# Observations of Decision-Making in the Mechanical Design Process in a Start-Up Company

by

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in partial fulfillment of the requirements for the degree of
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## Abstract

This thesis examines the effect that working at a start-up company has on decisions and considerations during the mechanical design process, and is based on the experience of the author while interning at an AI robotics start-up as part of an MIT graduate students' team. An overview of the company is provided, the different stages of the product development are introduced and Miso's approach to the design of the modules for its product is discussed. Advantages and disadvantages of the approach are examined with examples, and suggestions for improvement are provided. In particular, the role of first-order-analysis (FOA) as a powerful tool to predict problems early is presented, the need for order as a necessary condition for growth is discussed, and next steps for the future production ramp-up stage are shared.

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# Contents

# List of Figures

# Chapter 1

# Introduction

This thesis describes two case studies of a mechanical design process at a small, early stage start-up company, and offers insights into the way design choices are made in such an environment.

This chapter will provide the reader context about the start-up company that serves as a case study for this thesis, its vision and goals, and the relevant specifications of the main product. Also, applicable norms and regulations for design in this field will be introduced. Finally, an overview of how this thesis will develop will be presented.

## 1.1 Miso Robotics

### 1.1.1 Company Background and Value Proposition

Miso Robotics is a start-up company based in Pasadena, California. It was founded in July 2016 by David Zito, Ryan Sinnet and Robert Anderson. The three entrepreneurs envisioned the integration of robotics to commercial kitchen environments to collaborate with humans in cooking tasks. The main features of the Robotic Kitchen Assistant is that it will be able to perform different tasks supporting of the human cooks, will learn new capabilities over time, will integrate easily to the kitchen work flows and speed up production, while increasing consistency. Ultimately, the robot will be able to do tasks that vary from chopping vegetables to flipping burgers, requiring at most a tool change.

### 1.1.2 The Robotic Kitchen Assistant

The Robotic Kitchen Assistant is called Flippy [6] because the first implemented functionality was cooking burgers on a grill. The first system is able to handle many burgers at the same time, distinguish cheese burgers from simple burgers, flip them when needed, control the progress of the cooking of each individual burger in the grill, deposit them in a tray once they are ready and scrape the grill afterwards.

Currently, the team is working on teaching the robot to fry. The goal is to handle fry baskets. The frying application will be discussed in more detail in section 3.1.

The first Flippy system installed can be visited at the CaliBurger branch in Pasadena. It is shown in Figure 1-1.

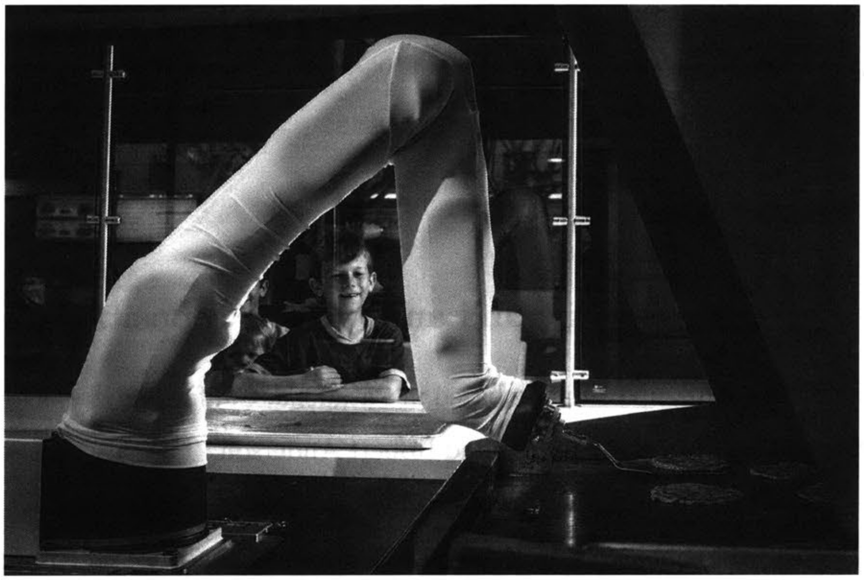


Figure 1-1: Flippy setup in CaliBurger.[2]

## 1.2 The Deterministic Design Process

The design process used follows the guidelines taught by professor Alexander Slocum at MIT. It consists of three phases and requires to iteratively consider six key components, as described in his freely available book "FUNdaMENTALS of Design" [7]. The three phases are: 1) Strategy and Concept, 2) Detailed Engineering and Development, and 3) Integration and Test. The six categories of thought that must be addressed in the process are Functional Requirements, Design Parameters, Analysis, References, Risks and Countermeasures.

## 1.3 Design Considerations for Kitchen Applications: NSF Standards

NSF international is a reference organization that writes standards and certifies products to protect the world's "food, water, consumer products, and environment" [3]. The protection of "global human health" is their mission. As far as food equipment is concerned, the NSF standards 169 ("Special Purpose Food Equipment and Devices") and 51 ("Food Equipment Materials") set the minimum sanitation requirements for food equipment design and materials. The practices suggested in the norms make the product surfaces easily cleanable and eliminate the possibility of dirt accumulation and vermin harborage. All of the design rules and requirements presented in the norms mentioned must be followed to obtain the NSF certification. In practice, this certification is required by the food equipment market for its recognized credibility on the field.

## 1.4 Overview of this Thesis

This thesis is structured in three chapters. Chapter two will present general reflections resulting from working as a Mechanical Design Engineer at the start-up Miso Robotics. The third chapter will present two case studies that illustrate the benefits or applications of some of those principles in practice.

# Chapter 2

# Mechanical Design in a Start-up Company

## 2.1 The Lean Start-Up for Hardware Companies

Miso Robotics has many aspects in common with the "lean start-up" approach proposed by Eric Ries in his book The Lean Start-Up. [5] The design process has short iteration times in the build-measure-learn loop and pursues a Minimum Viable Product to quickly build, install, test and learn. The objective is to maximize learning about the product before committing large amounts of resources to its development. This resources are usually limited for a start-up company.

As for the design of mechanical components, two requirements are automatically added: the design cycle has to be short (in the order of a couple of days to a few weeks, depending on the complexity of the module being designed), and the product must work satisfactorily and reliably. This translates into a preference for off-the-shelf, short-lead-time, easy-to-adapt, already-NSF-certified components.

Although the approach has led to great results they could be improved even further by noting the following opportunities:

1. To maintain lead-times as short as possible, an even more important place could be given to in-depth analysis. In general, analysis may be viewed as an

inefficient process because it can be developed to different levels of depth and complexity and take an unlimited amount of time. However, in section 2.5 some examples will be presented to understand what the optimum depth of analysis is in order for it to help in predicting and avoiding important problems without resulting in a waste of valuable time for the company.

2. Design cycle times can be shortened considerably during the sketching and prototyping phase. However, the final product includes lead-times that are not under the control of the company because vendors require time to manufacture the parts. This shows the interesting factor that generally hardware companies cannot completely lean start-up. Nevertheless Miso has managed to reduce manufacturing lead-times by the adequate selection and communication with the suppliers which could be improved even further as the company grows.

## 2.2 Hardware Product Development

According to Professor Karl T. Ulrich [8] the generic product development process consists of the following stages:

- Planning
- Concept Development
- System-Level Design
- Detail Design
- Testing and Refinement
- Production Ramp-Up

Ulrich also presents variants to this general structure dependent on the product being developed. According to the descriptions he gives, Miso is approaching its product as a Quick-Build product using a spiral product development process. The company relies heavily on prototyping to do rapid modelling, shorten their iteration design-build-test cycles and repeat them many times, in line with the lean start-up techniques already discussed.

