USING ENGINEERING TO CREATE AN ADAPTIVE SELF-FEEDING SYSTEM FOR PATIENTS WITH UPPER BODY DISABILITIES

An Undergraduate Research Scholars Thesis

by

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We, Almotazbelah Eledrisi[1], Hourig Ohanian[2], Marwan Badreldin[3], Reem Elhadi[4], Zeina Barghouti[5], certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Research Faculty Advisors prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

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ABSTRACT

Using Engineering to Create an Adaptive Self-feeding System for Patients with Upper Body Disabilities

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This research project aims to provide a self-feeding manipulator system to accommodate those who have upper-body motor disabilities. The purpose of the device is to allow patients to rely less on their caregivers during a meal. The patient's safe feeding without injury or malfunction at home or in a public setting will successfully achieve this form of assistance. The target cost is USD 1096 with a minimum of six months to make it a marketable product and nine months to develop a prototype. People have created similar devices such as the Neater Eater, Mealtime Partners, and the Obi Robotic Feeder in the past. These devices stem from one general need: provide a means to assist people with disabilities in feeding themselves. However, the

disadvantage to all the existing products is that they are very costly, ranging between 4000 – 8000 USD apiece. In addition, they are inaccessible to people in Qatar due to their production and market being overseas.

We use engineering methods to create a device that is more versatile and accessible. This thesis discusses all the alternatives created to build the manipulator. The manipulator's design is one with four degrees of freedom, and the actuators used to mobilize the joints were Servo Motors. The manipulator is to work automatically using Denavit-Hartenberg, Forward Kinematics, and Jacobian robotics methods. Some parts of the manipulator require 3D printing and CNC machining, which will be accessible in the TAMUQ building. In addition, some parts will be bought based on our requirements calculations. Another engineering method used to control the manipulation of the system is by using an Arduino board.

The device consists of four main subsystems. Firstly, there is the base which mounts on any flat surface. Also, a plate, divided into four sections, that attaches to the base and can rotate. The manipulator is also attached to the base, along with a spoon attached to the manipulator.

Finally, the user-interface is a critical component of the system to allow easy communication between the user and the device. Since this device targets patients with upper-body disabilities, a user-interface that functions using the patient's feet would be suitable. We aim to have the device ready to test by the end of April 2021 and allow patients from Sidra Hospital to test the device.

DEDICATION

This thesis is dedicated to our friends, families, instructors, and peers who supported us throughout our undergraduate years while we pursued our Mechanical Engineering degrees.

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All other work conducted for the thesis was completed by the students independently.

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NOMENCLATURE

Acronym/Abbreviation/Symbol	**Definition**
A	Ampere
FMEA	Failure mode and effects analysis
H	Height
HMC	Hamad Medical Corporation
L	Length
m	Meters
N	Newton
PMT	Provide a means to
QR	Qatari Riyals
s	Seconds
RPM	Revolutions per minute
TAMUQ	Texas A&M University at Qatar
TBD	To be determined
V	Volts
W	Watts

1. INTRODUCTION

1.1 Purpose of the Project

In 2019 alone, twelve million people worldwide were reported to have a physical disability that required them to need some assistance with everyday tasks [1]. People with upper body disabilities have even voiced their struggle in feeding themselves, a task that most people without upper body disabilities find trivial. Unlike people with upper body disabilities, most people do not have to worry about feeling frustrated or helpless in front of a plate of food and a fork. They tend to feel a loss in their dignity due to their dependence on caregivers to feed them every meal and discomfort with the feeding process. In addition to the physical eating process, people with upper body disabilities struggle with social interactions during meals for reasons such as the caregiver's unavailability during a lunch meeting or a dinner with friends, or simply not being comfortable with the caregiver's presence during such social interactions.

This project aims to engineer a solution to assist patients with upper-body motor disabilities in independent eating. A self-feeding device, or manipulator, can be engineered to accomplish self-feeding tasks by providing a lifting force equivalent to the force required to lift a spoonful of food from a bowl to the patient's mouth. These foods can vary from solid to liquid and from hot to cold. The patients would require assistance in placing the food on the plate or bowl, powering the device, attaching the desired utensil, and cleaning the dishes afterward. However, during the entire period that the patient is eating, he/she will be entirely independent of the caregiver.

A manipulator accommodates patients with upper-body motor disabilities (neurological diseases) in feeding themselves, making up for their limitations. These limitations include muscle diseases, stiffness in the upper body, amputations, motor neuron diseases, and more. Muscle diseases include muscular dystrophy - when the muscle is weak and there is a loss of muscle mass. Another muscle disease is myopathy, where muscle fibers do not function properly. When it comes to the limitation of stiffness in the upper body, it may be due to severe burns or arthrogryposis where the joints are stiff, and the patient cannot bend their arms. There are also amputation limitations from birth or bilateral amputation from a trauma. In addition, motor neuron diseases such as spinal muscular atrophy which are genetic or if spinal nerves are affected negatively. Other limitations are spinal cord injuries involving the neck, broken bones from accidents, or pain in the upper body. The target age for the device is above three years old. However, small children will require a smaller size than someone older. Also, the size of the person's body matters for their comfort. An assumption made is that the device is not utilizable by patients with swallowing difficulties or are liable to choking.

The manipulator aims to give the patients as much independence as possible when feeding themselves. Providing patients control over the device through an interface would achieve such independence. In turn, the patients should feel free to eat at their own pace. Assisting the patients would mean that the device must be able to feed them independently without help from other people, starting from when the filled plate is placed on the device until they finish eating. Improving this manipulator's quality and distinctiveness can be achieved by incorporating features that will increase the patient's independence, reduce the caregiver's responsibilities, help with social interaction, and improve posture and head control. The device should be simple, straightforward, and easy to use daily, during every meal. Therefore, its setup, usage, and interface need to be user-friendly.

1.2 Past Solutions

People have created similar devices such as the Neater Eater, Mealtime Partners, and the Obi Robotic Feeder [1][2][3]. These devices stem from one general need: provide a means to assist people with disabilities in feeding themselves. However, the devices differ in some functions: autonomy, performance requirements, and initial constraints. These devices have helped many patients with these limitations in social interactions, dignity, and independence. Such devices also helped improve the patients’ postures and head control and relieved some burden from the caregiver.

Previous solutions similar to a self-feeding device exist, such as the Neater Eater, where users can control the manipulator using an interface [2]. The device fits one plate or dish at a time [2]. The product in the market closest to the customer’s need is the Obi Robot. It follows the same concept as that of the Neater Eater; however, it allows more independence due to its higher autonomy level. It has four separate bowls for food and a manipulator with a spoon that can learn the food delivery location after being calibrated by a caregiver. It also has an impressive safety feature where it can detect and prevent collisions [3]. Another previous solution is the Mealtime Partner device, which follows the same concept as the devices mentioned above. However, it is suitable for a broader range of disabilities due to its flexibility in mounting and positioning. It also adapts to the user if their condition worsens by adjusting the level of autonomy as well as their eating patterns and movements through recalibration [4].

1.3 Need Statement

Provide a means to assist people with upper body motor disabilities in feeding themselves without relying on any other human. The patient's safe feeding without injury or malfunction at home or in a public setting will successfully achieve this form of assistance. The allocated budget is QR 4000 with a minimum of six months to make it a marketable product and nine months to develop a prototype.

1.4 Need Analysis

This project intends to enhance the functionality, accessibility, affordability, and the ease-of-use of the self-feeding device. The device would be functional at home, schools, and public areas, signifying its portability. Also, the device will be placed on a flat surface when in use and should also be portable to use on several surfaces such as wooden tables, glass tables, and plastic tables. However, the caregiver would need to assist the patient in setting up the system and clean up after the patient's meal. The disadvantage to all the existing products is that they are very costly, ranging between 4000 - 8000 USD apiece. They are inaccessible to Qatar's people due to their production and market being overseas. Therefore, this research project will focus on designing and manufacturing a self-feeding device in the State of Qatar. As a result, the repairs and maintenance for the device will be available to customers locally. Throughout this project, resources such as materials and technology will be accessible and available in the university. The customer allocated project budget is QR 4,000, which details the production cost of manufacturing. Note that the intention is to design and manufacture the product in the State of Qatar. Therefore, the materials and manufacturing methods must be available locally.

Regarding maintenance of the device, replaceable parts should be easily accessible in Qatar and inexpensive. In the case of needing international parts, their arrival will be in a timely and cost-effective manner. Finally, the time constraint for building the prototype is nine months, with a six-month period to put the product on the market afterward. This research project's target customers are patients in Sidra Hospital; over 1300 patients with upper-body disabilities in Qatar use it. However, the initial number of patients requested to accommodate is 20, which means that the device's manufactured components should account for at least 20 patients; the tentative initial number of patients to which Sidra will begin providing this device. The large-scale manufacturing process for this product would need to come from a reliable manufacturer with an appropriate number of resources.

This research project will introduce the design process used in developing a portable, autonomous, accessible, feasible, and user-friendly self-feeding device. When innovating a mechanical design such as the manipulator for users with upper motor disabilities, the research and analysis are crucial to meet the system's standard functions and requirements.

2. METHODS

2.1 Design Methodology

This project complies with all the codes and standards of the Ministry of Public Health (MoPH) in Qatar, the American National Standards Institute (ANSI), and the Sidra Medicine IRB as highlighted below [37][38]:

- During the design and testing phase of this project, all of the MoPH social distancing guidelines were closely followed.
- The ANSI dimension standards were used when producing 3D models of the design.
- The Sidra Medicine IRB's safety and privacy of the patients involved in this project were given close consideration.

Behind every research project lies a motive or goal. The researchers must establish a clear and concrete approach to the research to remain focused on its objectives. Therefore, the first step was to identify the issue that the project aimed to tackle. From that, the objectives of this research project were consummated in a need statement. Next, a need analysis was developed to elaborate on the statement and define the mission clearly. These steps belong to what is known as the engineering design process. The process starts with identifying the need for this project – the purpose of the project. The next step in the engineering design process was to determine what the design had to do, in other words, the design's functions. Functions were split into two sections: the primary functions of the components and their respective sub-components sub-functions. The aim of the manipulator is to give the patients as much independence as possible when feeding themselves. This independence should be achieved by giving the patients control over the device through an interface. In turn, the patients should feel free to eat at their own pace. Assisting the patients would mean that the device must be able to feed them independently without the help from other people, starting from the moment the filled plate is placed on the device, up until the moment the patient is done eating. Improving the quality and distinctiveness of this manipulator can be achieved by incorporating features that will increase the patient’s independence, reduce the caregiver’s responsibilities, help with social interaction, and improve posture and head control. The device should be simple, straightforward, and easy to use on a daily basis, during every meal. Therefore, it is important for its setup, usage, and interface to be user friendly. As a result, this research's primary functions include:

1. Delivering food from the plate to the patient's mouth
2. Interfacing with the user
3. Operating in many places or locations

By understanding the functions of the mechanical device, the requirements of the device were identified. The requirements specify how well the device will have to function. For instance, the speed at which the food will be delivered to the patient's mouth is crucial – fast delivery could be overwhelming to the user and, in turn, cause discomfort. This step will also help screen any unnecessary products; thus, identify the potential solutions – the physical and non-physical components that will carry out the functions established. Several concepts were created for each component and evaluated into an assembly; this step is called the conceptual design. A design develops by distinguishing the possible solutions, which is the form of the functions and could be both physical and informational. Since the developing design is a prototype, a physical or mechanical design, using SOLIDWORKS or any other AutoCAD software would be convenient to design and run simulations. After the parts' manufacturing and assembly, the tests run on the mechanical design are the second type of simulation. The last step of the engineering design process is running tests on the developed prototype because it is crucial to ensure that the design meets the project's needs and requirements. It is also essential to run the same test multiple times and throughout a considerable period.

