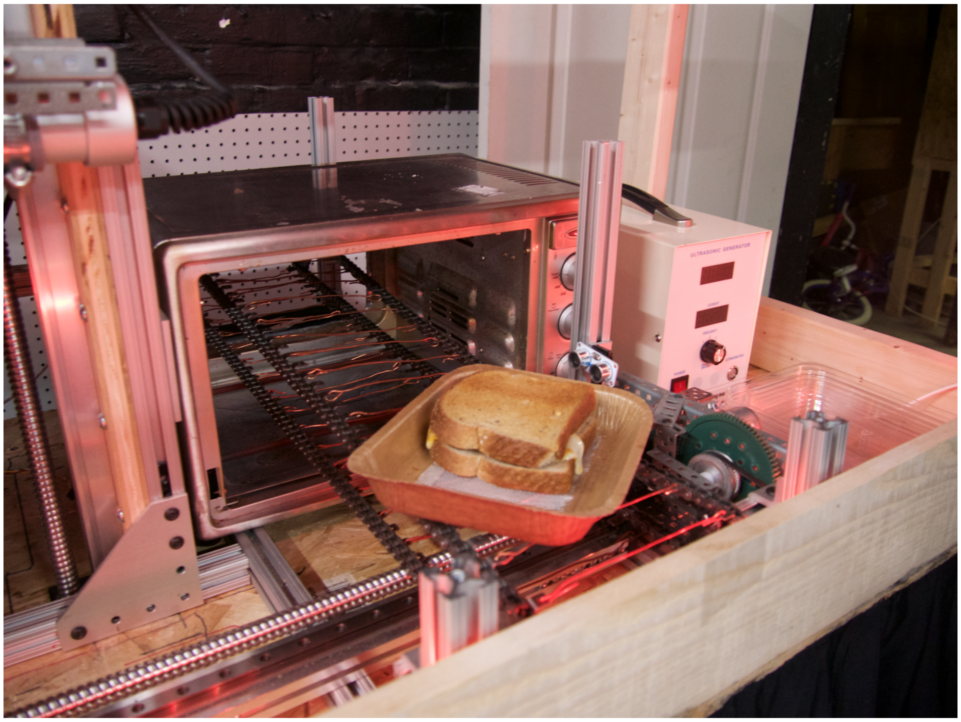


Figure 30:Conveyor Oven Module

5.1.4 Assembly Module

The assembly module is comprised of a 1000mm long servo motor actuated by a NEMA 17 motor. The module transports the sandwich tray and its contents to the main modules. Also the carriage features a load cell that measures the weight of added ingredients to confirm the proper amount has been added before the sandwich is transported to the next module.

5.1.5 Sanitation Module

The sanitation module features 3 cleaning vats of dish soap, water, and sanitizer. The vats are fixed by their weight and velcro squares on the bottom of their containers. The vats rotate on a lazy susan moved by a vex servo motor.

Figure 31: Sanitation Module

5.1.6 Embedded System

The embedded system deals with controlling the entire actuation and sensor systems within the kiosk. The embedded system contains embedded logic within the microcontroller to time the specific activation of these motors and sensors for certain system requirements. These requirements include the weight of ingredients on the scale. certain bump switches/potentiometers/encoders for the motor distances and direction, and proximity sensors. With all this information, the microcontroller actuates the motors with certain logic sent to motor drivers and controllers.

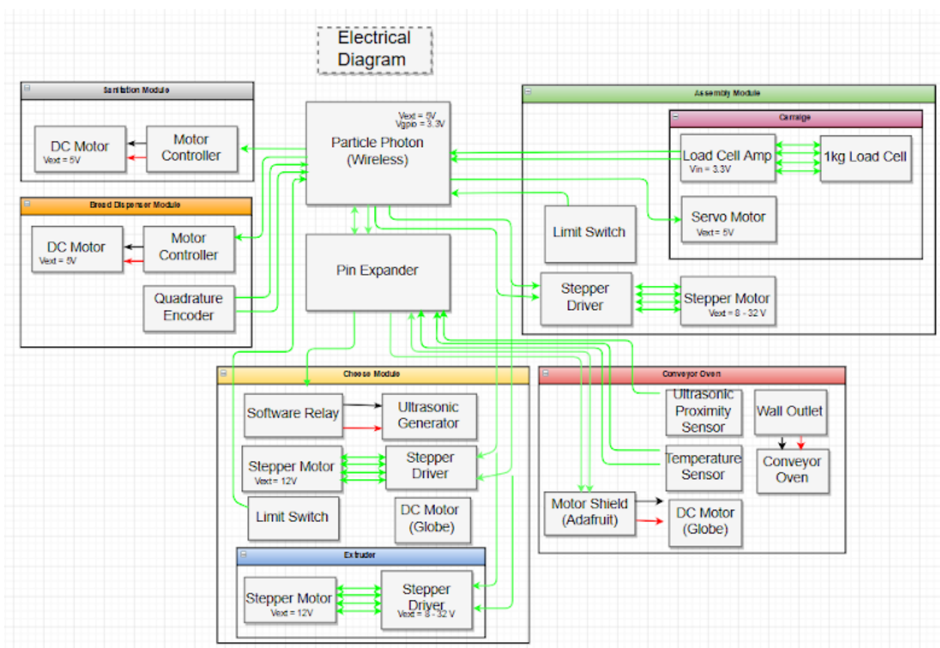


Figure 32: Embedded System Data Line Schematic

5.1.7 Ordering Web App and Web Server

The order application can be accessed through any web enabled device and their is one of these devices connected to the frame of the system. The application displays the cloud based menu on the display and provides real time updates whenever a menu item needs to be edited or changed. Alternatively, the orders are also sent to the database priority queue and transmitted to the system using HTTP protocol.