Currently Miso is at the Testing and Refinement stages, about to enter the Production Ramp-Up stage. Thus, the priority has been to reach a reliable Minimum Viable Product (MVP) on top of which updates and upgrades will be done continuously. With this goal in mind, time and functionality have been the leading considerations in all the design decisions. It should be noted, though, that in the future stage of Production Ramp-Up cost will play an even more relevant place to increase the margins of the company and reduce the break-even point. Ergonomics has already been an important requirement in the designs, as will be seen in the Basket Transfer Station example in section 3.1. Design for Assembly and Manufacturing (DfAM) techniques have already been used, as will be illustrated in section 3.2 and will gain considerable importance for the Production Ramp-Up stage.

In conclusion, given the current stage Miso is at in the product development process, the main implications for the mechanical design decisions have been to set the design cycle time and functionality as the most important functional requirements.

## 2.3 The Importance of Order

Another observation that has been made over the development of this work has been related to the issue of order. Order is being used in this work as a general term to encompass activities that range from planning and having a Product Data Management (PDM) system to track parts, to having written procedures for the assembly of modules and all the bolts and tools that are needed to perform a certain assembly in known standard places.

In a start-up company whose priority is to shorten lead-times and have an MVP, order is key in being efficient with the use of time. Once that either the product or the company reaches a certain complexity it is not possible to make an efficient use of the resources to grow without order.

The underlying trade-off concerning order is that on the one hand, it takes time and energy to initiate it and keep it, and on the other hand it saves future time. For example, keeping all the screws into known places will reduce the time needed to find the right screw size when it is required as part of an assembly. However, ordering the bolts and keeping them in specific places takes time. The same applies to finding a CAD file on the database with or without a PDM. The first thing to note here is that the balance of this trade-off is different at different stages of the company. In the beginning, when the start-up is small, few parts are being used and few people are working on the project, order is not as relevant. However, when more than two or three people need to be able to find a certain CAD file or to assemble a system module that someone else designed, order becomes an enabler for growth. To illustrate how important order is, the experiment was made to assemble a component without having the parts and screws ordered initially and to assemble the same component with all the parts and screws needed in place at the beginning of the operation. In the first case, assembly took around twice the time it took in the second case.

During the MIT team's time spent at Miso Robotics order had to be improved to accommodate company growth and the increase in product complexity. The author's work with respect to this issue was to write lists of components to assemble the Sensor Box. Also, some design upgrades to facilitate the assembly have been proposed that will be discussed in further detail in Chapter 3. In addition, workshop rules to make use of the tools that are shared have been suggested and implemented.

All improvements concerning order will bring benefits in the Production Ramp-Up stage. Specifically, the written procedures and bill of materials that have already been produced at Miso will be necessary when more people are involved in the assembly processes.

Order is the base of development.

## 2.4 3D Printing, its Uses and Limitations in the Product Development Process

3D printing has proved to be extremely useful to speed up design iterations in the current product development phase. However, the limitations of this manufacturing process must also be understood to make an efficient use of it. From what the author has learned from the company, the most important things to take into account when using 3D printing processes are:

1. Design for 3D printing of plastics is different than design for other materials and processes. For example, when a part is designed for 3D printing then in the end it has to be accommodated for the final metal process, which adds one step. An example in section 2.5.1 will illustrate this point. Design should be done at least for the end material and process of the part.
2. To test robustness and reliability, the final part has to be used.
3. In the case of food applications, 3D printing parts produced by Fusion Deposition Modelling (FDM) cannot be NSF certified because of their high porosity and irregular surface finish. This may not be the case for Stereolithography (SLA), where the part can have an easily cleanable surface finish. However, the resins that are food safe tend to be significantly more expensive and brittle.

This points make 3D printing as a vital tool to reduce cycle times while at the same time it is unsuitable for the final product. That's why Miso balances the use of this tool accordingly.

## 2.5 The Role of Analysis

The fundamental trade-off behind doing analysis in the design process as one of time it takes versus problems it prevents has already been discussed in section 2.1. Early First-Order-Analysis (FOA) is proposed as a good solution to this trade-off. Here, some examples where analysis predicted a problem and saved time will be discussed.

### 2.5.1 Example 1: Basket Tilting

Fry baskets are manipulated by the robot. In order for the robot to be able to manipulate a basket, a custom handle is attached to the basket and a complementary gripper is attached to the robot arm end-effector. The model of the basket assembly is presented in Figure 2-1. Initially the handles (in white) were 3D printed and attached to the baskets with screws. When it was required to build the final part machined out of Aluminum, the question arose of whether the new heavier handle would cause the assembly to tilt backwards due to the heavier handle when left in the fryers with oil.

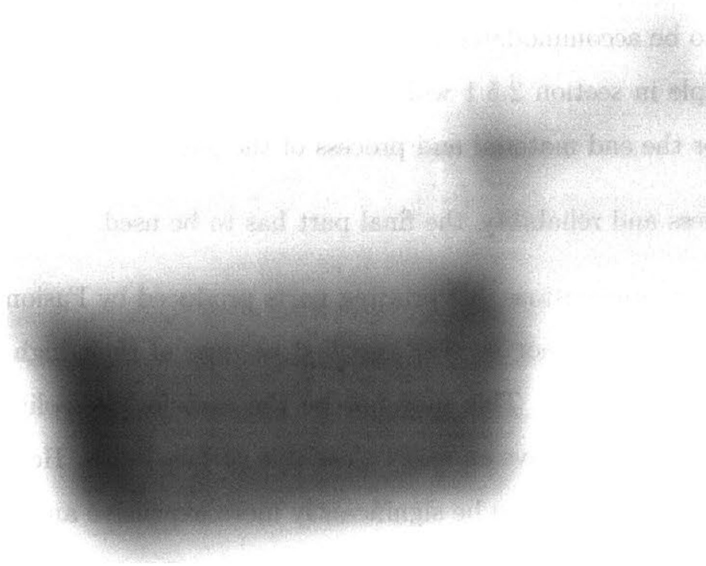


Figure 2-1: Basket and basket handle arrangement CAD model

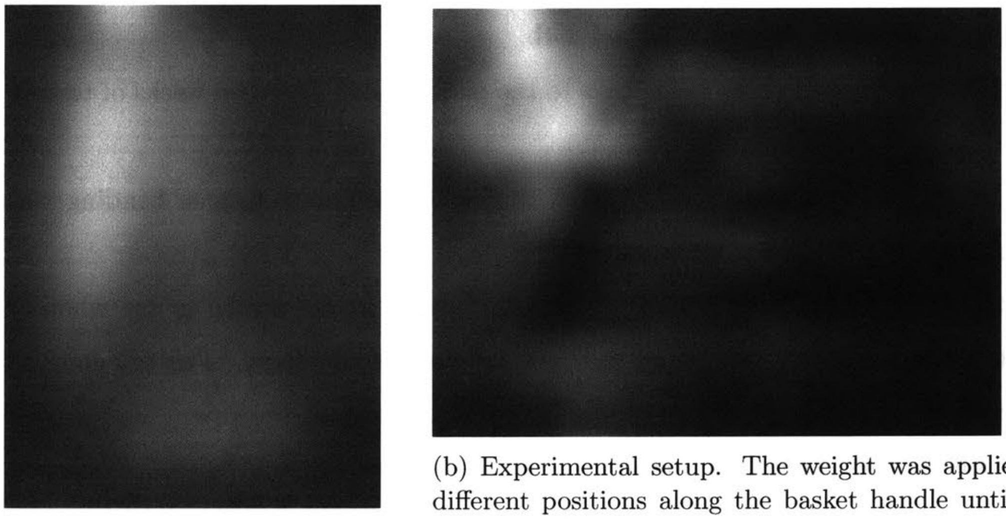
The author measured the moment necessary to cause an empty basket to tilt while it is submerged in hot oil. This was done by placing an empty basket in hot oil and measuring at which distance along the basket's handle a known mass caused the basket to tilt. The setup can be seen in Figure 2-2b. Another measurement was done to know the moment with which, if initially tilted, the basket would recover and go back to the upright position. Both results for this experiments were indicated by lines in the handle of the basket (Figure 2-3). The numerical values are shown in

Appendix A.