These main functions of each are further broken down and detailed in the function structure diagram provided in Appendix A. Following the conceptual design is the preliminary design. The concept is taken and improved on by coming up with requirements and solutions for each design function. The different sub-component of the system was designed. Simultaneously, several alternatives were considered for each sub-component, and based on the failure mode and effects analysis; a decision was made. This design process was the project's approach because, as the objective implies, a design will be developed.

The device as a whole is a system that includes a plate - the food's vessel, the utensil, the manipulator, the base of the device that will support the arm and plate, and the power supply. The following are the major components and their respective functions – the top-level functions:

1. User-interface: Provide a means to allow the user to input commands to the device.
2. Plate: Provide a means to hold the food through its delivery to the patient's mouth.
3. Utensil: Provide a means to hold and carry the food from the plate to the patient's mouth.
4. Manipulator: Provide a means to transport the food from the plate to the patient's mouth.
5. Power Supply: Provide a means to supply/store energy.

The device's design intends to maximize autonomy. Autonomy is the ability to function independently with minimizing the control of a caregiver. The device will include multiple types of sensors to accommodate the functional requirements. These sensors will detect, lift, carry, and deliver the food to the patient. The system should calibrate its position to the patient's mouth position. The calibration is achieved in two ways: either by adjusting the patient's mouth level once before every meal or by providing the system with a sensor to detect the patient's mouth and automatically calibrate the device. The manipulator will need to be programmed to achieve all the required movements and tasks. This device should also provide little to no head movement of the patient when eating from the utensil. Patients with muscular dystrophy are generally older. They usually rest their elbows on the table when they are young but sit in a more extensive and bulkier wheelchair as they grow older. Therefore, the manipulator should account for more considerable distances between the user and plate and the plate and utensil. This way, the patient can rely on the manipulator to feed them comfortably so that they do not need to lean over to eat their food. The device's weight is taken into consideration since it will be carried from one place to another. That is assuming that the patients with no range of motion or extreme weakness will require some assistance in lifting the device to set it up; however, the patients with more strength should lift it. For this reason, the mass limit of the device should not exceed 5 kg.

The product will also include a set of utensils specially designed to help maximize the patient's safety. The device must consider many safety measures. The first measure is ensuring a safe way to feed the patient while minimizing the chances of injuries. Injuries caused by utensils are a common issue [2]. The device should follow a precise and stable path to the patient's mouth, allowing the device to carry utensils and deliver food safely to the patient's mouth without stabbing, poking, or scraping the mouth of the patient. To ensure the device's safe functionality, the limited speed of motion such that no injuries occur or there is enough time to help a patient if the device goes out of control. Factoring the device's material selection can act as a safety measure towards certain mechanical and electric failures and several errors: control, sensor, and human errors. Another safety measure would include preventative maintenance done on the device, including system updates and mobility checkups that would evade common mistakes and failures.

The major requirements to each these top-level functions are determined in different ways.

1. User-interface, it is important that it did not take long to feed the user, this meant that a feeding time of approximately 40 to 60 sec/bite is accepted as that would be an acceptable amount when feeding the patient based on the average time it takes to eat a meal over the number of bites a person takes on average per meal [39] [40].
2. Plate must be able to hold between 150 – 250 grams of food per section [41].
3. By taking the average number of bites per meal and weight of food per each section, the utensil must be able to hold at least 5 – 8 grams of food [40] [41].
4. Manipulator: The vertical and horizontal reach of the device were determined based on a quick model made from PVC pipes and tubes shown in Figure 2.1. The model was designed in order to estimate dimensions of the manipulator links. The setup was on several test users of different heights from 150 cm to 185 cm height. It was found that the average maximum horizontal and vertical reaches were 30 cm each. The final model dimensions were approximated on the obtained values.

Figure 2.1: Manipulator Model

5. Power Supply: The main requirement of the power supply is to provide a voltage of 7-8V and a power of around 60 W for at least 2 hours of continuous operation. This was determined through calculation shown in *Appendix C.*

2.2 Theory

This project's main objective is to develop a design that would assist patients with upper-body motor disabilities in feeding themselves without relying on any other human. Since it is a feeding device, the first concept that stood out was that of the human arm since most human beings use it to feed themselves. From that, the motion of an arm brought about the concept of degrees of freedom. Since implementing that on the device – manipulator, the design had to be simplified to the minimum degrees of freedom to remain functional. *Figure 2.2* shows the degrees of freedom chosen to ensure the design was fully functional.

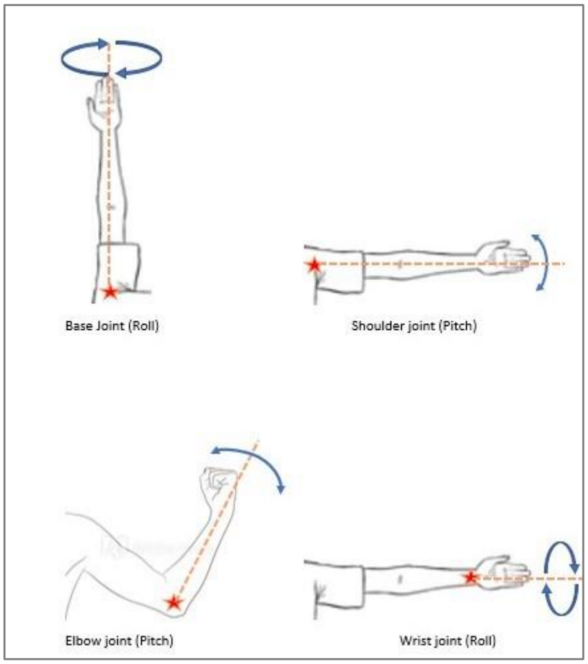


Figure 2.2: Degrees of freedom of the manipulator

The human arm was modeled and compared to the five standard manipulators which exist in robotics. There are two different motions to look at when comparing the manipulators: linear and angular motion, also known as prismatic and revolute joints. The five different manipulators are the cartesian, SCARA, Cylindrical, Spherical, and Articulated. These options will be evaluated relatively and absolutely in the results.

Preliminary static calculations were carried out to clarify the power and motor requirements needed for the device. At this stage, the device's control system, the manipulator's movement, and its pathways are undefined. Instead, the designs of the components and solutions and the system requirements are optimized. Due to these reasons, the device's dynamic analysis will carry out in the next stage of the project.

Tables C.1-C.4 in *Appendix C* shows all of the centers of mass calculations discussed in this section and sample force, torque, and power calculations for all four motors. The masses of the components were calculated using *Equation 2.1*, with the volume of the components used directly from SOLIDWORKS. The density used was the maximum density of the material candidates discussed in the report's materials section. *Table C.5* in *Appendix C* shows a summary of each component's maximum density, volume, and maximum mass.

$$m = rV \tag{2.1}$$

Firstly, *Figure 2.2.2* shows and identifies the static configuration that has the maximum load on the device. The device was split into its components and the analysis began from the spoon and worked its way towards the base.

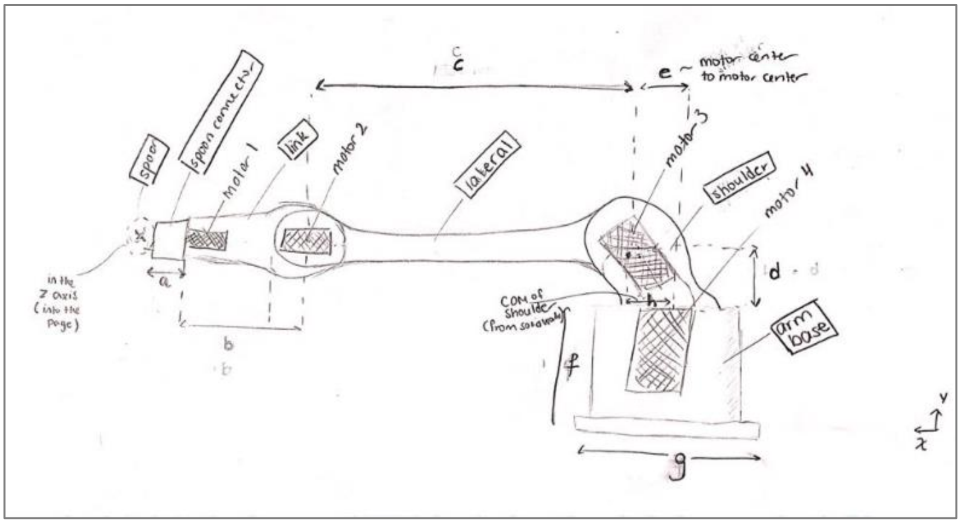


Figure 2.3: Sketch of device static maximum load configuration.

The power required for each motor to produce the necessary torque needed to be calculated. In order to calculate the power required for the first motor that rotates the spoon. The center of mass of the spoon, spoon, spoon holder, wrist joint, and shoulder joint was calculated using *Equation 2.2* The mass of the food on the spoon was assumed to be 20 g and the center of mass of the spoon was assumed to be 4 cm away from the spoon holder.

$$x_{bar} = \frac{\sum_{i=1}^{N} m_i x_i}{M} \tag{2.2}$$

Next, the sum of forces and torques in the horizontal axis were calculated. The torque was calculated using *Equation 2.3* and then used to calculate the power required to deliver it using *Equation 2.4*. The maximum speed that the motor is required to operate at is assumed to be 25 rpm, as seen in previous eater devices on the market [1][2][3].

$$T\ [Nm]\ =\ F\ [N] \times d_{\perp}[m] \tag{2.3}$$

$$P\ [W] = T\ [Nm] \times \omega\ [rpm] \times \frac{2\pi}{60} \tag{2.4}$$

A factor of safety of three was used in all of the torque calculations to account for the mass of the motors, wiring, and other components such as bolts, screws, and circuit components as well as added safety. If the power that can be delivered by the motor is less than what is required, then it may not function at a lower speed and/or torque than needed. However, if the power it can deliver is more than required, there is no harm to the device. Therefore, adding this factor of safety is beneficial to the performance of the device overall. This process was repeated for each of the 4 motors and the power required for each one is summarized in *Table 2.1*, where motor 5 is the one closest to the spoon and motor 5 is the one that rotates the plate. The power required increases for the motors closer to the base as they have to accommodate for the added load of the arm components.

Table 2.1: Power calculated for each motor.

Motor No.	Power (W)
1	0.000092
2	4.261
3	4.065
4	1.391
5	0.107

Since the arm is connected to the base at its end and moves, there is the concern of instability that causes the device to tip over. To ensure that this does not occur, a static equilibrium calculation was made for the device in the maximum load configuration. Assuming that the mass of the base is unknown, it was calculated at equilibrium to find out what its minimum value must be to prevent loss of equilibrium. *Figure 2.4* shows the schematic and *Figure C.5* in Appendix C shows the full calculation. The minimum required mass of the base is 1.84 kg. The maximum mass of the base according to the maximum density found in the materials analysis is 2.2 kg, which meets this requirement. This will be kept in mind in case there is a change in material choice during the next project stage.