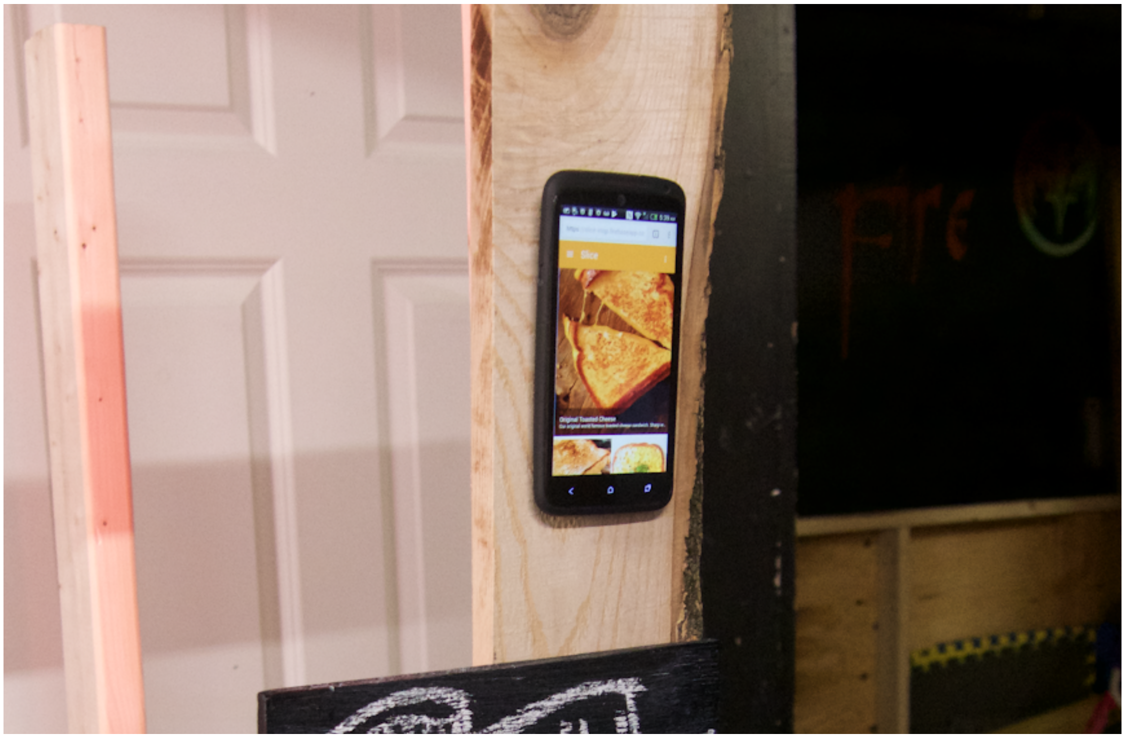


Figure 33: System Device Ordering Application

5.2 Timing, Cycles, and Profit

The team researched average life expectancies for motors, servos, toaster ovens, and the ultrasonic transducer to calculate the amount of cycles (how many times each module can complete an order without breaking. Additionally the team conducted time trials for each key module action to Identify reliability and areas of improvement. Below is a table of the amount of sequential runs could be conducted before an issue that prevented a satisfactory result occurred.

Table 16: Module/Action Timing and Life

Action/Module	Cycles Equation	Approximate Successful Cycles	Total Time to Complete Module (MM:SS)
Dispensing Bread (Per loaf of bread)	[1] 1,000 hours minimum life of globe motor/ 10 seconds of use per order	360,000	0:10
Ultrasonic Transducer	1 year lifespan/ 30 seconds max use per sandwich	43,800	0:27
Slicing Cheese (Per order)	[2] 30,000 hours for ball bearings/ 2 minutes of use per order	900,000	0:27
Assembly	[2] 30,000 hours for ball bearings/ 5 minutes of use per order	360,000	1:08
Transfer to Conveyor Oven	[3] 50 hours continuous use/2 seconds of operation per order	90,000	0:02
Toasting	[4] 5 years minimum life expectancy of toaster oven / Total time per order	262,800	5:30
Sanitation	[3] 50 hours continuous use/10 seconds of servo operation per order	18,000	1:20

[1]http://www.mavin.com/pdf/Globe%20Industries%2033A643.pdf
[2]https://download.beckhoff.com/download/Document/Catalog/Main_Catalog/english/Beckhoff_Stepper-Motors.pdf
[3] https://www.vexforum.com/index.php/8348-how-do-motors-break/0
[4]https://www.energystar.gov/sites/default/files/asset/document/ENERGY_STAR_Scoping_Report_Toaster_Ovens.pdf

The total time it takes to create one sandwich ended up being 7:55. Which means that over 180 sandwiches can be made each day. It is important to note that the total time to make a sandwich is not merely the sum of all the times because the sanitation sequence can run when the grilled cheese is being transferred to the conveyor oven and when the sandwich is being toasted and the assembly time is merely the duration the tray is moving along the carriage.