Then, a spreadsheet was made to predict whether a particular design would tip or not, based on the mass and location of the center of mass of the basket accessories with respect to the pivot point. This information can be directly obtained from a software such as Solidworks for a particular design. This spreadsheet was then taken by Abhimanyu Bhakuni [1] to study different designs for the basket handles in the redesign process.

FOA should be used in the early beginning and it should at least be applied to the part produced with the final material and process.

In this particular case, the author estimates that due to the use of analytic tools to aid the design instead of using the trial-and-error method approximately a day of work was saved.



(a) Weight used for the experiment

(b) Experimental setup. The weight was applied at different positions along the basket handle until the basket tilted

Figure 2-2: Experimental setup

### 2.5.2 Example 2: Agitator Failure

During frying the product, the contents of the basket have to be agitated to prevent the individual pieces of it from sticking to each other.

The first design that was quickly assembled consisted of installing a pneumatic

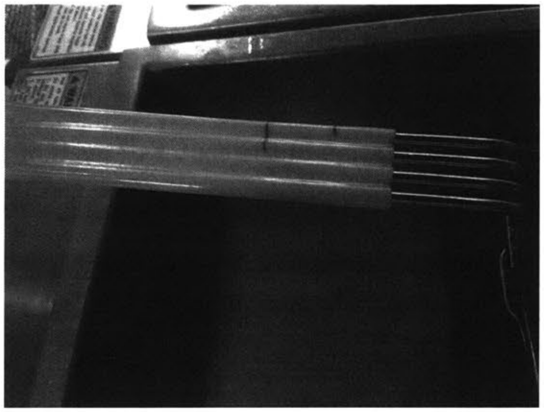


Figure 2-3: Marks resulting from the experiment. The mark to the left represents the position apart from which the basket tilts. The mark to the right indicates the position at which the basket recovers from a tilted position

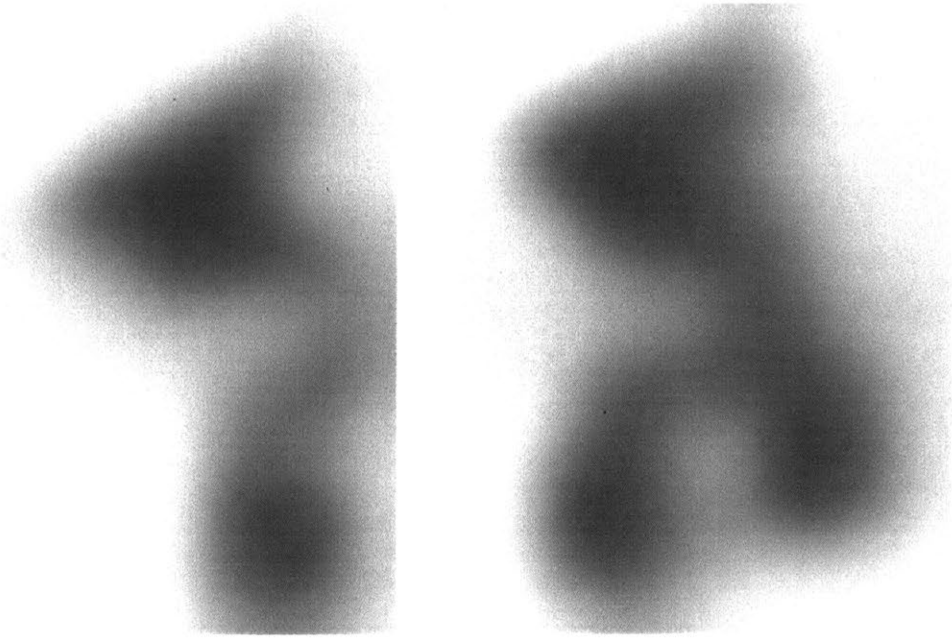
cylinder with piston. The cylinder part was attached to the extreme of the robot arm and the gripper that interfaces with the baskets was attached to the piston part. The assembly is shown in Figures 2-4a and 2-4b.

The bolts that joined the guide rails to the piston failed after two weeks of testing of the piston to validate it (Figure 2-5b).

Observing the broken screws and the timing of the failure fatigue bending was concluded as the main reason for the failure.

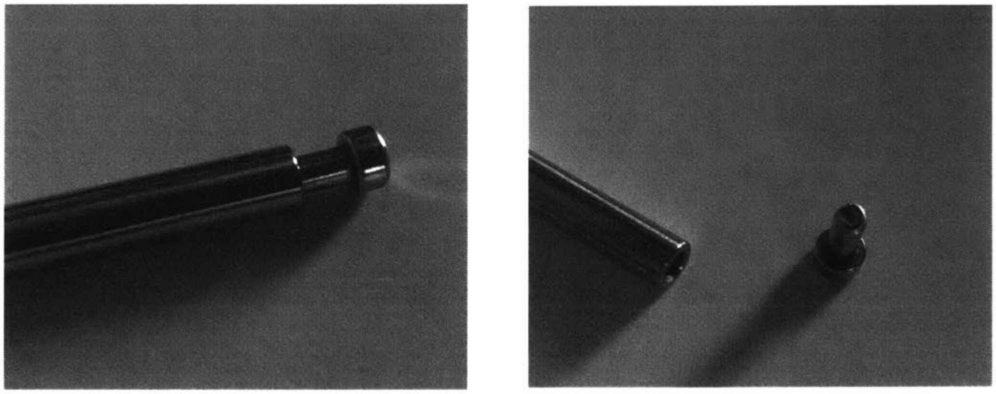
The next step was to calculate the kinetic energy in the stroke to see whether or not it was exceeding the rating provided by the manufacturer. The calculations (attached in Appendix B) predicted the failure of the piston.

This is another example of how doing a test and a First-Order-Analysis calculation to check the operating conditions against the limits of the components predicted failures accurately and saved time for future iterations. An adequate piston could be selected from the validation and calculations.



(a) Side View (b) Inclined View

Figure 2-4: Agitator assembly



(a) Rail with screw (b) Rail and failed screw

Figure 2-5: Screw failure

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# Chapter 3

# Design Case Studies

In this chapter, two design cases are presented: the Basket Transfer Station and the Sensor Box. The first one illustrates how lead-time is one of the most important functional requirements. The second case illustrates how a design was improved to ease assembly of an important part of the system.

## 3.1 Basket Transfer Station

The Basket Transfer Station is an important part required for the frying operation of Flippy. The robot has to handle baskets in four fryers which provide a total of eight basket slots. Baskets will be prepared either by a human being or by an automatic dispenser system and will enter the robot's operating area. The food will be fried and finally, the cooked baskets will be given to the human operator who will check for an adequate temperature and dispense the food in the final selling units. The Basket Transfer Station will be the interface between the robot system and the rest of the kitchen.