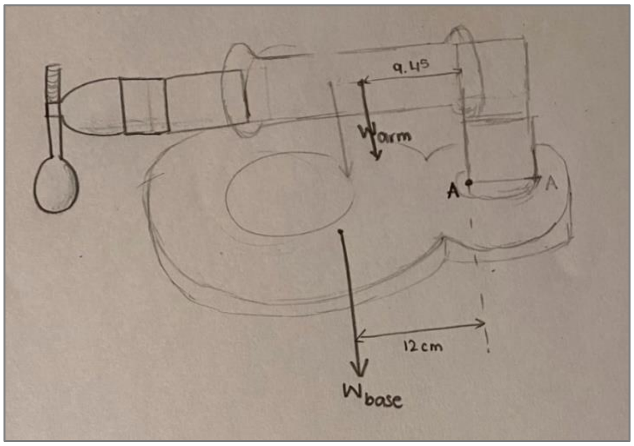


Figure 2.4: Schematic of Equilibrium Calculation

3. RESULTS

3.1 Concept Evaluation

3.1.1 Absolute Evaluation

After developing the concepts, these designs must be safe, feasible, and meet the customer’s needs. Concepts are eliminated if they are not safe, feasible, or do not meet the customer’s need. This process of elimination, or absolute evaluation, was done for each concept in every subcomponent.

When moving to concept ideation, decisions needed to be made about different embodiments of the design. In order for the self-feeding device to achieve all of the functions previously defined, different sub-components were identified to embody the top-level functions. The three sub-components identified were the manipulator arm, the plate, and the user interface. Design concepts were developed for each subcomponent and will be discussed in detail throughout this section of the report.

The main goal of this project is to produce a device that is as maneuverable as a human arm and to do so, the degrees of freedom of the device must be maximized. The actuators for such a manipulator can be provided in three different ways: An electric motor such as an AC- or DC-motor, a hydraulically powered, or pneumatically powered. The electric motor is most suitable since it is cheap and easy to use, the hydraulic powered system is usually used to pump fluids, and the pneumatically powered is not easy to control and is limited in range. [35]

The manipulators are also known as a form of a humanoid because humanoids are based on the parts of a human body. In the case of manipulators, they are based on the human arm. Human arms generally have 6 degrees of freedom when you exclude the fingers. The following concepts presented are standard configurations of one major concept which is that of manipulators with three degrees of freedom. Degrees of freedom are determined by the number of joints in the manipulator. For prismatic joints, the three degrees of freedom are the linear motions: up-down (elevate), left-right (reach) and front-back (travel) directions. For revolute joints, the three degrees of freedom are the angular motions: yaw (left-right rotation), pitch (up-down rotation) and roll (rotation about the arm's axis).

Concept 1 - Cartesian manipulator (PPP)

This concept addresses cartesian manipulators which as the name indicates, use the cartesian coordinates, x-y-z as seen in Figure 6. If this mechanism is taken with three prismatic joints (PPP): the shoulder, elbow and wrist, the manipulator will act similar to an arm. An advantage of this manipulator is that its simple kinematics model makes it easy to visualize the manipulator's motion, the kinematics are how the joints and links are connected. However, the disadvantage of this design is that the workspace is very limited, and the scooping mechanism of the utensil will be hard to achieve without a revolute joint. In addition to that, the manipulator's size is much larger than the workspace it operates within.

Concept 2 - SCARA manipulator (RRP)

This concept addresses the SCARA robot which is an acronym for Selective Compliance Articulated Manipulator Arm. This manipulator comprises two revolute joints and prismatic where the shoulder and elbow are revolute joints and the wrist is a prismatic one. The revolute joints move in a horizontal planar workspace while the prismatic joint moves in the vertical direction, so they produce a cylindrical workspace when functioning. The advantages of this manipulator are its cost-effectiveness and its ability to operate at high speed and accuracy, in fact it is the fastest in the market. On the other hand, the SCARA robot faces the same issue as the previous manipulator in the sense that it lacks the revolute joint at the wrist to produce that scooping mechanism. In addition, its workspace is even smaller than that of a cartesian manipulator with the same reach.

Concept 3 - Cylindrical manipulator (RPP)

The cylindrical robot differs is made up of a one revolute at the shoulder and two prismatic joints at the elbow and wrist which form a cylindrical workspace. The joint variables are the cylindrical coordinates with respect to the base. [6] Although this is similar to the SCARA, the application of the SCARA manipulator is different from the cylindrical manipulator. The cylindrical manipulator operates linearly along two axes and rotates about another. They are usually used in simple applications where materials are just picked up, rotated and then placed around it. They are also useful for larger payloads, have good repeatability, and they are easy to visualize due to their simple kinematic. They have minimal assembly, and the installation and use are not complex [7]. The disadvantages include the restricted workspace and that the prismatic guides will be hard to protect against dust and liquid accumulation, which may affect the lifespan of the arm.

Concept 4 - Spherical manipulator (RRP)

Made up from two revolute joints and one prismatic joint, a manipulator is called a spherical manipulator if all the links perform spherical motions about a common stationary point. The point is usually a joint known as the ball-and-socket joint. This allows three degrees of rotational freedom about the center of the joint. Advantages of the spherical manipulator is that it covers a large volume of space from a central support. The disadvantages of this concept include its complex kinematic model which makes it difficult to visualize.

Concept 5 - Articulated manipulator (RRR)

Unlike other configurations, the articulated manipulator consists of revolute joints only, which means that the motion is purely rotational. This manipulator is known for its ease of assembly. An articulated manipulator can range from a two-jointed structure to an infinite number of joints to form a system. In comparison to other manipulator configurations, the articulated manipulator covers the largest workspace. The high range of flexibility offered by this manipulator will definitely maximize the level of autonomy given by the system. However, a setback to this particular manipulator can be its complexity in controlling the linear motion. Unlike other manipulators, the structure will lose its rigidity at full range of motion. In addition, this revolute joint at the shoulder is designed to reach a planar angle of 330° rather than the full 360°.

Table 3.1 outlines the absolute evaluation of the manipulator subcomponent's concepts. When analyzing the manipulator concepts, it was seen that all the concepts passed the absolute evaluation as they were all safe, feasible, and met the customer's needs.

Table 3.1: Absolute Evaluation of Manipulator Concepts

Concept	**Meets Customer Need?**	**Safe?**	**Feasible?**	**Absolute Evaluation**
Cartesian	Yes	Yes	Yes	Pass
SCARA	Yes	Yes	Yes	Pass
Cylindrical	Yes	Yes	Yes	Pass
Spherical	Yes	Yes	Yes	Pass
Articulated	Yes	Yes	Yes	Pass

The following schematics are examples of the possible plate designs. The plate can come in different shapes and motions. It can be either rotated or fixed in place, ideally the circular plate is a more suitable option for rotation. The plate may also come in a rectangular or square shape but will be fixed. The plate can come either be divided into sections to hold a variety of foods to prevent cross contamination or a single plate with no dividers to hold only one type of food

Concept 1 - Circular Divided Plate

The concept of designing a circular divided plate is suitable to hold a variety of food at once. The plate is mainly divided into 4 different sections which are able to separate protein, carbs, soup, and vegetables. The plate would be attached to the base of the device with a feature of rotating the plate to help the patient shift easily through different sections of the plate. The dimensions are as shown in *Figure 3.1* having a diameter of 34 cm. Implementing this concept will definitely increase the variety of food available to the patient and the arm can be manipulated easier in such a way the patient has more freedom to pick what they want to eat from the plate.

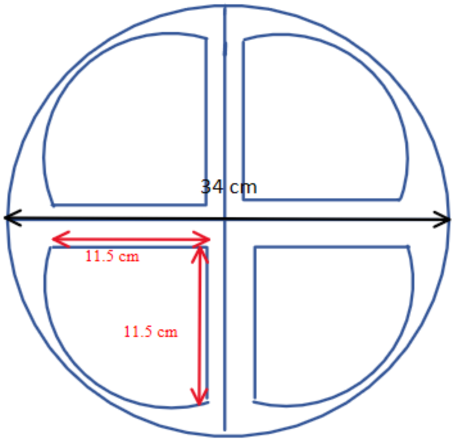


Figure 3.1: Circular Divided Plate

Concept 2 - Rectangular Divided Plate

Similarly, this concept achieves the same function as that of the circular divided plate. However, the shape is rectangular, as seen in *Figure 3.2,* which limits the plate from rotating which will definitely require a higher range of motion from the user. Therefore, this plate is designed to be held fixed and the arm will be programmed to get the food specified by the patient. The dimensions are shown in Figure 12 to have a length of 10 cm and a width of 30 cm. Without rotation the arm will need to have a wider range of motion and workspace to deliver the food to the user.

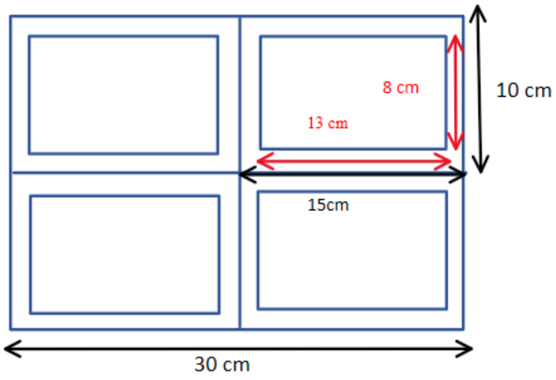


Figure 3.2: Rectangular Divided Plate

Concept 3 - Circular Plate

This concept is a basic circular plate without any dividers, similar to plates used every day as seen in *Figure 3.3*. This design would only contain one type of food or a maximum of two. Since the plate is circular it does have the option to rotate or remain fixed, but without dividers it is difficult to direct the arm to go to a specific location.

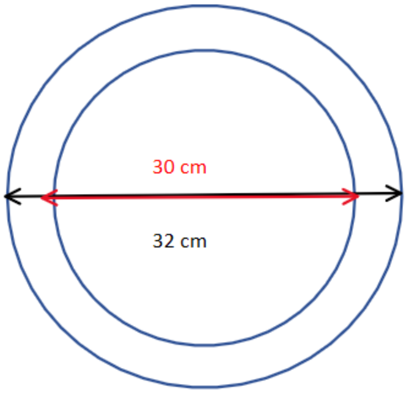


Figure 3.3: Circular Plate

Table 3.2 shows the absolute evaluation of the plate concepts, which all passed the evaluation.

Table 3.2: Absolute Evaluation of Plate Concepts

Concept	Meets Customer Need?	Safe?	Feasible?	Absolute Evaluation
Circular Divided Plate	Yes	Yes	Yes	Pass
Rectangular Divided Plate	Yes	Yes	Yes	Pass
Circular Plate	Yes	Yes	Yes	Pass

An interface determines how the user interacts with the device; it gives the user different options to control specific functions of the device. This can be controlled in three different ways: graphical user interface, joystick interface, menu-driven interface.

Concept 1 - Graphical User Interface (GUI)

A Graphical user interface (GUI) is an interface that is implemented on Windows and Macintosh systems which operates on computers and tablets. The interface provides the user with several independent commands which successfully achieve the desired functions of feeding a patient. This includes food acquisition which performs scooping and stabbing. Another main command is the delivery of the food from the plate to the user’s mouth. An additional command that can be implemented is removing excess food from the utensil by wiping it against the plate’s rim. The GUI is considerably an easy-to-use interface in comparison to others provided in the market.

Concept 2 - Joystick

The joystick interface is considered a pure manual operated interface. The user has full control of the device by the joystick. The joystick is designed to ensure the simplicity of managing different functions the device offers. Since this interface is built on a pure manual operator, it fails to maintain a high independence level. Limitations include patients who have problems with chewing and swallowing, patients who fail to operate a joystick or press a button, and patients with difficulty in understanding how the device is operated.