Theoretically, we can calculate the profit we can make from the prototype if we were to take the component with the smallest successful cycles, multiply that by the average price of a grilled cheese on the market today, subtract the cost for ingredients, and subtract the initial cost of the entire system to generate the lowest possible profit margin. granted we are assuming that all sandwiches will sell fast enough that no food will go bad, not calculating rent cost for the space used by the system, etc. but it will give us a general idea of the viability of the machine. Below is that calculation and the smallest scale of profit we can expect to see before having to service the machine.

$$(18{,}000 *(\$3.99-\$0.48))-\$2{,}000 = \$61{,}180$$

5.3 Placement

Since there are objects being moved mechanically there is some error associated with placement. For example, the bread may not land in the same place every time or the cheese may not land on the bread in the exact same spot every time.

During observation we found that the plastic flap on the bread dispenser acted as a stabilizer for the bread placement onto the container. The bread was extremely accurate and depended on the positioning of the carriage more so when dispensing bread. When referring to the cheese slicer module the fall distance became more problematic. Depending on the slice width the placement became irregular. Larger solid slices of cheese became more predictable and fell more steadily. Thinner slices of cheese tended to fold over and would fall at different rates making it difficult to predict. Lowering the distance between the slicer and the carriage could help prevent error in this phase of assembly.

Chapter 6: Future Improvements

6.1 Future Work

Over the course of the project the team made several adjustments, refinements, and had formed new ideas for the next prototype. Below are some of the suggestions the team could not get to in the timeframe of the product but would like to see be done in the 2nd prototype to improve the quality of the machine.

6.1.1 System

Include heated lockers to store sandwiches. To maximize the time the system is making sandwiches, the system can place the sandwich into heated lockers instead of waiting for the customer to pick up the sandwich on the conveyor belt.

Include condiments, vegetable slicers, chip dispensers, and soup. increasing the ingredients included in the system will help diversify the menu. make sure to use key ingredients that locals would like to limit any food going bad. Adding a chip dispenser may also make the meal more appealing. Even tomato soup may be a nice touch as well to make the kiosk more well rounded and appealing to customers.

Incorporate fire suppression and security systems. Need to meet regulations and safety standards if the prototype is to be implemented in industry. These standards include fire protection systems to prevent any possibility of fire damage. And also security systems to prevent any individual from trying to break the machine and collect money or ingredients.

6.1.2 Mechanical

Incorporate a bread maker in the back of the bread dispenser to produce the aromatic smells that attract customers to the average sandwich shop/bakery. The team noticed that one of the key attributes to a successful restaurant is the smell. The system itself did not give off any pleasing smells that would entice members. Originally the bread dispenser was made so that it could fit 2 loaves of bread, but instead of including the second loaf of bread a bread maker could be incorporated in the back compartment, sliced, and placed in the proper location. Automating this part of the system would give the pleasing aroma with the potential to fit more than 2 loaves of bread at a time. (if it were robust enough the yeast, flour, etc. could be inputted rather than pre sliced bread). The downside is that only one type of bread can be dispensed per dispenser so multiple would be needed if different bread types were desired.

Utilize a spring loaded dispensing mechanism or piston to dispense the bread. Originally the team utilized a rack and pinion design so that the dispensing shelf would never get misaligned or stuck. unfortunately despite testing over 5 motors with the shelf and multiple gear ratios, the team could not get the adequate speed we wanted out of the design to get a proper placement of the bread onto the carriage. To get the consistency the team had to sacrifice limiting contact surfaces and added a tongue to the current design to allow consistent placement of bread slices onto the carriage. For prototype 1, the tongue will simply need to be cleaned daily.

Utilize a crumb tray on the Carriage. When the bread is dispensed onto its container we noticed that crumbs become scattered on the carriage. Instead of reaching into the machine to clean the surface a removable tray could be added to throw away debris and clean the surface with more ease

Use a rotary shelving system in the Refrigeration unit to incorporate more deli meats and cheeses. The way the refrigeration unit was set up to only dispense one log of cheese for proof of concept. With the 48 gallon refrigeration space, a rotary style shelving unit could maximize space and introduce different meats and cheeses to reduce the need to refill the machine after a log is exhausted.

6.1.2 Embedded System

The current prototype utilizes a centralized controller, a Particle Photon, to control the movements of the entire system. This minimizes cost of the system, but causes failures in the system to be difficult to detect to the complexity of the system. Multiple motor driver boards for stepper, DC, Vex Servo, and 2-wire Motors are controlled by the Photon and yields significant noise in the system to the point of altering the position of servo motors in the system. Additionally, failures in the system due to system due to back EMF or motor stalls cause motor drivers and the central controllers to fail. These issues would be able to be addressed faster in a distributed system.

Distributed Control to maximize Modular Flexibility: A distributed system would allow each module to have fewer dependencies on the other modules in addition to isolating failures in the system, resulting in faster identification and fixes to the system. This would also minimize noise in A distributed system would also allow for plug and play functionality to add modules such as meat cutting, vegetable modules and condiments modules without having to modify the firmware of the system and expand the system's menu. This would expand the modular flexibility of the system, providing benefits for both the developer and the customer.

More Robust Ingredient Addition Verification: The system currently employs a load cell to measure weight changes on the main carriage. This is used to verify ingredient addition to the system. However, this sensor failures to provide a full picture of what is occurring in the system. It provides zero information about the placement of ingredients on the sandwich or the tray itself. A more robust system including critical information about placement could be implemented using computer vision to monitor ingredient addition as well as toasting level in case of variance in the oven heating. This would allow for the system to ensure a quality final product and react if a mistake was made. This is currently not the case as the system just throws an error. In an ideal system, the kiosk would discard the failed sandwich and start from scratch to craft the perfect sandwich.