### 3.1.1 Functional Requirements

The functional requirements evolved through the design process to finally condense into the following:

FR1) It must be able to guarantee the safety of the workers, the food and the system.

FR2) It must be able to support a given production rate in steady-state.

FR3) Must be ergonomic for the Chefs working in collaboration with Flippy.

FR4) Tested and completed by the 6/20/18.[1]

Some other considerations that were taken into account is that Flippy can easily identify and pick up baskets in a First-In-First-Out way.

Many actors were introduced to the discussions at this stage, even from outside of the hardware team of the company. The author highly recommends to do this, if possible, because radically different people may contribute to requirements which may be overlooked by the rest of the team.

Another factor to note is that cost is not among the requirements. Functionality and cycle time are prioritized over cost in the pursuit of a Minimum Viable Product keeping iteration times as short as possible, in accordance with the lean start-up approach. For the Production Rump-Up stage (refer to section 2.2), however, this system may have to be redesigned to make it cheaper.

### 3.1.2 Design Parameters

At this level the design parameters are the possible ideas or concepts with which to meet the functional requirements. To meet these, the following parameters were considered:

DP1.1) In order to keep people safe from the robot, the robot already has two scanners mounted that decelerate or stop the robot depending on how close an unknown object is to it. However, taking this kind of measures reduces throughput. Thus, to keep both people safety and throughput at their best level it was decided that the system devised should eliminate contact between the human and the robot, and decouple the two work areas.

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[1] The requirements were defined on 6/1/2018

DP1.2) To guarantee the safety of the food, the hardware is required to be NSF compliant. This involves designing it to be easily cleanable and wipeable and using materials or coatings that are approved by NSF.

DP2.1) From the flow rate given, the operation time of the robot per basket was calculated.

DP3.1) It should not require more work than is currently performed by chefs. If possible, reduce the work required to make the user experience better and let chefs have a good impression and expectation about the product.

DP4.1) All of the design cycles have to be short. Time involved in the design process as well as lead time for getting the parts and assemble it should be short. Of-the-shelf components with minor modifications and short lead times are preferred. Also, using the same hardware for the input transfer station and the output station would reduce design times.

### 3.1.3 Concepts

After a brainstorming of the entire MIT team the concepts were classified into four types of solutions:

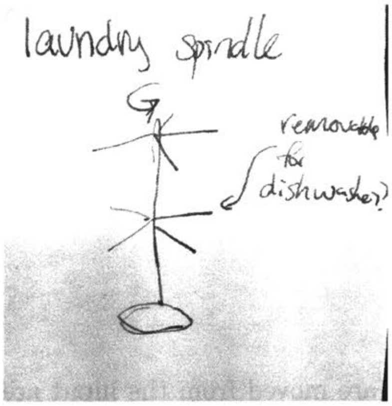
1. Rotating Lines

   In this case, one basket or many baskets are moved from the input area to the robot work area by being rotated with respect to an axis. Some of the sketches for the concepts in this group are presented in Figure 3-1.

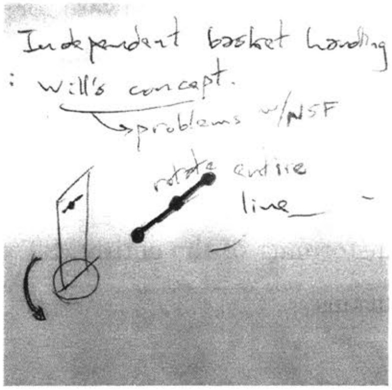
   The differences are mostly in how to power the rotation motion and whether or not to rotate many baskets at the same time. In some concepts, the rotation can be caused by having an inclined rotation axis with respect to the vertical and using gravity. In others, a thread-like joint with a spring causes the hanger to return after a basket is removed by the robot, and in others it is just powered by the human with a button and a motor.

(a) Rotating line where the shielded interface is able to rotate when it does not pose a danger to the people around.

(b) Lazy Susans could be used to create the rotation movement. Detants could be implemented to stop the rotation in the desired positions

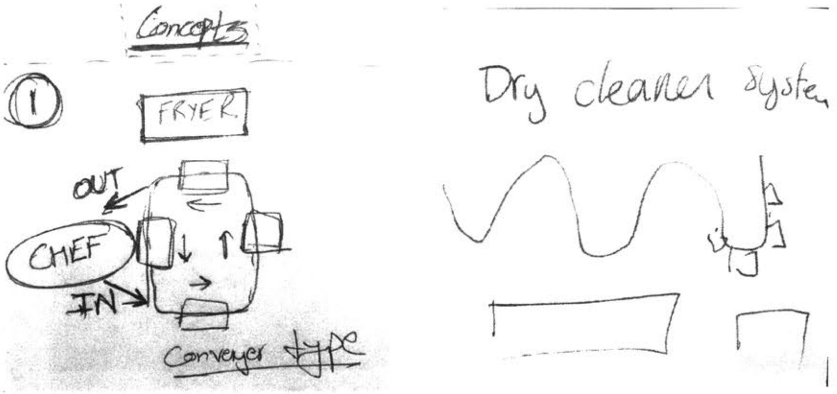


(c) This concept is similar to the laundry spindle. Each level of the arrangement can rotate independently.



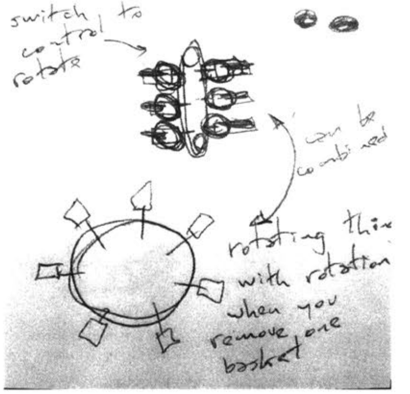
(d) Columns of devices on which baskets can be hang that rotate under the action of the weight of the basket and return to their original position with a spring once the basket is removed. This kind of device was proposed by Miso's colleague Will Werst.

Figure 3-1: Rotating lines concepts



(a) Close-loop conveyor type system.

(b) Dry cleaner system



(c) Pulley system with baskets hanging from a rail.

Figure 3-2: Circular arrangements concepts

2. Circular Arrangements

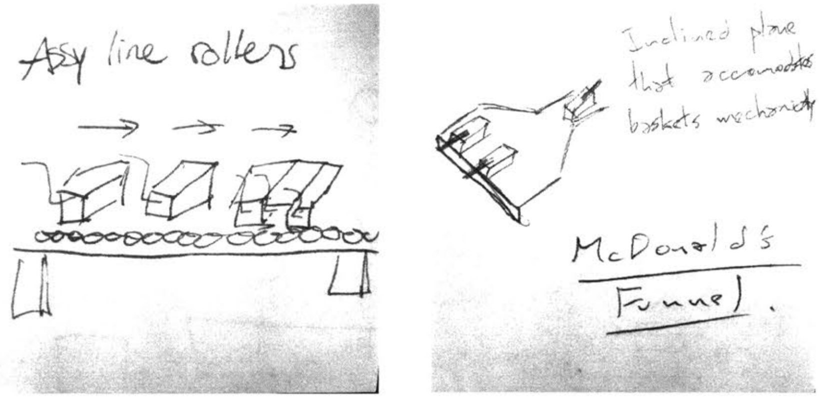
   In this arrangement baskets follow each other and the transporting system forms a closed loop. The transporting system does not rotate.