Concept 3: Menu - Driven Interface

A menu driven is a list of options from which you can choose what you want to do. Application programs use menus as an easy alternative to having to learn program commands. Menu-driven interfaces were developed in order to make the interface ‘friendlier’ and ‘easier to learn’. You can control the interface by a computer by choosing commands and available options from a menu [36]. This interface would allow options of simple tasks and to be adjusted or controlled. These tasks can include; powering up and shutting down the device, rotating the plate, adjusting the arm height and more.

Table 3.3 shows the absolute evaluation of the interface concepts. It can be seen that the GUI and Menu-Driven Interface concepts passed the absolute evaluation while the Joystick concept did not. This was due to it not meeting the customer's needs as it could require the help for another human being to control the joystick, decreasing its autonomy.

Table 3.3: Absolute Evaluation of Interface Concepts

Concept	**Meets Customer Need?**	**Safe?**	**Feasible?**	**Absolute Evaluation**
GUI	Yes	Yes	Yes	Pass
Joystick	No	Yes	Yes	Fail
Menu-Driven	Yes	Yes	Yes	Pass

3.1.2 Relative Evaluation

Now that the concepts have made it through the absolute evaluation stage, they can undergo relative evaluation where the concepts are compared to each other based on a set of weighted criteria derived from the functions and requirements. First, the design selection criteria were selected and assigned a weight factor. The weight factor shows how important it is for the concept to meet the selection criteria on a scale of 1 – 5, with 1 being of low importance and 5 being of high importance. Then, each concept was ranked indicating on how well the criteria was met on a scale of 1-5 as well, with 1 meaning the concept excelled the most and 5 meaning it excelled the least. Finally, the total score was calculated as the sum of the products of the weights and rankings.

Table 3.4 shows the relative evaluation of the manipulator subcomponent. The weight of the device and its price was given the highest weighing factor of 5, which means it has a high importance in the manipulator design. This is because portability and low cost are the objectives desired to achieve, which can be aided by the design having a low weight. The workspace range, defined as the range of movement of the arm, has a high weighting factor since it adds to the autonomy of the device. An increase in the range of movement of the manipulator arm would mean that the user would not be required to lean forward or move their head forward when eating using the self-feeding device. Size, assembly, manufacturing, and programmability were given an average weight of 3 since they mainly concern the way the product is produced rather than improving its features. Lastly, the aesthetic of the device, which is important for the product to look appealing, however it is not as important as the functionality of the design and ease of manufacturing.

After evaluating all the concepts based on their attributes discussed in the concept stage, it was found that the articulated manipulator scored the highest at 115 out of the highest possible total of 135 and was the selected design. This means that it scored well against the specific criteria looking to be achieved. The cartesian and spherical manipulators were the runner ups with very similar scores of 93 and 92, respectively. Due to this, both the concepts were combined in an effort to increase their score and re-evaluated against the articulated manipulator.

Table 3.4: Selection matrix for the manipulator sub-component

Criteria	**Weight Factor**	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**
		Cartesian Manipulator	SCARA Manipulator	Cylindrical Manipulator	Spherical Manipulator	Articulated Manipulator
Weight	5	5	2	5	5	5
Workspace range	4	1	1	4	3	5
Price	5	3	4	3	4	3
Size	3	2	3	2	2	4
Easy to Assemble	3	5	4	2	3	4
Manufacturing	3	4	3	2	3	5
Aesthetics	1	1	4	3	2	4
Programmability	3	5	4	3	3	4
Total	-	**93/135**	**80/135**	**86/135**	**92/135**	**115/135**

The combined desired concept is in the cartesian and spherical coordinates. The difference between them is that the cartesian is purely in translational motion and very easy to assemble while the spherical coordinates have both translational and rotational movement and is harder to assemble. The problem with cartesian is that there is no rotational motion, meaning that the food won't be scooped and fed directly to the user's mouth as they would need to move their head and eat which will cause discomfort. Even if more joints were added, meaning more degrees of freedom, the cartesian manipulator takes up a large space as a device and that would still be a disadvantage. The spherical coordinates, however, already have some translational motion, the only disadvantage is the programming and the ease of assembly. In addition, all the options provided have half the degrees of freedom that a human hand has. Therefore, producing a combination of the standard manipulators would be the best option to maximize the degrees of freedom. An idea for a design could be building the first three joints in the same form as in a cylindrical manipulator achieving yaw, elevation, and reach. Adding onto it, two more joints both achieving pitch motion. *Table 3.5* shows the re-evaluation of the two design concepts, where it can be seen that the Articulated manipulator was still the better choice.

Table 3.5: Re-evaluation Selection matrix for the manipulator sub-component

Criteria	**Weight Factor**	**Concept 1**	**Concept 2**
		Cartesian & Spherical Manipulator	Articulated Manipulator
Weight	5	5	5
Workspace range	4	4	5
Price	5	3	3
Size	3	2	4
Easy to Assemble	3	3	4

Manufacturing	3	3	5
Aesthetics	1	2	4
Programmability	3	4	4
Total	-	**94/135**	**115/135**

Table 3.6 shows the design evaluation for the plate sub-component of the manipulator. The selection criteria were chosen in a similar manner to that of the manipulator. The weight of the device was given the highest weight due to its contribution to making the device portable and low cost, so a lower weight is more desirable. The size of the plate is important because it determines how much food it would be able to hold. A size that is similar to standard everyday plates is more desirable since the intention of the device is to cater to a wide range of ages. The manufacturing of the plate is important in order to make it easier to produce, but not as important as the weight and size of the plate. Aesthetics play an important role in the design of the plate; it must be appealing to the user since they will be using it frequently inside and outside of their homes. For this reason, it was added as a selection criterion but was given a lower weight factor. After the evaluation was made, it can be seen from the table that the circular divided plate scored the highest at 56/70, making it the most suitable design selection for the plate.

Table 3.6: Selection matrix for the plate sub-component

Criteria	**Weight Factor**	**Concept 1**	**Concept 2**	**Concept 3**
		Circular Divided Plate	Rectangular Divided Plate	Circular Plate-
Weight	5	4	3	2
Size	4	5	3	1
Manufacturing	3	2	3	5
Aesthetics	2	5	3	1
TOTAL	-	**56/70**	**42/70**	**31/70**

Table 3.7 shows the design evaluation for the interface sub-component of the device. The joystick concept was not included as part of the relative evaluation since it did not pass the absolute evaluation. Making it user-friendly, easy to use, and aesthetic were the most important factors since the interface would serve as the main communication method between the user and the device. It should be easy for anyone, especially the patient, to understand how to turn it off and on and adjust the settings. If something were to go wrong such as a malfunction, it should be able to clearly state the issue to the user. The size and price of the interface were also important criteria to include since the cost of the device is desired to be minimized. As seen in the table, the menu driven interface had the highest total score of 98/115, making it the selected design for the interface.

Table 3.7: Selection matrix for the plate sub-component

Criteria	Weight Factor	**Concept 1**	**Concept 3**
		GUI	Menu-Driven
Size	3	2	5
Price	3	3	2
User-friendly	5	5	4
Ease-of-use	5	5	5
Programming	3	2	4
Aesthetics	4	2	5
Total	-	79/115	98/115

3.1.3 Final Concept

The study of different concepts of each component a self-feeding device is required to have has been achieved. Based on the evaluation process (absolute and relative), it has been seen best that the final design will consist of the selected subcomponents: the articulated manipulator, the divided circular plate. A sketch of the final design concept can be seen in *Figure 3.4*.

When comparing the final design to the products available in the market, neater eater and obi robot, the designed product differs in the main three subcomponents in several ways. The plate selected in the final design is a circular plate divided into four quarter circular bowls to categorize the food. The plate is planned to rotate to the desired food group to allow the arm to scoop the food. This differs from other products where the arm moves to the desired food group or to a certain part of the plate. In the neater eater design no dividers are included and the arm scoops the food. Unlike the complexity of the neater eaters' interface offering a lot of options for the user, four different functions are seen necessary to be implemented in the design. These include power button, adjusting mouth position, plate rotation, and food delivery. These options can be selected on a button positioned on the base of the device. To ensure a high level of autonomy the device can offer, 4 degrees of freedom was chosen to be the optimum number. Uniquely from the other products the device includes a prismatic joint in addition to the revolute joints. The prismatic joints maximize the workspace area and increase the range of motion from the device to the patient's mouth. Implementing these concepts on the final design will successfully achieve the desired main goals and make it stand out from different devices available in the market.

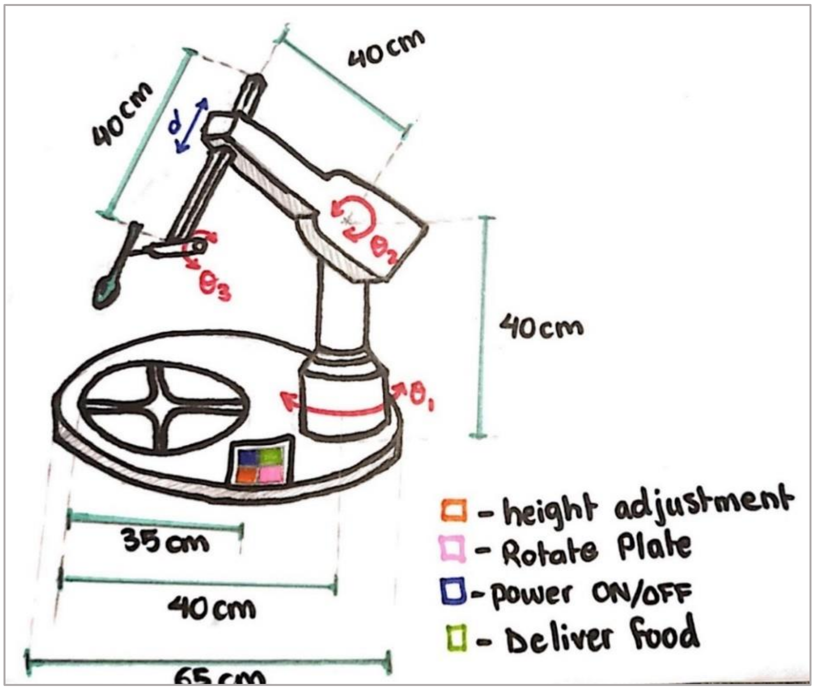


Figure 3.4: Final Design Concept Sketch

3.2 Failure Modes and Effects Analysis

A Failure Modes and Effects Analysis (FMEA) is a type of qualitative analysis to determine the different failure modes of a part, system, or subsystem as well as their effects and possible causes and rank them based on their likelihood and severity. An FMEA table was developed for the different “items” in each of the four subsystems: power source, manipulator, plate and utensil, and user interface. The potential failure modes were identified, and their effects were discussed. The effects were rated for their severity on a scale of 1 to 10, from least to most severe. Possible causes for these failures were also identified and rated based on their likelihood of occurrence on a scale of 1 to 10, from least to most likely. The risk priority number (RPN) is a measure of the numerical assessment of the risk of a failure mode. It was calculated for each failure mode and effect by multiplying the severity and likelihood of occurrence to get an RPN value scored out of 100. Recommendations were made for each failure mode to reduce the severity or likelihood of occurrence of the failure mode.

The FMEA was used during the design process to guide the design decisions by incorporating the recommendations of some of the failure modes in order to increase the reliability of the device. Any failure mode RPN value above 50 was considered unacceptable and its respective recommendation was added as an alteration on each subsystem design. The low-cost recommendations for the remaining failure modes were also incorporated as best as possible into the design and design requirements to create a tradeoff between reliability and cost. It was also used to aid in decision making between design alternatives and their configurations. Appendix D shows the FMEA developed for the device, broken down into its subsystems.