6.1.3 Ordering Application

The prototype of the ordering web application demonstrated the basic desired functionality of an ordering system for the kiosk, however, much work would need to be down to produce an application that could meet the needs of a minimum viable product kiosk, serving real customers. The team identified several key areas for improvement in the application:

Migrate from Firebase to a more scalable cloud platform: While Firebase served the project well in the prototyping phase, in order to build a more scalable software system, migrating to a more expandable and enterprise-grade cloud platform such as Amazon Web Services may necessary for long term support and efficient scaling.

More robust and ordering infrastructure: In order to make the application functional for everyday use, it would also need to include more complex ordering flow, including server-side storing of orders, support for multiple items in an order, and the ability to cancel and order.

Move business logic to back-end and secure ordering API: Some of the business logic in the application is handled on the front-end. In the future, this logic should be move to the back-end in order to make the application more secure and to ensure the front and back-end are loosely coupled.

Administrator application: The application needs several administrator features including storing menu item information, and ingredient levels, for the system to be able to function completely. This administrator application could also include the ability to initiate cleaning mode and ingredient stocking mode and to calibrate the different modules.

6.1.4 Sandwich Complexity

Overall the team envisions that this technology could be built upon to develop a fully automated robotic kiosk that could make more complicated sandwiches. The prototype's capabilities however are limited to producing a grilled cheese. Despite its status as a simplified sandwich, a grilled cheese comes with its own challenges that other sandwiches do not encounter. For example, a grilled cheese sandwich must be toasted on the top and bottom evenly. Other subs only need to be toasted on the top and the bottom is merely forgotten. This required us to tweak our tray design accordingly to allow for the grilled cheese to even cook properly.

The Slice team is still confident a Slice system is both desirable and profitable. To give some profit potential reference for the system, an average subway sells 300 sandwiches a day and with 44,000 locations worldwide they generate 13.2 million sandwiches a day (Alvarez, 2017b). Which would mean that if 44,000 slice machines were to replace every Subway the initial capital cost would be 88 million yet the daily profit would be 46.3 million dollars. Meaning in two days the capital costs for making the prototype would be paid for. Additionally the system would be able to operate confidentiality for 60 days until the servo for the sanitation vat would need to be replaced; equating to a profit of 2.69 billion in 60 days. granted our system can only make grilled cheeses and only 180 sandwiches a day therefore the profit is certainly lower than one would expect for a fully automated sandwich kiosk. However, the high profit margin gives the slice team confidence that the system will be desirable once the major challenges are addressed and a refined system is created.

6.2 Conclusion

Our team initially decided to work with sandwiches because of the market potential and because they consist mainly of ready-to-eat foods. While this decision did simplify to process of ensuring the food was fully cooked and safe to eat, sandwiches also came with their own reliability and complexity challenges. Assembling a sandwich required sufficient dexterity to precisely dispense and place ingredients that varied in size and shape. This process required a great deal of tuning and trial and error and the overall process was not totally reliable. When it comes to operating a restaurant for a continuous period of time, it is critical that the automated process does not fail at a significant rate that would hinder restaurant operations, cause downtime or damage customer perception. After researching this automation challenge for the past nine months, we have determined that sandwiches may not be the ideal target for food automation at the current time.

Despite the roadblocks in the sandwich industry, other food segments, specifically salads, bowls and other less precise foods allow for more reliable autonomous assembly and a better looking final result. Robotics technology currently allows for these food segments to be success in producing food to an equal, if not superior level. This is supported by other food startups launching across the country with Spyce in Boston, MA launching their first commercial location in April of 2018. Other startups are certainly not far behind, attacking other food segments and it will be interesting to see how long large chain restaurants wait to invest in these types of technologies.

While a fully automated Subway appears to be unattainable in the immediate future, we believe that as the dexterity of robotic actuators improves in the future, automation will be able to take on food segments with more difficult food preparation and assembly. The next step in the food automation world in a restaurant setting may be to study how people react to "robots" making their food and how to address any concerns.

Another major roadblock for food automation is its side effect of eliminating jobs in restaurants and fast-food chains. This technology doesn't only threaten 100's of jobs, but millions. This became clear throughout our project as we presented our vision to alumni, business professionals, and professors and were questioned on how this very issue. It was an extremely difficult question to answer and we believe that our team, like most of society, has still not totally figured out how to address this issue. We believe that many jobs in the future could be eliminated due to automation across all industries. This is a larger societal problem, leading to a critical question that the world will have to answer: How can human labor and automation coexist to provide maximum benefit to society?