   Again, the main differences are how the system is powered to move and where the basket is being grabbed from.

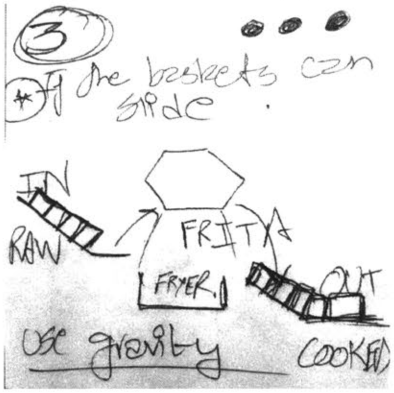
3. Linear Arrangements

   In this case, the baskets again follow each other in sequence but the loop is open. It begins at the input spot and finishes at the robot intake area. The sketches made during this phase are shown in Figure 3-3.

   The two main differences are whether the baskets move on rollers or on a sliding



(a) Rollers line (b) McDonald's type funnel



(c) Gravity fed slide

Figure 3-3: Linear arrangements concepts

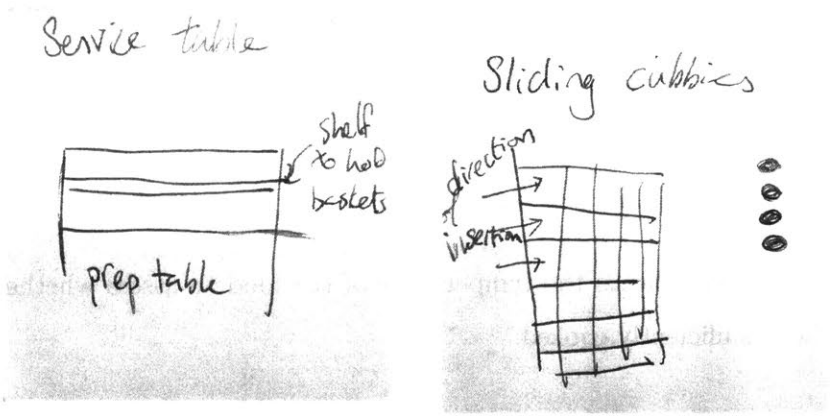
surface. Also in the case of rollers the movement could be powered either by a motor or gravity.

4. Sliding shelves

   In this case the baskets are placed in a shelved structure from one side and are picked up by the robot from the other side. This allows a larger storage or buffer space in a more reduced floor area.

### 3.1.4 First Order Analysis of Buffer Size for the Rack

The rack holding capacity affects two things: 1) Space the rack will take and 2) buffer behavior of the transfer station. The first point is important because it directly affects the footprint of the system and thus it limits how many kitchens the system may fit in.



(a) Shelves attached to preparation table

(b) Independent shelf

Figure 3-4: Sliding shelves

The smaller the system is, the more kitchens it is likely to fit in. On the other hand, the second point is important in that a higher buffer space allows more decoupling between the person feeding the system and the robot stage.

To understand the effect of the baskets holding capacity the system was modelled as a production line with deterministic processing times and assuming that the bottleneck is the robot. The best information available didn't include failure rates at the point this estimate was done. This was not found an issue to perform a First Order Analysis (FOA) calculation.

The production line was modelled as follows:

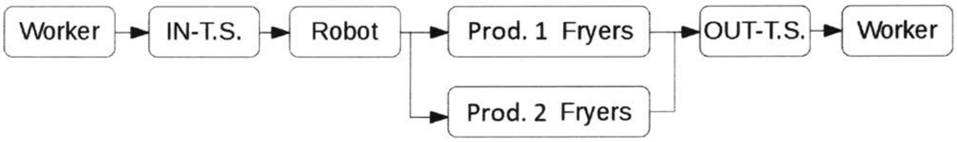


Figure 3-5: Line model for Flippy in the frying operation. T.S. stands for transfer station.

1. The line begins with a worker that provides the baskets loaded with product one and two to the input transfer station.
2. Then the robot grabs the baskets from the station and deposits it into the fryer. In the current setup, there are two fryers appointed to cooking product one and

two baskets appointed to cooking product two. During the time the basket is in the fryer the robot is required to agitate and dip it.

3. After the food is sufficiently cooked the robot removes the basket and deposits it in the output transfer station.
4. Finally, a worker checks the temperature of the food to assess whether or not it has been sufficiently cooked.

Assumptions in the calculation:

- The time the robot dedicates to each basket does not depend on whether there is product one or two in the basket and it matches the target production rate.
- The robot is the bottleneck.
- The robot dedicates a given time (cycle time) handling a certain basket and is perfectly reliable.
- The robot can be assumed in line with the fryers, although in practice the robot moves the basket before, during and after being on the fryer. However, the total time the robot spends in manipulating one basket is considered.
- Half of the fryers are dedicated to product one while the other fryers are dedicated to product two. This is how the system operates currently.

The target production rate was used in conjunction with the desired decoupling time between the human area and the robot area to estimate a reasonable size for the buffer space in the transfer station in terms of number of baskets. The specific calculation results are proprietary information and cannot be disclosed.

The number of fryers needed so that the robot is the bottleneck and not the fryers was estimated in Appendix C.

It was decided that a holding size of four baskets was an adequate result for the trade-off discussed.

### 3.1.5 Selection of Final Concept and Execution

The concept selected was a sliding concept. That is, to have an inclined sliding surface that guides the baskets from the workers to the robot area (fulfilling the design parameter DP1.1 in Section 3.1.2) which can be put next to or in continuation to the table to minimize the need for lifting the baskets by the workers (design parameter DP3.1). A sketch model quickly built with 8021 Aluminum profiles to test the concept is shown in Figure 3-6.

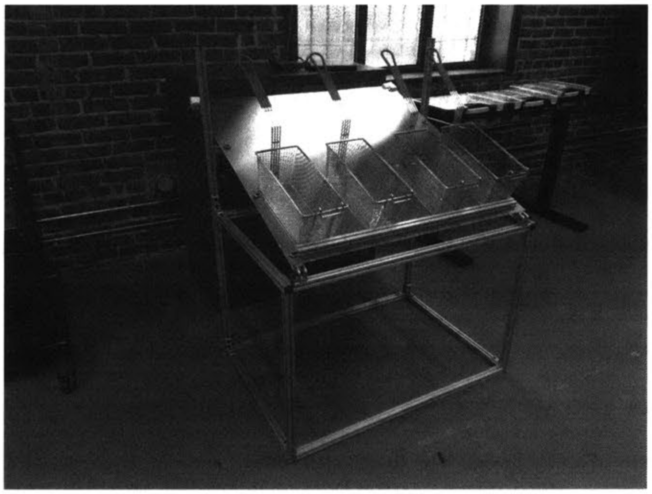


Figure 3-6: Sketch model of the sliding solution with the baskets in position.

The simplicity of the design was a decisive factor considered in order to reduce development times and meet the deadline requirement (section 3.1.1) even if a custom design was required. The final implementation consists of a kitchen rack with slanted shelves wide enough to hold four baskets.

Although a custom sheet-metal component was being designed, an off-the-shelf one-day-lead-time component was found and immediately ordered (design parameter DP4.1 in Section 3.1.2). The selected rack was already NSF approved (design parameter DP1.2 in Section 3.1.2). The decisive factor in selecting this rack was lead time and, again, simplicity. The rack bought is shown in Figure 3-7.