3.3 Preliminary Design

3.3.1 Performance Requirements

Based on the need analysis and the preliminary calculations found in *Appendix C*, the basic performance requirements of each subsystem were identified and are outlined in *Table 3.8* below.

Table 3.8: Summary of Performance Requirements

Subsystem	Performance Requirement
Power	Supply 7-8 V of electrical energy
	Transmit 60-70 W of electrical energy
	Store 7 Ah of energy storage rate
	Store 2 hours of charge
	Operating current of 0.1-5 A, with a limit of 7.5A
	Isolate all electrically conductive components from parts that the user can touch
Manipulator Arm	Angular speed of the motors = 10-20 RPM
	Arm must have a payload of 0.5 kg while the entire system must weigh 5kg.
	Must have a horizontal and vertical reach of 30 cm.
Motors	Motor 1 for the plate requires a torque of 0.000879 Nm
	Motor 2 for the arm base requires a torque of 4.069 Nm
	Motor 3 for the waist requires a torque of 3.882 Nm
	Motor 4 for the link requires a torque of 1.328 Nm
	Motor 5 for the spoon connector requires a torque of 0.102 Nm
Plate and Utensil	Min volume of the plate 15.5 cm^3 divided into 4 sections Plate must hold 150-200 g of food Plate needs a torque of X
	Depth of the spoon of 3 cm & a diameter of 3-4 cm Spoon must hold 15-30 g of food
User-Interface	200 to 250 ms button’s response time [42]
	84 x 63 mm (L x H) LCD Screen

3.3.2 Operating the Device

The device will be ensured to be charged and placed on a suitable flat platform. The plate is to be fixed and locked on the base of the device, while the spoon is screwed on to the connection. The device is then to be powered on by the power button. Once the user is seated across the device and food is placed on the plate, the caregiver is to press the learn button and move the arm of the device until the spoon is at the position of the patient’s mouth. The device will learn and save this position for that seating. Next, the user will press the feed button for the device to begin feeding the patient. The patient must press the feed button by their feet or hand before every bite. The user can also select the desired food that is placed on the plate compartments by pressing the plate rotation button. Once the user has completed their meal the caregiver is to power off the device and disassemble the plate and spoon to be washed and for the device to be packed away.

After completing the conceptual design and looking at all the functions and requirements the device should be able to accomplish, the design was translated into drawings. SOLIDWORKS was used to design the different components of the device individually and assemblies. As mentioned previously the main components of the device consisted of the arm, base, plate, and utensil. *Figure 3.4* shows the final concept design that was sketched in the earlier stages of the project. This design was then developed based on innovation, functions, and requirements to the SOLIDWORKS initial design shown in *Figure 3.5.* The initial design was also changed to fit the requirements of having a 300mm reach, whereas here it is only 210 mm. The final design of the model after modifications and adjustments is shown in *Figure 3.6.*

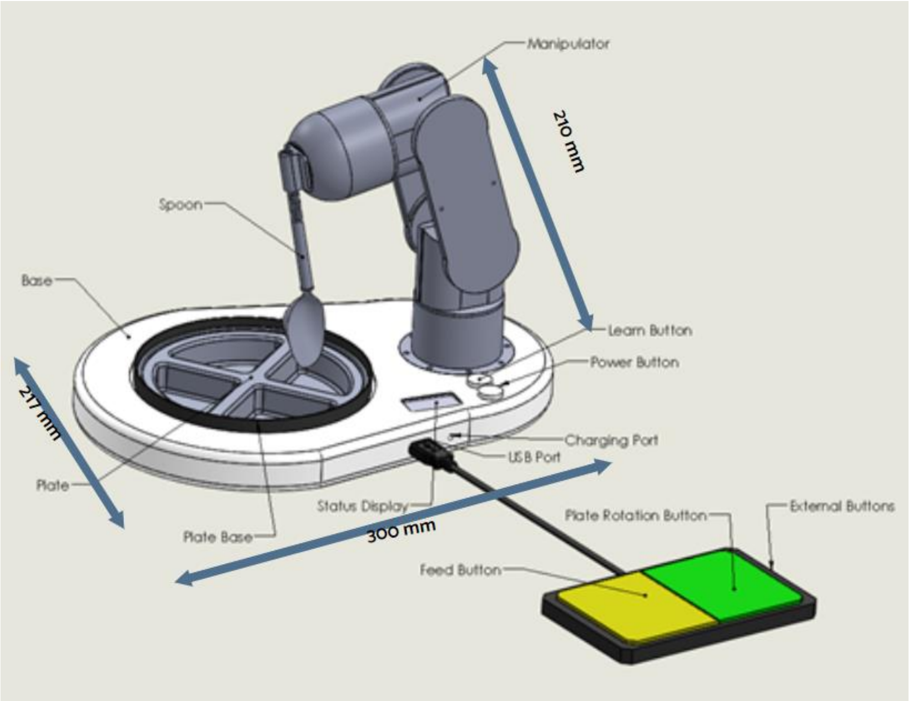


Figure 3.5: Initial Assembly Isometric View

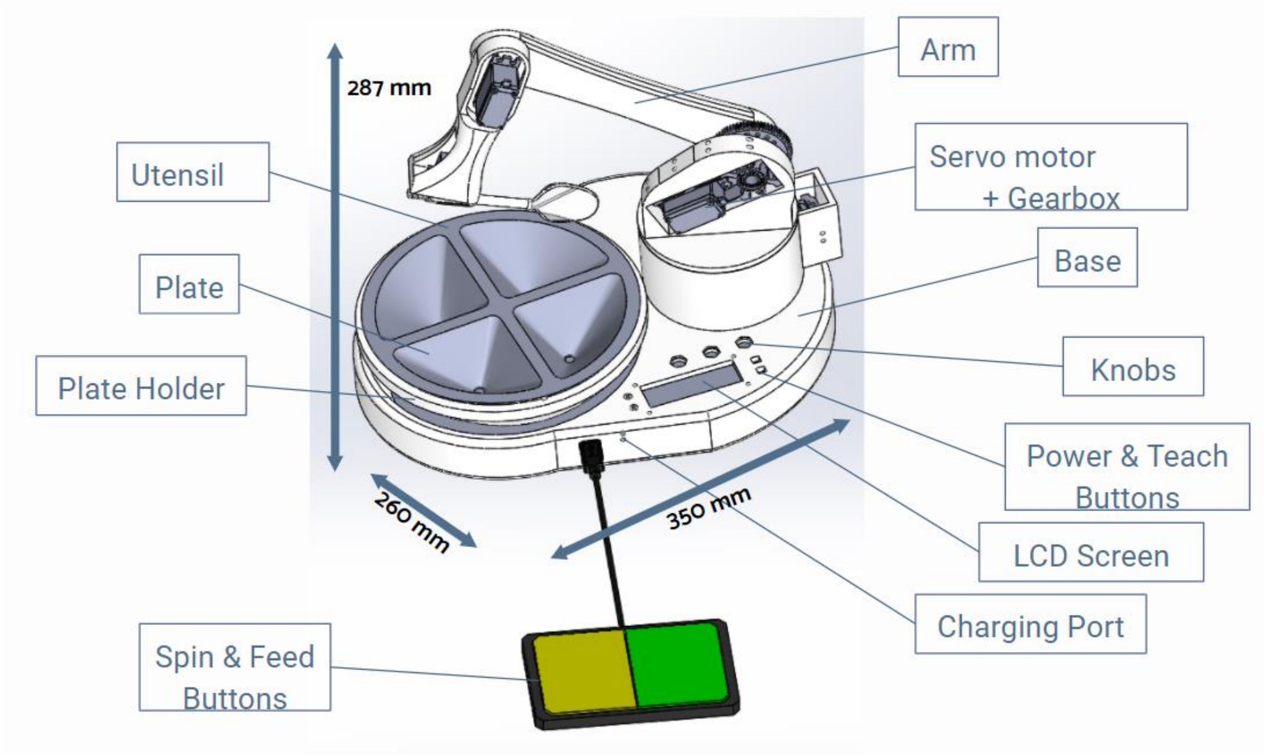


Figure 3.6: Final Assembly

3.4 Detailed Design

3.4.1 Power

Under the power supply subsystem, there are three subsystems under the power supply: The AC power supply that is supplied from the building. In Qatar, the power supplied has a standard voltage that ranges from 220 to 240 V. The second subsystem is the Lithium-ion battery charger that has an operating voltage of 3.7 V. This is used to charge the Lithium-ion batteries – the third subsystem - used in the device. Each battery is rechargeable with a voltage of 3.7 V and an energy capacity of 3800 mAh. In this device, four rechargeable batteries were connected such that two pairs of batteries are connected in series and then the pairs are then connected in parallel as shown in *Figure 3.7* Note that the red box indicates how each battery is represented.

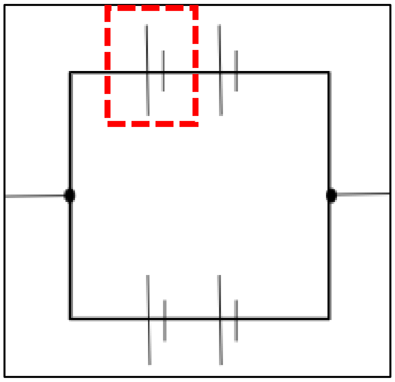


Figure 3.7: Schematic of the Battery Connections

3.4.2 Base

Looking at the different sub-components of the system, the first main component, the base, can be seen in *Figure 3.8*. This component combines all the system components onto one platform. The base considers the internal and external interfaces of the device. It consists of two buttons, output display screen, charger port, USB port for external buttons, and accommodates for other sub-components to be mounted onto the base. The dimensions of the base along with its multiple subcomponents can be seen in *Figure 3.8*, the base maximum length and width are 350 mm and

266.25 mm respectively, and a depth of 40 mm. There is a plate mounted at the top of the base with a height of 28 mm. The engineering drawing of the base where all the dimensions are specified in detail is shown in *Appendix H.1*. Shown in *Figure 3.9* is the base cover that will accommodate for all the different electrical subcomponent being attached to it. Furthermore, motor mounts are added on the base cover to accommodate for the motor responsible for the rotation of the plate. The total mass of the base is 522.11 g.