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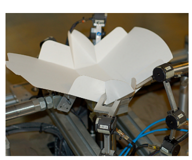
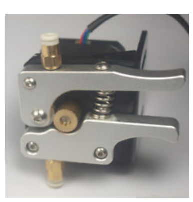
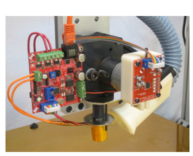
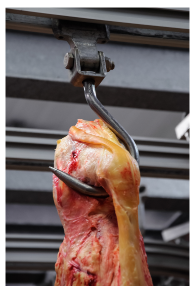
Appendices:

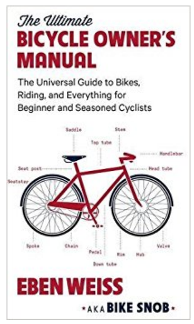
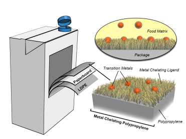
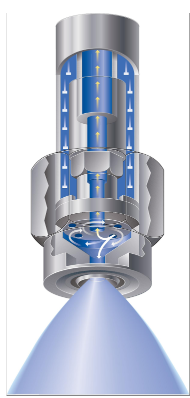
Appendix A: Mechanical Component Options

Design Type	Design	Picture	Pros	Cons	Materials
Motion	Linear Slide (Newmark Systems Incorporated, 2016)		One Sandwich at a time, Easier to control, Less error	Needs a home switch	Slides, Motor, Belt
	Conveyor (IndiaMART, 2017)		Can handle multiple sandwiches at a time		Conveyor Belt, 2 cylinders, motors
Packaging	Printer Style (HP Printer Support, 2011)		easy to load, pre-cut packaging	Requires folding and pressing of some sort	foil, components of printer feeder
	Roll and Cut (Wenzhou Qichen Industry & Trade Co., Lt, 2013)		Continuous roll	Requires cutting mechanism, must stop assembly to load, and must be folded and pressed	Roll of packing material, cutting mechanism, motor to unroll
	Box (Be Green Packaging Store, 2017)		Container can funnel any droppings onto sandwich, no folding required	More expensive, need unloading mechanism to take off box from stack	Unloading mechanism, box fixture, packaging boxes
	Origami Folded Container (Dai & Caldwell, 2010)		Sophistication appeals to customer	More moving parts than necessary	Origami designed folding mechanism, pre-folded packaging
	Plate (Be Green Packaging Store, 2017)		Simple	Cannot take sandwich on the go	Plate

Refrigera tion	Modular Refrigerator (Catering Equipment Ireland, 2017)		only cools the ingredients, maximizes space for sandwich assembly	Sliding door mechanism	Refrigeration unit
	Entire Refrigerator (73-- food service equipment - shelves & appliances.2 015)		Refrigerate everything except electronics and motors, keeps everything fresh	Higher cost, must	Retrofit refrigeration display unit or refrigeration components and construct insulated box
Slicers	Deli Slicer (Amazon.co m, 2017)		high speed blade, high inertia keeps blade momentum for optimum cuts, automatic settings,can slice thin	Tedious work to clean surfaces, bulky	Deli Slicer
	Electric knife (Amazon.co m Inc., 2017)		minimal surface to clean, reciprocation makes cutting easier,	Potential food debris from sawing motion, one fixed point	Electric knife
	Sonic Vibration Knife (Alibaba.co m, 2017)		clean cuts, does not dull fast	Expensive, bulky, replacement blades expensive	Sonic vibrator, knife blade, knife fixture
	Wire Slicer		virtually no cleaning surface. swap out wire	May need to heat up to cut through some meats, smell issue, wire breaking	Wire, wire fixture, 4 bar linkage or piston
	Potato Slicer Table (Ebay.com, 2017)		one blade, single surface to clean		Mandolin potato slicer

	Spiral Potato Peeler (Ebay.com, 2017b)		leaves no food left behind, cuts spiral continuous stands, minimal surfaces to clean	Requires cutting mechanism to cut strand onto sandwich	Crank, vice screw, stop plate and blade
	Food processing blades (*Dito sama TRS: Vegetable slicers*. 2010)		high powered and can cut meats, cheeses, and vegetables. small containment into processor, requires manual operation for most	Processes too much food at once, tough to control, lots of surfaces to clean, multiple blades to clean	Food Processor
	Reciprocating Band-Saw		can spool long band saw for multiple uses, reciprocates for cleaner cut	Complex with 2 gear systems and 4 motors, not most aesthetically pleasing	Band saw blade, 2 reciprocating rack and pinions, spools,
Dispensers	Cereal DIspensers (Wal-Mart Stores, 2017)		simple, precut vegetables	Difficult to keep vegetables like cut tomatoes fresh	DIspenser
	Bread Dispenser (Buf-Tec,)		Can drop a slice of bread straight down, load a full loaf and multiple loaves, compact, vertical design	Cost	Dispenser
Extruders	Spring Action Extrusion		Easy to implement	Force constant changes over time affecting extrusion of condiments	Spring, Extruding nozzle, Fixture, Container
	Motor Powered extrusion		Maximum control	Variable speed may be challenging, must power each extruder	DC motor, Extruding nozzle, FIxture, Container