To implement the safety barrier, two measures were taken: 1) one safety scanner was placed on the rack and connected to the safety control loops of the robot to

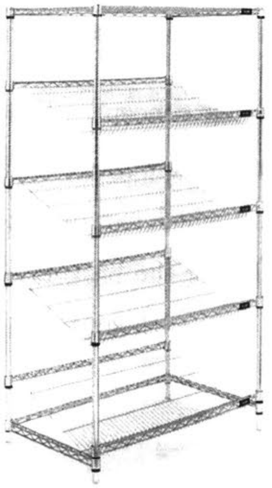


Figure 3-7: Slanted wire shelving from the vendor's website.

prevent the robot from moving baskets in the rack area when an unknown object enters the scanner curtain. This type of scanner is already implemented in the robot's base for safety if people enter the robot area. Apart from that, Abhimanyu Bhakuni [1] added a poly-carbonate physical barrier to the rack so that people cannot have access to the robot area. (Figure 3-8) Last, a dripping tray was added below the rack to prevent oil from dripping on the floor.

### 3.1.6 Conclusions and Learnings

This case is an example of fast, off-the-shelf design. Lead-time was the priority, leading to the preference of simple designs. Further analysis will study how optimum this solution is in terms of costs, manufacturing and assembly for the Production Ramp-Up Stage (refer to section 2.2).

## 3.2 Sensor Box

The author of this work was in charge of assembling the sensor box for pilot installation. During that work a list of parts and suggestions to reduce assembly times were written. Some of them were implemented and some others are in process of being

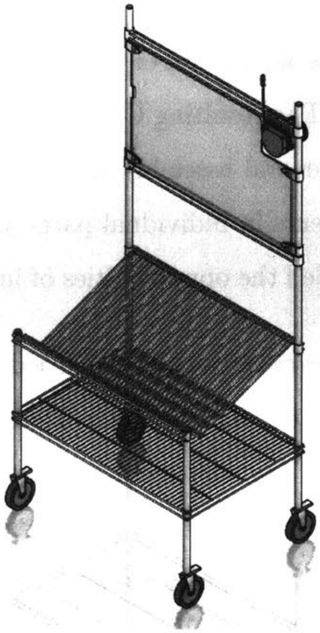


Figure 3-8: CAD model of the transfer station with a poly-carbonate barrier

implemented. In this case the general layout of the design was given and the work was limited to making the design easier for assembly and usability.

The Sensor Box Assembly is shown in Figure 3-9. At this point some changes had already been introduced.

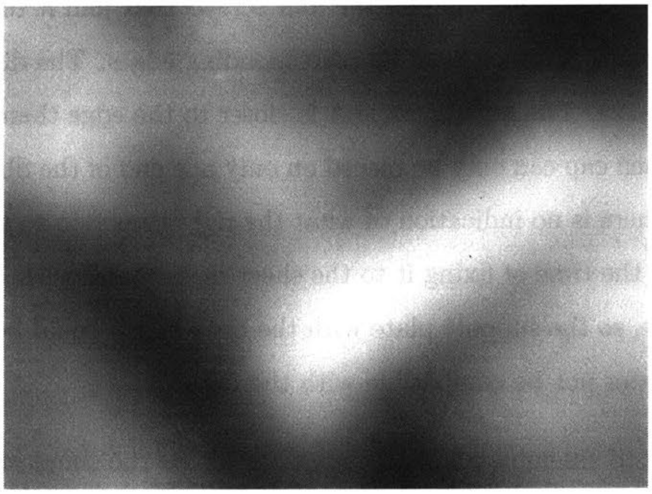


Figure 3-9: Assembled Sensor Box

### 3.2.1 Opportunities for Improvement

The first step was to suppress all the parts that were not being used in the actual assembly from the CAD file. The resulting CAD was used as the basis for this work. The specifics of the module general assembly are confidential and cannot be shown. Thus, features and improvements in individual parts are shown separately.

When the box was assembled the opportunities of improvement encountered were:

1. The sensor box was over-constrained, which led to interference between parts and a high assembly effort. Having extra parts adds up directly to the total time the assembly takes. The over-constraint came from the fact that one part is bolted into another part on the one hand, and to a third part on the other hand. However, these last two parts are both bolted together through a fourth part. Thus, one of the linking parts was redundant.

2. Since the design had previously gone over many iterations there were unused screw holes. These made it difficult to understand the right configuration of some components such as the circuit board with respect to the Sheet Metal Base, which made assembly non intuitive.

3. The sheet metal cover of the module is not symmetric, since the four screws that join it to the front cap and the four screws that join it to the rear cap are not at the same distance from its corresponding edges. The difference is shown in Figure 3-12a. The hole in circle A is closer to the edge than the one in circle B. Thus, each cap can only be placed on only one end of the Sheet Metal Cover. However, there is no indication of what the right direction to mount the circuit board is at the time of fixing it to the sheet metal base, when the caps are still not in place, so the support plate with the board on it could be bolted in a way that may later not be compatible with the caps.

4. Using bolts to assemble all of the box may not be the simplest from the standpoint of assembly. In particular the front and rear cover plates are currently held in place by 4 bolts each. This is a problem because once the Sensor Box

is installed and power is connected to the circuit board, it has to be turned on. To do this a button that is physically installed onto the board has to be pushed. That button should be easily accessible.

5. Clearance holes for bolts in the Sheet Metal Cover are not sufficiently large and this causes problems when assembling the box.

6. No clearance was provided between the front cap or the rear cap with respect to the sheet metal cover. This makes alignment and assembly difficult.

7. The method of plugging and unplugging the power cable and Ethernet cable to the board is not favorable for assembly. The problem is that this cables must enter through sealed holes in the rear cap and plug onto the board. The current assembly order is to drill adequate holes in the rear cap, put the cables through the back cover, connect them to the board and finally bolt the rear cap by pushing it in.

### 3.2.2 Suggestions for Improvement

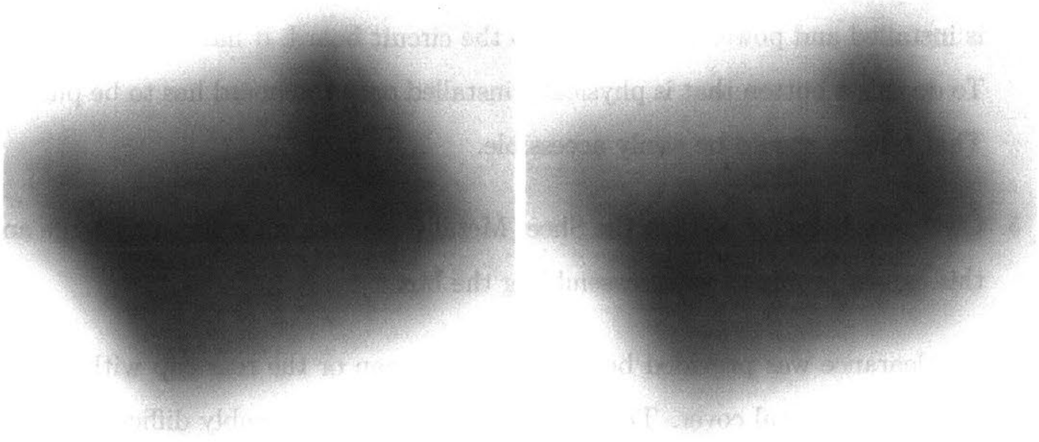
For each of the points listed a solution was suggested. They are listed in order.

1. Eliminate the part that is redundant. In particular, an L bracket was removed. This reduces the number of parts by one, the number of heat set inserts to be installed in the parts by eight and the number of screws needed by eight.