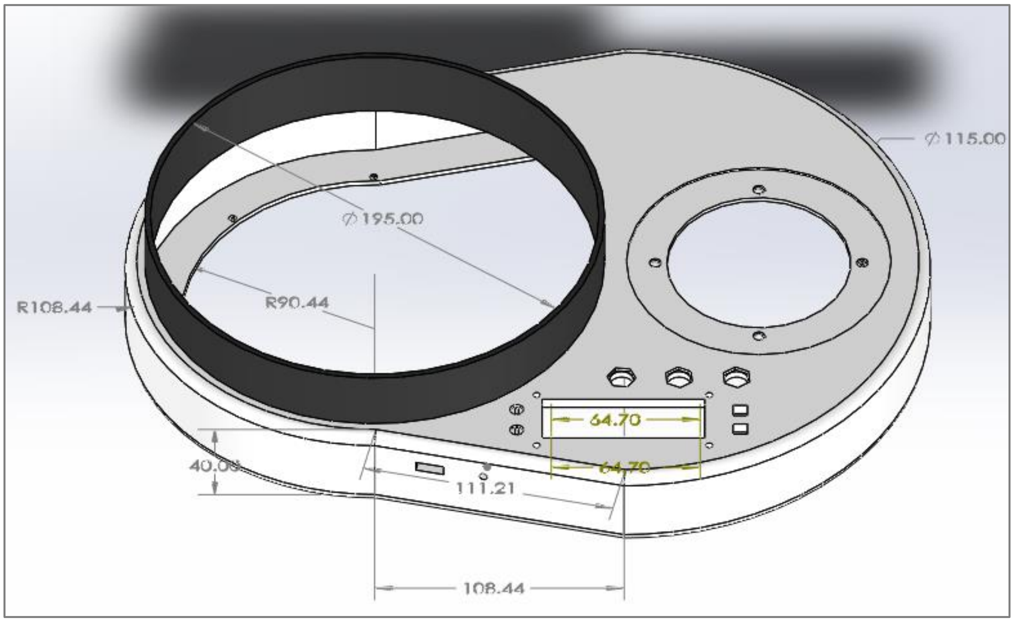


Figure 3.8: Base Isometric View

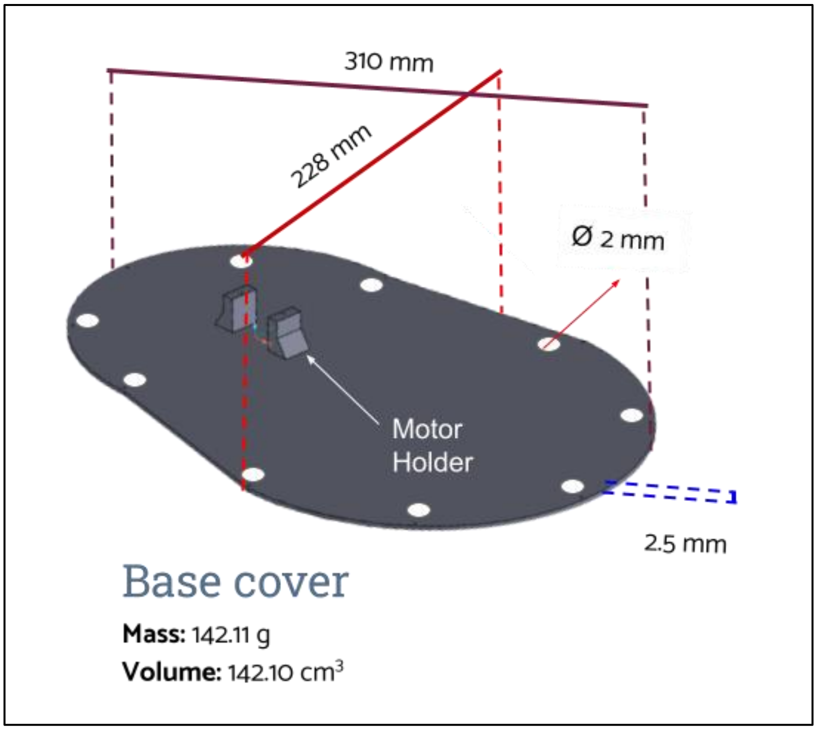


Figure 3.9: Base Cover Isometric View

3.4.3 Manipulator

The most important and complex component of the system is the arm which is referred to as the manipulator. This component consists of seven sub-components. *Figure 3.10* shows all the components attached to assemble the arm. As mentioned previously the arm has four revolute joints that allow the arm to transfer the food from the plate to the patient's mouth. The spoon connection at the end of the arm, also known as the end effector, connects the spoon to the arm. The arm stands at a height of 285 mm and has a maximum span of 235 mm. *Figure 3.10* shows the dimensions of the arm assembly. The total mass of the arm was calculated to be 2.6179 kg. While the total mass of the system was calculated to be 3.7087 kg. *Figure 3.11 and 3.12* show the new schematic of the arm, it has sleeker links making it lighter and more aesthetic. From the first design, design modifications were done to make the arm less bulky and operate smoothly. Furthermore, the modified design accommodated for the position of the motors and their attachments. In addition to that, the assembly simulation worked more efficiently. Dimensions were adjusted and finalized based on the need of the design. The updated arm design is shown in *Figure 3.13* where the total mass of the arm was calculated to be 551.1 g and has a reach of 352 mm. Th engineering drawings of the arm is shown in *Appendix H.2*.

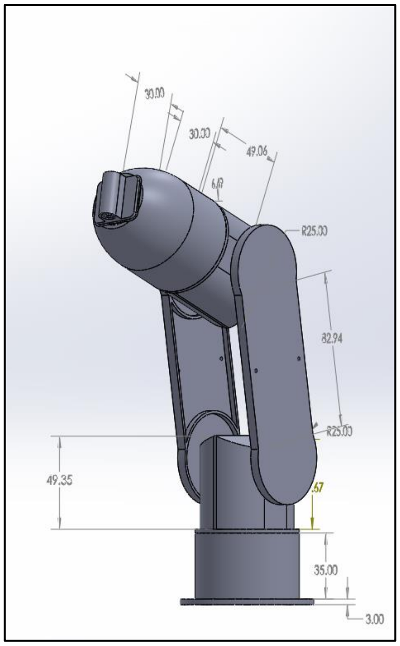


Figure 3.10: Configured links design of the arm

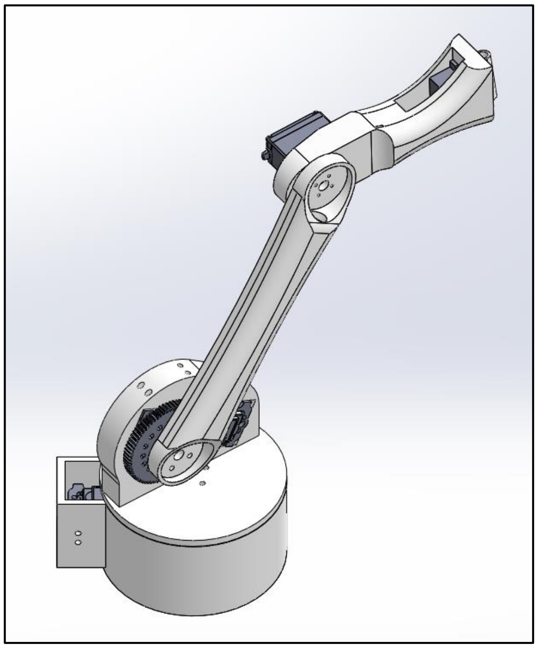


Figure 3.11: Updated design of the arm

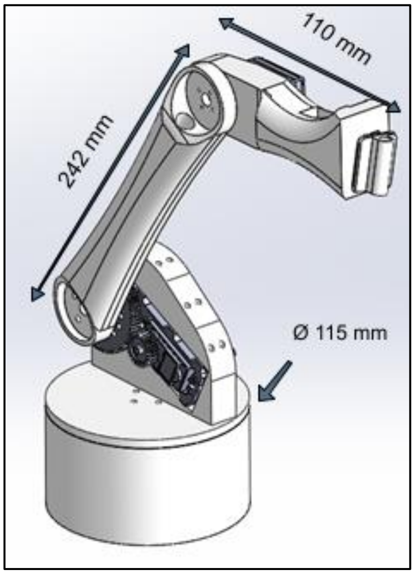


Figure 3.12: Updated design of the arm (second view)

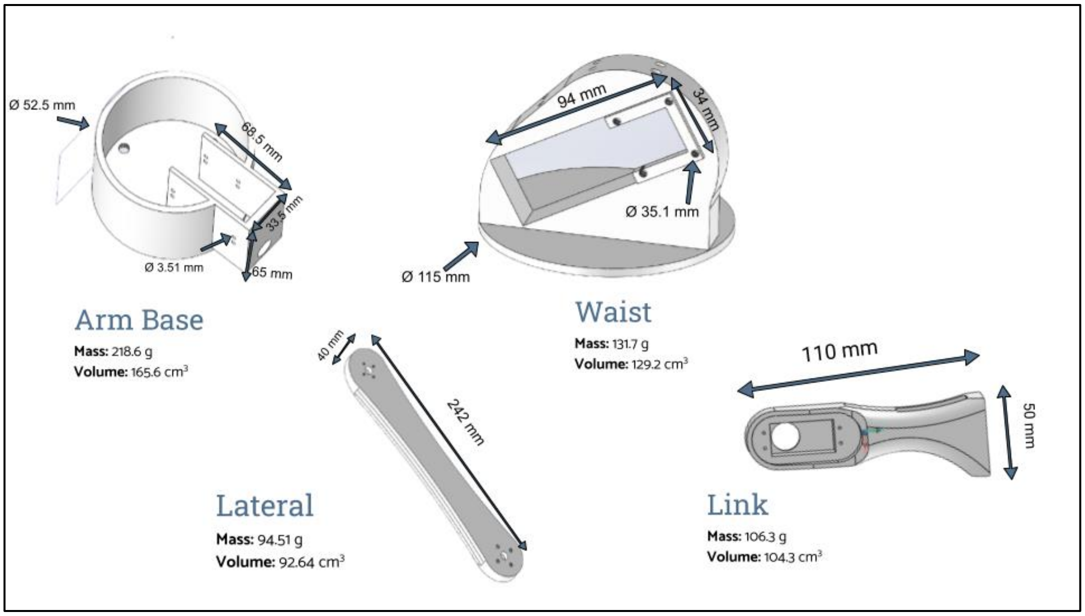


Figure 3.13: Detailed Dimensions, Mass, and Volume of the arm components

3.4.4 Plate and Utensil

The next component is the plate shown in *Figure 3.14*. The plate is categorized into four divided compartments, each compartment can be allocated to one of the four main food categories which are: grains, protein, carbohydrates, and fruits/vegetables. The dimension of the entire plate has a diameter of 200 mm the plate depth is 50 mm. The length of the plate and plate holder are 200 mm and 209 mm, respectively. The engineering drawing of the plate and spoon utensil where all the dimensions are specified in detail is shown in *Appendix H.3.* Shown in *Figure 3.15* the configured plate holder where it accommodates for the locking mechanism of the plate. Once it's secured the plate holder will be responsible for rotating.