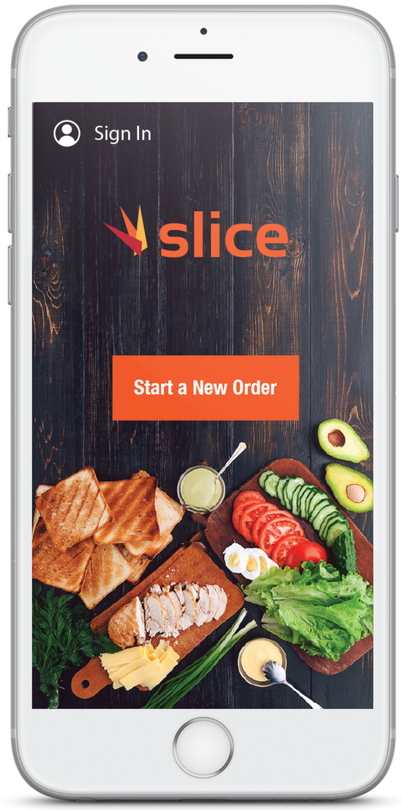
	Pneumatic Extruder (Landoni, 2015)		Good control, and perfect for extruding soft materials like condiments	Variable speed may be challenging, must power each extruder	Syringe, Piston, Extruding nozzle
Heating Mechanism	Panini Press (Hamilton Beach Brands, 2017)		Adds nice pressing motion to sandwich to put it all together	Difficult to get sandwhich onto and off surface	Panini Press, Piston or motor with crank
	Conveyor Oven (Belleco, 2006)		250 to 500 degree farenheit, toasts through sandwich, aesthetically pleasing and public comfortable	Large	Conveyor Oven
Fixtures	Meat Hooks		Simple	May rip the meat or cheese and no longer be attached	Hook
	Tac Clamp		Firm grip around surfaces of the meat or cheese	difficult to get motion right, may have difficulty with different shaped meats and cheeses	Clamps with tacs, hinges, 3 pistons
	Suction Cup		Maximizes surface available to be cut	Suction cup would likely require a compressor with constant suction since a mechanical cup may become undone	Suction cup, compressor, tube
Guides	Funnel		Mechanically guide the log to the correct cutting surface. No need to control electronically	No error detection	Funnel

	Pneumatic Clamps		Maximum control	2 pistons and 2 motors	Clamps, hinges, 3 pistons
	Tube		Simple, translucent, functions as a container	may be difficult to clean inside	PVC pipe
Sanitation	Cleaning Manual		Easy to guide	May miss something, or may not do an effective clean	Paper
	UV Light		Sterilizes majority of surfaces it shines on	Only Kills certain type of bacteria, May not be aesthetically pleasing and look like a lab instead of a sandwich maker	UV lights
	Vacuum Sealed Assembly Area		Ensures no bacteria is present	Must seal properly, and difficult to implement	Insulation and sealed containers
	Rinsing Nozzles		Can automate, can do at night	Decent amount of sensing to implement	Nozzle, tubing

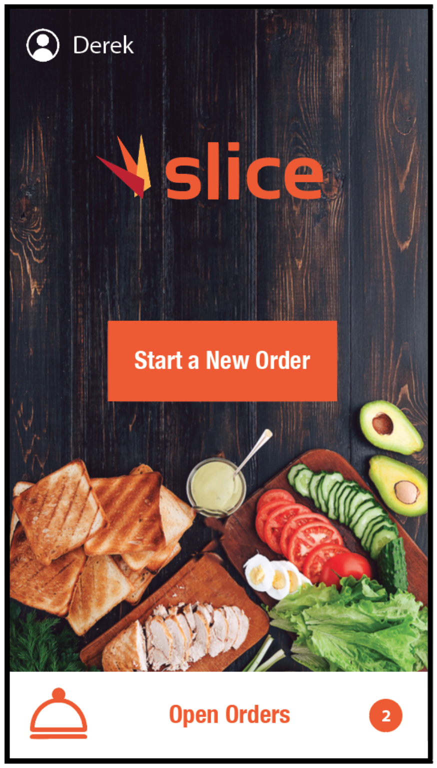
(Newmark Systems Incorporated, 2016)
(IndiaMART, 2017)
(HP Printer Support, 2011)
(Wenzhou Qichen Industry & Trade Co., Lt, 2013)
(Be Green Packaging Store, 2017)
(Dai & Caldwell, 2010)

(Catering Equipment Ireland, 2017)
(73-- food service equipment - shelves & appliances.2015)
(Amazon.com, 2017)
(Amazon.com Inc., 2017)
(Alibaba.com, 2017)
(Belleco, 2006)
(Ebay.com, 2017a)
(Ebay.com, 2017b)
(*Dito sama TRS: Vegetable slicers.* 2010)
(Wal-Mart Stores, 2017)
(Buf-Tec,)
(Landoni, 2015)
(Hamilton Beach Brands, 2017)

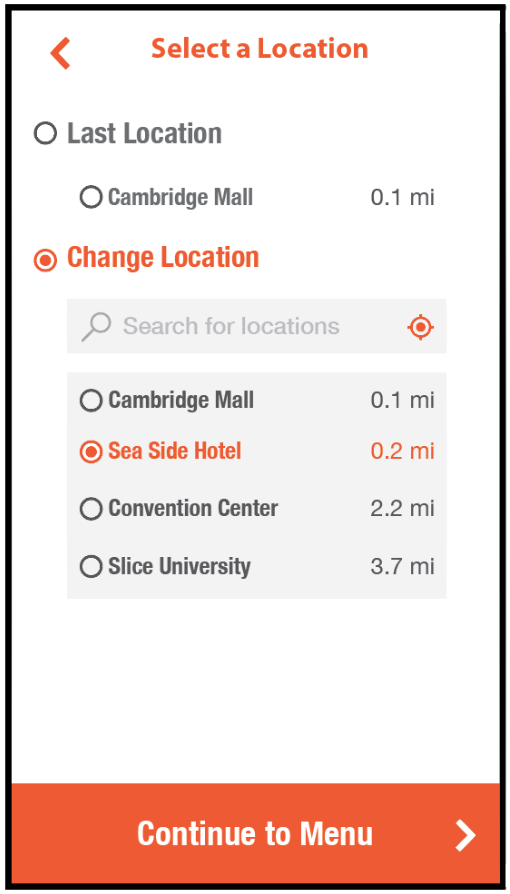
Appendix B: Concept rendering of Slice app running on a mobile phone