2. Delete redundant screw holes.

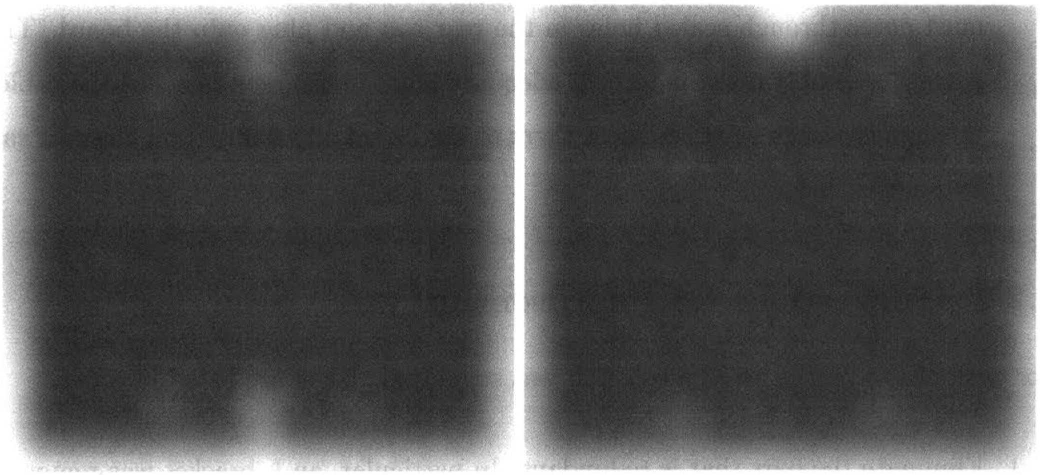
3. Make the sheet metal housing totally invertible by making the bolt patterns exactly the same in both ends. (Figure 3-12b) Also make features in the plate that supports the board so that the end covers cannot be put in the wrong way once the support plate is mounted onto the sheet metal base. (Figure 3-11b)

4. For testing of the system implementing a slot in the sheet metal cover so that the button is easily reachable with the fingers is a fast solution. (Figure 3-12b)



(a) Before changes (b) After changes

Figure 3-10: Box interior changes

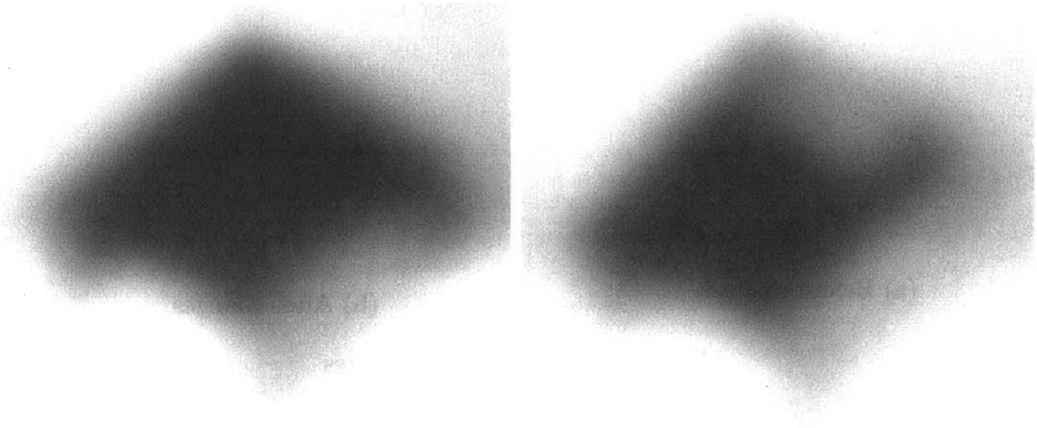


(a) Before changes (b) After changes

Figure 3-11: Support plate holes pattern

However, latch and hinge systems as well as snap-fits should be explored for a longer term NSF-compliant and safer solution.

5. Enlarge the corresponding holes. To determine the magnitude of the increase in size the error of placement of the heat inserts was estimated at about 0.50 mm. This considers the error due to the manufacturing process used for the front and rear plates (measured to be 0.25 mm approximately) and an allowance for the error when placing the insert (estimated as 0.25 mm more). The diameter



(a) Before changes

(b) After changes

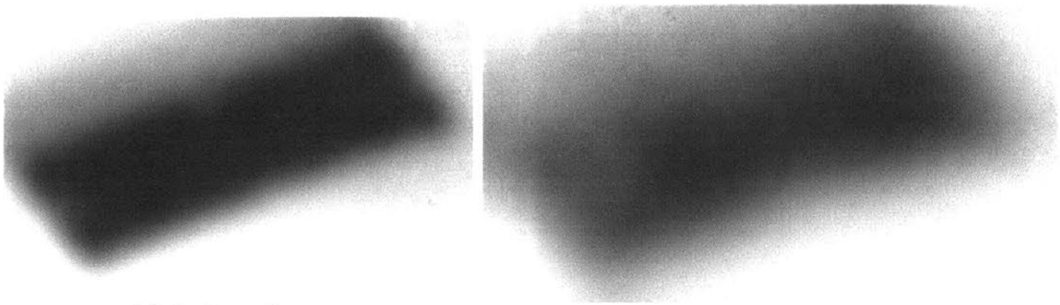
Figure 3-12: Sheet metal cover

of the clearance hole should then be the addition of the diameter of a regular clearance hole for an M3 bolt (3.5 mm) plus twice the error estimated (1.0 mm). This gives a 4.5 mm hole size. The bolt is a hex head bolt, that has a minimum hex dimension of 5.5 mm, so the entire hole will be covered by the hex head in all cases.

6. Use the concept of elastic averaging [7] to place the cup or add clearances between the cap and the sheet metal cover plate. The last approach was followed since the resulting accuracy was still under specification considering that the last tuning of the positioning of the Sensor Box is done by eye.

7. Implement the use of feed-through connectors to easily connect the cables. For this, holes were placed in the Rear Cap. The rear cap final design is shown in Figure 3-13b and the feed through connectors selected are shown in figure 3-14.

Up to the present all point were implemented except for point four. The slot was not cut yet. However, this point should still be further considered to completely solve for the NSF requirements.



(a) Before changes

(b) After changes

Figure 3-13: Rear cap changes

(a) Ethernet connector

(b) DC power connector

Figure 3-14: Feed-through connectors used

### 3.2.3 Future Work

To finish the changes, step four is still to be implemented. After that, assembly times can be measured and compared to the previous ones to assess the improvement. It should be noted that this sensor box will not be the final one, although it is required to be convenient to work with at this point. Another functional requirement that arose while the changes were being implemented was to make plugging of the cables easy by authorized personal and easy to detect when someone else tries to intentionally disconnect the box. Another idea for the future manufacturing of the sensor boxes is to make them completely out of plastic. Currently we are limited by manufacturing processes available, prices and lead-time.

# Chapter 4

# Conclusions and Future Work

Firstly, the influence that "short design cycle time" has as a functional requirement is probably the most critical difference between a start-up company and a more established firm. In the case of a start-up, this is often the sole factor that leads to prioritize one solution to a problem and discard most of the other possible technical solutions. This strong requirement together with the fact that production volumes are still in the order of the tens tends to favor the selection of off-the-shelf components that can be adapted to solve the problem.

Secondly, it is concluded that order should definitely be pursued to maximize throughput in the ramp-up stage and reduce waste of engineering hours. The implementation of a PDM system will be essential not only in this respect but also in reducing manufacturing waste due to miss-communication between the company and potential contract manufacturers in the future.