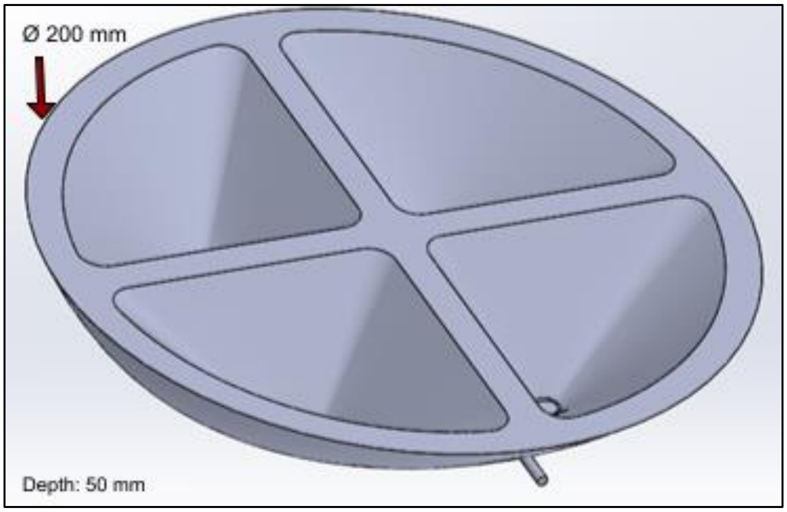


Figure 3.14: Configured Plate Mechanism

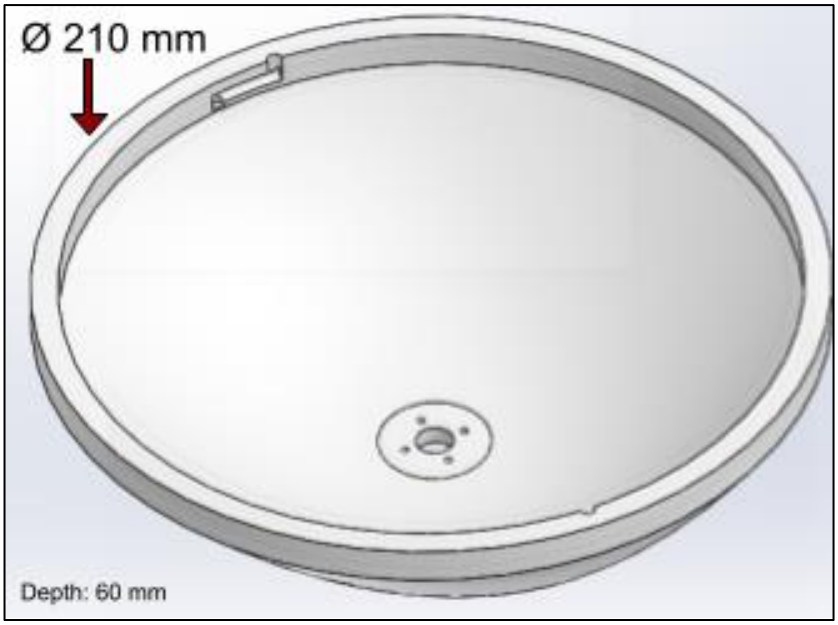


Figure 3.15: Configured Plate Holder Mechanism

The utensil component, the spoon, is shown in *Figure 3.16*. This component can be attached to the arm in a screw method. The spoon has a full length of 144.23 mm, with the spoon handle being 89 mm and the bowl of the spoon being 54.23 mm. The handle of the spoon will have a nut at the threaded part to prevent the spoon from coming off while rotating.

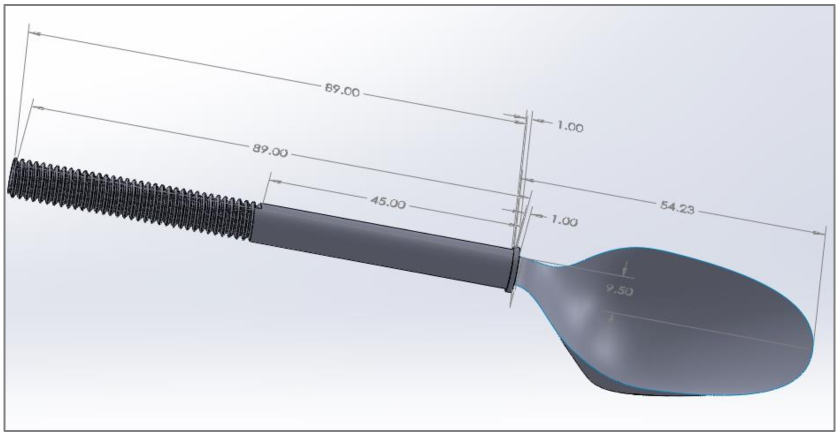


Figure 3.16: Configured Spoon Mechanism

3.4.5 Failure, Modes, Effects, and Criticality Analysis

In the conceptual and preliminary phase, several design improvements and changes were made based on the Failure Modes and Effects Analysis (FMEA). In the detailed design phase, the selected designs' failure criticality is observed and analyzed. The method used to perform the Failure, Modes, Effects, and Criticality Analysis (FMECA) was derived from the NASA Systems Engineering Handbook [32]. The analysis is done by initially creating fault trees to determine major possible reasons for a specific failure occurring and obtaining a probability of its occurrence per year. Then, an event tree is created to observe the outcomes and consequences of an unwanted initiating event that may occur, as well as its probability of occurrence per year. The pivotal events, which are selected as preventative measures or mitigations of the initiating event, are then listed afterwards with their probability of success described per event. The probability of the pivotal event's failure is calculated by subtracting the probability of success from one. The outcome consequences of each branch of the event tree gives us the total expected loss per year due to the initiating event. The total expected life of the entire system is three years, based on the lifetime of the links, motors. The overall subsystem has a lifetime of at least three years based on the life expectancy of the links. Given that the total expected life, if the total expected loss over this lifespan is too high, design changes may be made to lower this cost. A cost-benefit analysis is performed to determine if the design changes significantly decreased the losses to inform on whether they should be implemented. *Appendix F* shows the development of the fault trees and event trees for each subsystem.

3.4.5.1 Power Supply FMECA

The three major ways in which a lithium-ion battery can fail is the cell can overheat due to excessive current draw or faulty insulation, excessive battery vibration can be caused by impact of the device, and the battery being loose in the base [34]. This shows that the cell has a probability of failure of 0.212 per year. If a cell fails, the chances of the circuit remaining closed is only 50% per event. With the design configuration, however, it is beneficial to have the circuit open due to the cell failure; an open circuit stops the current flow to that branch, and the device can rely on the other pair of cells in parallel with the failed cell. Finally, the faulty cell would need to be replaced, along with the cell beside it, since a faulty lithium-ion cell drains other cells that are placed in series with it. The cost of a single cell is USD 3, however if the cells are not able to be replaced for any reason, the device becomes redundant. The total expected loss per year is only USD 3.50, and USD 10.50 over 3 years. Although these numbers are low, the biggest risk occurs if the circuit segment remains closed and drains the battery beside it, which is not the ideal scenario. A minor design change that can be implemented as a solution to this problem is the Schottky diode. Placing these diodes in parallel with each cell protects the other cells in series from being drained in case that cell was to fail. Since Schottky diodes are cheap and readily available locally, implementing this design change seems to be practical. By implementing this design change, the total expected loss per year drops to USD 1.87 and the total expected loss is only USD 5.62.

3.4.5.2 Manipulator FMECA

There can easily be a fracture in the link due to an impact force such as the device being dropped on the floor or it could have gotten hit against a hard surface. Overall, this failure is considered, relatively, a critical failure. As such, the probabilities of failure were looked at and design changes were made based on their event and fault trees. The link has a probability of failure of 0.257 per year.

If a link fails, there is a 95% chance that the caregiver will be able to successfully shut down the device for that event, then will be able to successfully patch the link temporarily 70% of the time the event occurs. As a result, the outcome of successfully shutting down the device and patching up the link is that the patient will be able to use the device but the life of the system may be reduced as the patches made are not permanent, hence there is no consequence. The outcome if the caregiver fails to patch up the link but successfully shuts down the device is that the link would need to be completely replaced; this would cost around USD 60 for the 3D printing of the new part and may need around 1 week for the new piece to be printed, therefore the patient will not be eating independently for a few days. The outcome if the caregiver fails to shut down can result in a "runaway" situation and cause the links to catastrophically break along with some minor damages to the gearbox or the motor if it falls on the floor. This would result in a consequence of fixing the links and the damage of the motors which is around USD 260. The total expected loss per year is USD 7.74 per year and USD 23.2 over three years.

A design change that is applicable to reduce the consequence of risk is by adding a protective case. This would reduce the damage done to the link, protects it from dents and minor fractures, and has a cost of around USD 30 [33]. When doing so, the initial pivotal event would be that the case carries the load of the arm when it fails, this also protects the patient from any catastrophic failure. It is assumed that the cover fails to carry the load 10% of the time. The total expected loss per year with the design change is USD 5.19 and USD 15.57 for the three years. The amount that is saved with the design change is only USD 7.63 over the three years which is USD 22.37 less than the cost of the design change, therefore, the design change is not needed and will not increase the benefit.

3.4.5.3 Plate and Spoon FMECA

There are three possibilities for this failure which are deformation, fatigue or any impact on the spoon. The possible failure that would cause the deformation would be having an excessive external load or exceeding the temperature of the service temperature of the spoon’s material, or if damage occurred to the spoon thread which is assumed to be 0.4 times per year. The spoon is assumed to be fatigued 1% of the time which is 0.01 per year. Possible failures that would cause the failure of the spoon impact is having excessive external load being applied or if the spoon is struck by an external force/object. This would result in an overall spoon failure occurrence to be 0.465/year.

The two main pivotal events were that the caregiver will successfully detect the malfunction of the spoon 95% of the time and the spoon will successfully be replaced by the caregiver 99% of the time. Once the spoon fails, the caregiver will be able to detect if the spoon is deflected 95% each time just by looking at it. If the caregiver fails to do so, then the entire system would just fail. However, if the caregiver detects the deflection, then the next pivotal would be to replace the spoon with the additional ones provided with the system package, if the extra spoons also failed overtime, the caregiver could request for new ones from the manufacturer. Once the device is shut down successfully then a visit to the manufacturer will have to be required and it would cost USD 10. If all the pivotal events fail, then it would cost USD 30 as a consequence. The total expected loss would be USD 1.6 per year and the expected loss over life of the spoon is USD 4.9 over 3 years.

The main failure modes for the plate's failure can be due to the plate impact or having a plate deformation. The possible causes of the impact of the plate can be due to the plate falling or is struck by another object. The possible causes of the deformation could be due to the plate being exposed to temperatures higher than the service temperature and an excessive load greater than the yield. As such, the annual failure rate of the plate is 0.328/year. There is a 75% chance that the plate holder mechanism is fully functioning during the event that the plate fails, if it succeeds then the next pivotal event would be to replace the plate with one of the extra available plates. If the plate holder fails to hold the plate, then the entire plate mechanism needs to be replaced, which results in high consequence due to the downtime, shipment, and the cost of manufacturing one plate. The total expected loss per year is USD 6.56 and only USD 19.68 for the three years of the life of the system.

3.4.5.4 User Interface FMECA

When a button is pressed it causes an electrical circuit to either close or open the circuit. One way it could fail is if the internal spring that is compressed when the button is pushed fails. Thus, not allowing the microswitch to be pressed down. This brings us to the microswitch, when depressed, it lifts a lever to move the contacts into the required position that thus close/open the circuit. Moving on we have the contact failure, meaning that the surface of the contacts has been worn out thus not allowing the circuit to be completely closed or open. If the wires are faulty or not connected properly, the button would not have a direct connection to the Arduino, thus not receiving power. When the switch is left unused or stored for long periods, the ambient conditions can have a great effect on the condition of the switch. In certain environments, leaving the switch exposed may result in deterioration (i.e., oxidation, or the creation of an oxide film) of the contacts and terminals, causing the contact resistance to increase, a large or sudden force, may deform or damage the switch, resulting in faulty or rough operation, or shortening of the switch life many of the switches are composed of resin so contact with sharp objects may result in damage to the surface. This kind of damage may or result in faulty operation. Subjecting the switch to severe vibrations or shock may result in faulty operation or damage since it may loosen the mounts or damage the internal components. As a result, the annual failure rate of the button is 0.62/year.

The first pivotal event is that the caregiver detects that the button is faulty, if the caregiver fails to detect the feed button malfunction, then the device is checked and replaced by a professional. If the caregiver successfully repairs the feed button, then no further action is required, and this results in little to no consequence. However, if the caregiver fails to do so, the button can be entirely replaced by the caregiver, which leads to a downtime of a few hours and the small cost of a button. If this is not possible, then a professional will be able to check and replace the button. The total expected loss of the button is USD 1.18 per year and USD 7.09 over six years, which is the expected lifetime of the button.