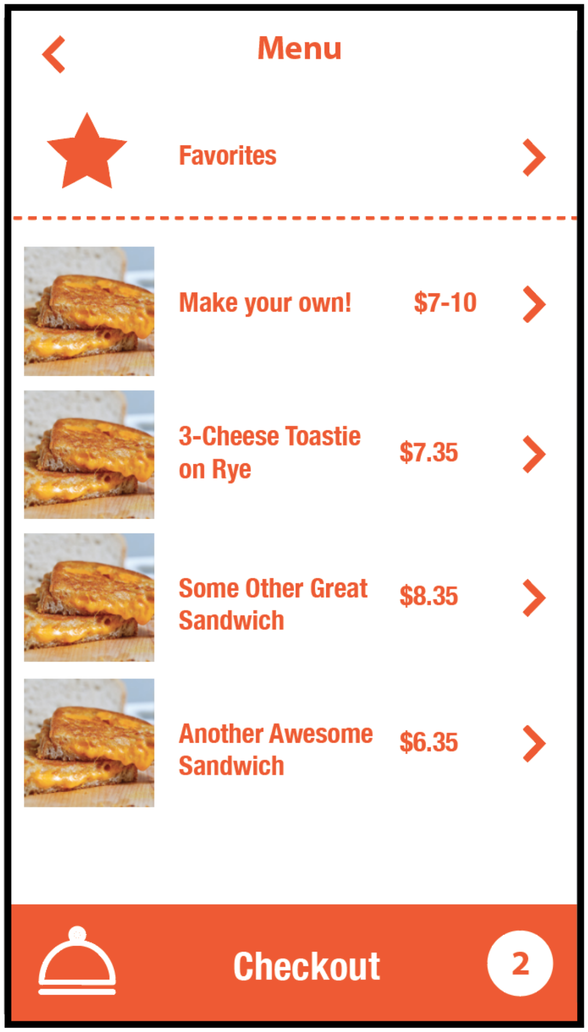
Appendix C: UI Mockup of app home screen when user is signed in and has orders that are in progress