Thirdly, the use of First-Order-Analysis calculations to assist design iterations can be an effective tool to save total design cycle time by detecting problems earlier, designing with them on mind, and reducing the number of steps in the trial-and-error design.

The next steps are:

1. Given that the next step in the process of Flippy's development is the Production Ramp-Up, optimize the designs for manufacturing, assembly and cost.

2. Introduce First-Order-Analysis in the design process. Communicate the benefits of it to the rest of the hardware team.
3. Study alternatives, select and implement a Product Data Management (PDM) system, which is vital for avoiding expensive errors when sending final versions of parts to contract manufacturers.
4. Write assembly manuals for all the modules of the system.
5. For short design cycle times, design directly for the final material and process. Use plastic 3D printing only for prototyping purposes.

# Appendix A

# Basket Tilting Analysis

From the experiments mentioned in section 2.5.1 the following moments were obtained:

| Mass (grams) | Force, $F$ (N) | Arm, $x$ (mm) | Moment (N.m) |
|---|---|---|---|
| 261 | 2.6 | 86 | 0.219 |
| 261 | 2.6 | 140 | 0.358 |

The loading situation is illustrated in the following sketch:

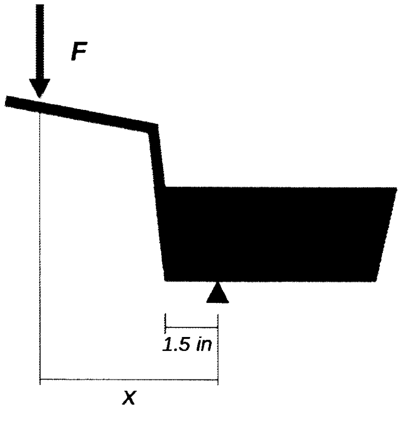


Figure A-1: Basket loading

The first moment value corresponds to the maximum moment that can be applied to an empty basket in hot oil once it is initially tilted, so that it still recovers the straight position. The second moment value corresponds to the maximum moment that can be applied to an empty basket in hot oil and initially in the straight position before it tilts.

Knowing the total weight of the accessories that are attached to the handle plus the location of their center of mass the behavior of the empty basket placed in the hot oil fryer can be predicted.

# Appendix B

# Agitator Loads First-Order Analysis

For the first order estimates the following assumptions where done:

The pneumatic cylinder is an MGQL12-40. In the product guide [4] the maximum kinetic energy it is able to stop is reported. To calculate the kinematic energy of the current arrangement during impact the following assumptions and information was taken into account:

- The piston is rigidly attached to the mass of the basket to which it is linked. The load mass was estimated as 4.6 kg. This includes the mass of the basket, the food on it, the accessories that are attached to the handle of the basket, and the agitator components between the grippers and the piston.
- The pressure of the air is constant at a value of 0.414 MPa. This is the value of the pressure in the normal use of the piston.
- Friction is neglected.
- The piston hits the end of the cylinder in each stroke.
- The piston travel is 40 mm and the bore diameter is 12 mm.

The formulas used were:

$$
\begin{aligned}
F &= p(\frac{\pi d^2}{4}) \\
a &= \frac{F}{m} \\
v_f &= a t_f \\
t_f &= \sqrt{\frac{2x}{a}} \\
K &= \frac{m v_f^2}{2}
\end{aligned}
$$

Where $F$ is the force on the load, $m$ is its mass, $a$ its acceleration, $v_f$ its speed at the end of the travel, $x$ is the travel of the piston, $t_f$ is the time it takes the piston to travel that distance under the constant force $F$ and $K$ is the kinetic energy of the load at the moment of reaching the end of travel of the piston.

The following table summarizes the results.

| | |
|---|---|
| Piston pressure, $p$ (MPa) | 0.41 |
| Piston diameter, $d$ (mm) | 12 |
| Mass attached to the piston, $m$ (kg) | 4.6 |
| Force on piston, $F$ (N) | 15.6 |
| Acceleration, $a$ (m/s$^2$) | 3.4 |
| Piston travel, $x$ (mm) | 40 |
| Travel time, $t_f$ (s) | 0.15 |
| Final velocity, $v_f$ (m/s) | 0.52 |
| Kinetic Energy, $K$ (J) | 0.62 |

The point of operation is shown in red in the plot provided by the manufacturer of the piston.

Although this approach gives a conservative estimate, it shows clearly that the piston will not be able to overcome the extreme operation condition. This analysis does not include the robot.

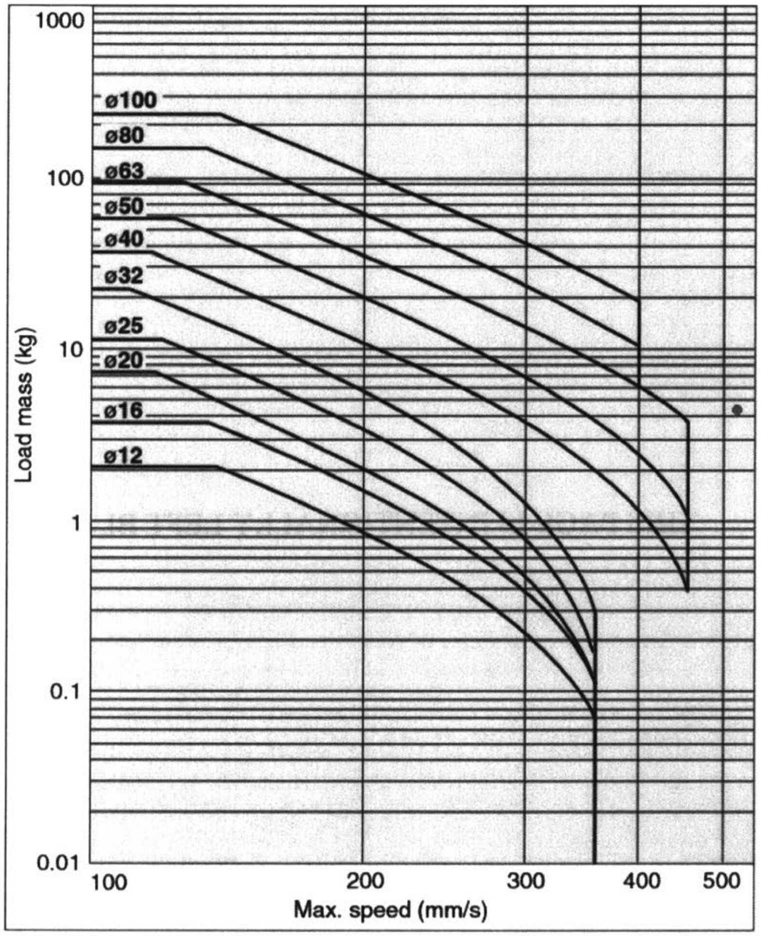


Figure B-1: Plot of allowable kinetic energy of the MGQL pneumatic cylinder family as provided by the supplier [4]. The red dot indicates the estimated point of operation.

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# Appendix C

# Fryers Needed not to Block the Robot

In the analysis of section 3.1.4 it was assumed that the fryers were as many as needed not to block the robot. The minimum number needed was calculated using Little's Law and assuming that the same number of fryers is used for frying products one and two.

The baskets to be produced, the time available and the cooking time were given. The average number of baskets in the system were calculated according to Little's Law, which relates the average inventory in the system $L$ ("Average number of baskets in the system"), the average production rate $\lambda$, and the average time a unit spends in the system $W$ ("Cooking time") according to the equation:

$$L = \lambda W$$

The exact results are confidential and are not shown.

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