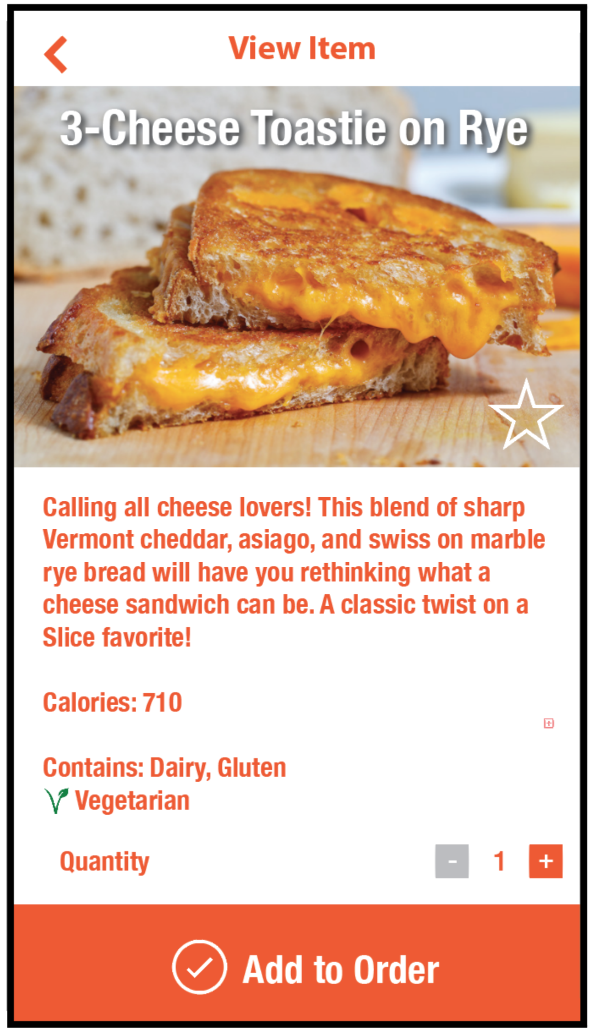


Appendix D: UI Mockup of location selection page

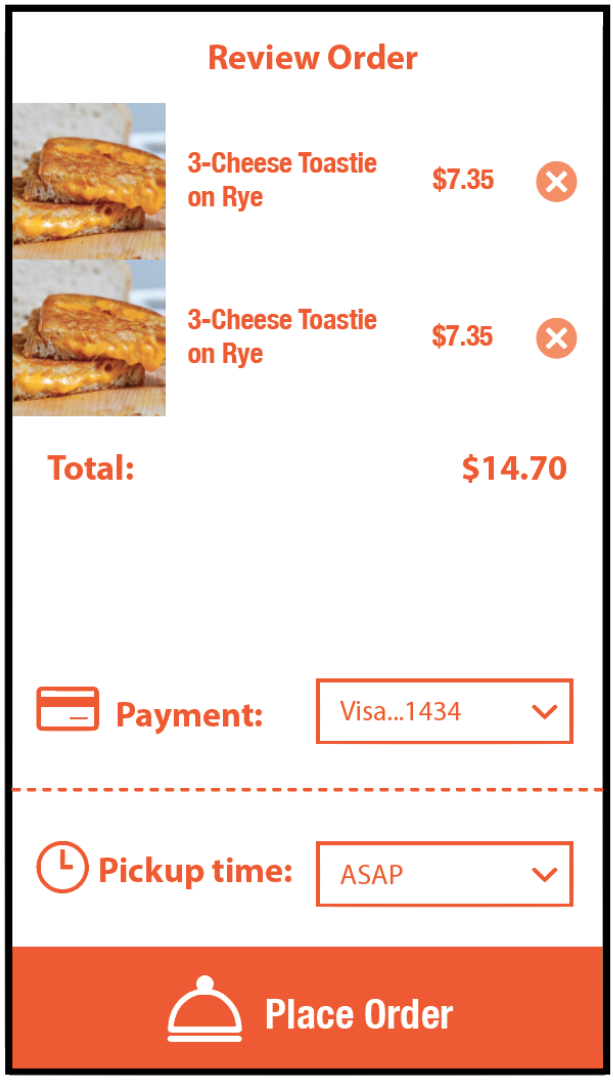


Appendix E: UI Mockups of menu page for a given location, and the item view page when a user selects an item.

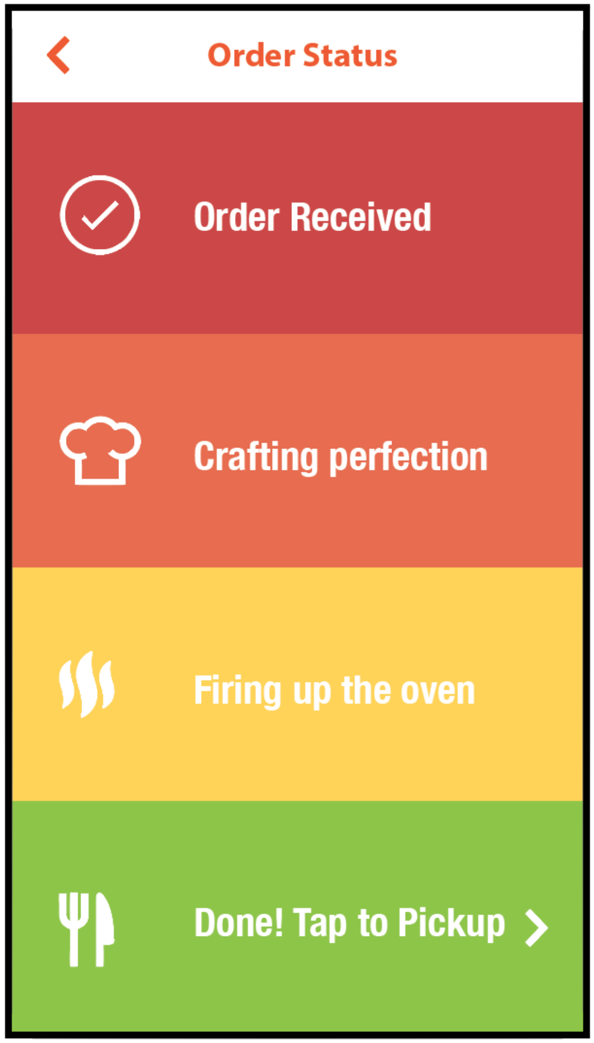




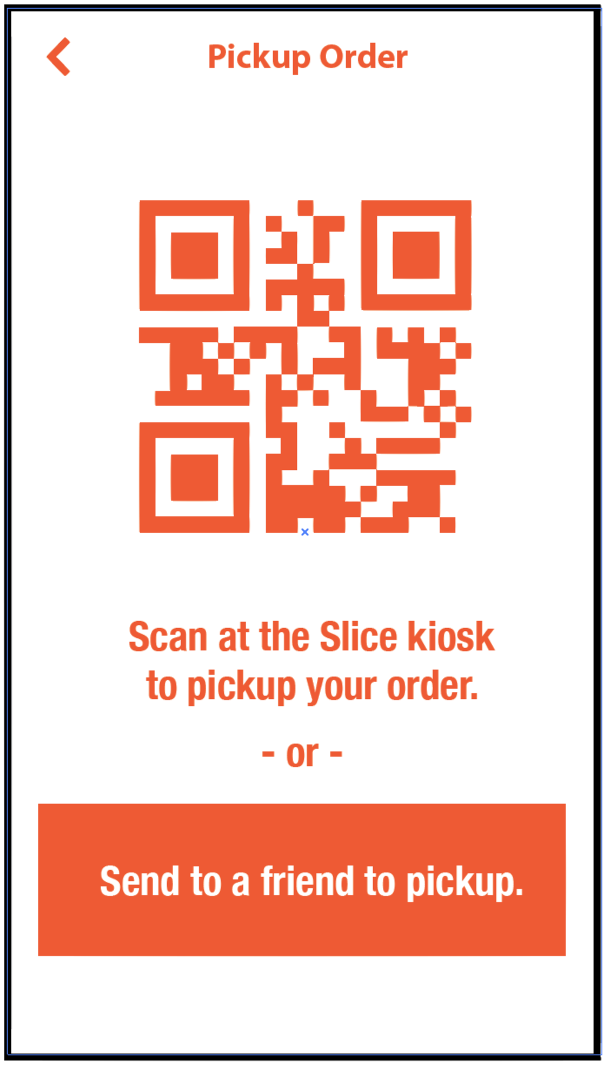
Appendix F: UI Mockup of the order review page



Appendix G: UI Mockup of the order status page



Appendix H: UI Mockup of the order pickup page



Appendix I: UI Mockup of the order pickup page