3.4.5.5 Motors FMECA

For an initiating event of a motor failure, the pivotal events are the detection of the motor’s heat with a success rate of 67% and notification of a change in the motor’s temperature with an 83% success rate, and the successful shutdown of the device. As for the detection of the motor’s heat is more likely to fail once every 3 years. Finally, the notifier which would be the LCD screen. It is assumed that it functions at room temperature without direct irradiation light. With that it is expected to fail once every 6 years. Hence the probability value of the motor failing is 0.749 per year.

If all safety functions succeed, the outcome would be that the device will be shut down successfully, but the motors will still need maintenance and repair is usually 50% of the motor’s price. Therefore, the consequence is USD 49. In the case of the second pivotal event’s failure and the third’s, regardless of whether the overheating of the motor is detected or not, if the caregiver isn’t notified or the device isn’t shutdown successfully, then the motor failure will occur and could result in a fire and damage to certain parts of the device. The consequences in both cases were USD 267, considering the damage to the arm, plate, and motors.

The total expected loss per year is around USD 17, but since the motors have an average life of 20 years, then expected loss over the lifespan would be USD 346. With that, the recommended modifications that can be made to the system could include adding VFD (Variable frequency drives) to control the load on the motor which will reduce the possibility of motor overheating and therefore, improve its performance. In addition, ensuring there’s proper ventilation for the motors within the device and install a thermistor on the motor to measure its temperature while it is in use.

3.4.6 Final Components Selection

The components that comprise the device are either manufactured or purchased. *Table 3.9* shows all the components organized based on the subsystems they belong to. The table is broken down to the component’s name, its mass to give an idea of how heavy that item is, and the specifications of which the operating voltage a physical dimension are considered most important. The components split into those that will be purchased and those that will be manufactured through 3D printing, as discussed in the previous section.

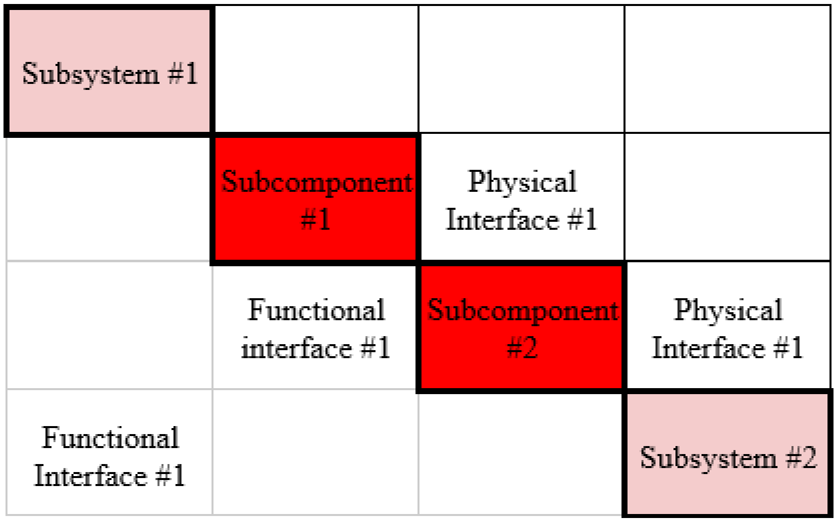
Table 3.9: Component Specifications

	Components	**Specifications**		
		Mass	**Operating Voltage**	**Other specifications**
Base	Arduino Board	30 g	7-12 V	-
	Arduino Transparent Enclosure	40.8 g	-	Size: 76.2x61x45.7 mm^3
	Breadboard	-	-	Size: 82x53x9 mm^3
	Jumper Wires	-	-	Length: 70 cm
		-	-	Length: 70 cm
	LCD Screen	50 g	7.0 V	Size: 80x36x13.5 mm^3
	Motor Drive Shield	32.6 g	5-12 V	
	Capacitor Kit	38 g	-	Capacitors: 0.22 to 470 μF
	Fuse	2.26 g	250 V	Size: 5x20 mm
	Fuse Holder	139 g	-	Size: 167x119x19 mm^3
	Potentiometers	-	-	Resistance: 10kΩ
	Knobs	-	-	Rotation: 240°
Arm	Servo Motor (Base, Shoulder & Elbow)	60 g	7.4V	Stall Torque @ 4.8 V: 240 oz-in (17.2 kg.cm)
	Servo Motor (Spoon)	12 g	4.8V	Stall torque @ 4.8 V: 1.2kg / 42.3oz
	Gearbox	200 g	-	Gear Ratio 3:1
	Temperature Sensor	-	3 to 5.5 V	Temperature Range: -55C to +125C
	Pressure Sensor	-	-	Temperature range: - 40 to +85 deg C
	Ultrasonic Sensor	-	-	Detection distance: 2cm-400cm
Power Supply	Lithium-Ion Battery	575 g	7.4 V	Capacity of 3000mAh
	Charger/Plug	96 g	100 - 240 V	Charging Current: 0.7A
	Battery Holder	-	-	-
Plate	Gearbox (Plate)	200 g	-	-
	Motor (Plate)	12 g	-	Gear Ratio 3:1
Overall	Arduino Kit	-	-	-
	ABS/PETG filament	3 kg	-	-

3.4.7 Interface Control

As aforementioned, the major functions of the device include delivering food to the patient, interfacing with the user, supplying and storing power while maintaining the safety of the patient. The functions of the device explain what the device has to do, or in other words, it explains how the device will interact with the patient. Therefore, the external interfaces – the interfaces between the device and the surrounding – can be identified. For instance, for the device to deliver food to the patient's mouth, the device must first detect the patient's mouth. To do so, the caregiver can adjust the position of the arm by turning the knobs that will actuate it. So, the interface between the device and patient when detecting the patient's mouth are the knobs; hence, they are external interfaces. However, in order for the knobs to result in the actuation of the arm, then there should be an interface between the motors in the arm and the knobs. This type of interface is called an internal interface – the interfaces between the subcomponents of the device. In addition to identifying the internal and external interfaces, each type is then characterized as a physical or functional interface. A physical interface would be a tangible form or fit such as a bolt, shaft, or a wire. On the other hand, a functional interface would be a form of information or action such as control signals, electrical flow, or data.

To understand the device's interfaces, the development of N2 diagrams would be useful, as the NASA Handbook suggests. An N2 diagram lists the subcomponents of the devices in the form presented in *Figure 3.4.7*. The internal interfaces, whether functional or physical, are listed in the cell between the two subcomponents. For instance, in the N2 diagram presented in *Figure 3.4.5,* the subcomponents of subsystem 1 are listed in the red boxes. In addition, there is a physical and functional interface between the two subcomponents. Furthermore, there is a physical interface between the second subcomponent and the second subsystem. Finally, the two subsystems share a functional internal interface between them. This diagram was developed for all subsystems and are presented in *Appendix F*.



Subsystem #1			
	Subcomponent #1	Physical Interface #1	
	Functional interface #1	Subcomponent #2	Physical Interface #1
Functional Interface #1			Subsystem #2

Figure 3.18: General breakdown of N2 diagram.

3.4.5.6 Power Supply Interfaces

The AC power supply coming from the building passes through a wall socket that connects to the battery charger; hence, the wall socket is the first physical internal interface. The charger which is composed of an adapter and a USB-to-USB cable is then connected to the base through a USB charging port. The USB port is then connected to a small breadboard through female jumper wires. The battery is then connected to the breadboard through the battery's wires. Note that both the battery and the breadboard are clipped to the base cover, such that the clips are 3D printed to the base. In terms of the functional interfaces, there is a flow of electric current between the battery charger and the power supply as displayed in *Figure 3.19*, which is the N2 diagram for the power supply subsystem.

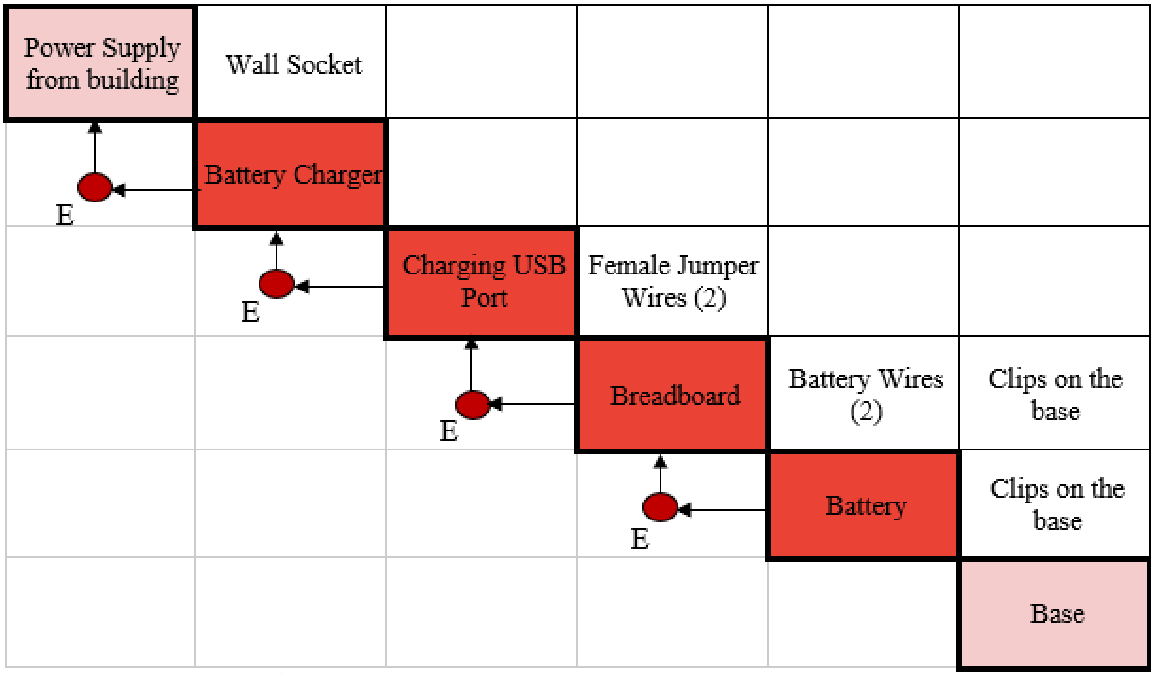


Figure 3.19: N2 Diagram for Power Supply subsystem

3.4.5.7 Base Interfaces

For the base subsystem, there are several subcomponents including the buttons – on-base and external on-ground buttons, the LCD screen, PCB, motor driver, potentiometers and knobs, the motor holder, and the plate's motor. In order to power the Arduino board, it is connected to the battery using jumper wires, hence it is expected to have an electric connection between them. The Arduino board acts as the brains of the device that controls the actuators in the device. However, to connect between the signals outputted from the Arduino board to different actuators, a motor driver is used. The motor driver serves as a voltage and speed controller for the motors. Therefore, the Arduino is connected to the motor driver which is then connected to the motors through jumper wires. This provides a flow of electric current between the motor driver and the Arduino and between the motors and motor driver.

In addition, the Arduino board connects to the Printed Circuit Board (PCB) through jumper wires. Note that both the motor driver and PCB are clipped to the base cover. A PCB is an internal interface which acts as an extension of terminals to connect the rest of electrical components in the system. Therefore, it is expected that the buttons (switches), Booleans, and LCD screens are connected to the PCB through jumper wires. To put that in perspective, the schematic in *Figure 3.20* has been developed. Based on the schematic, the N2 diagram for the base subsystem was developed in *Figures F.2 and F.3* in *Appendix F*.

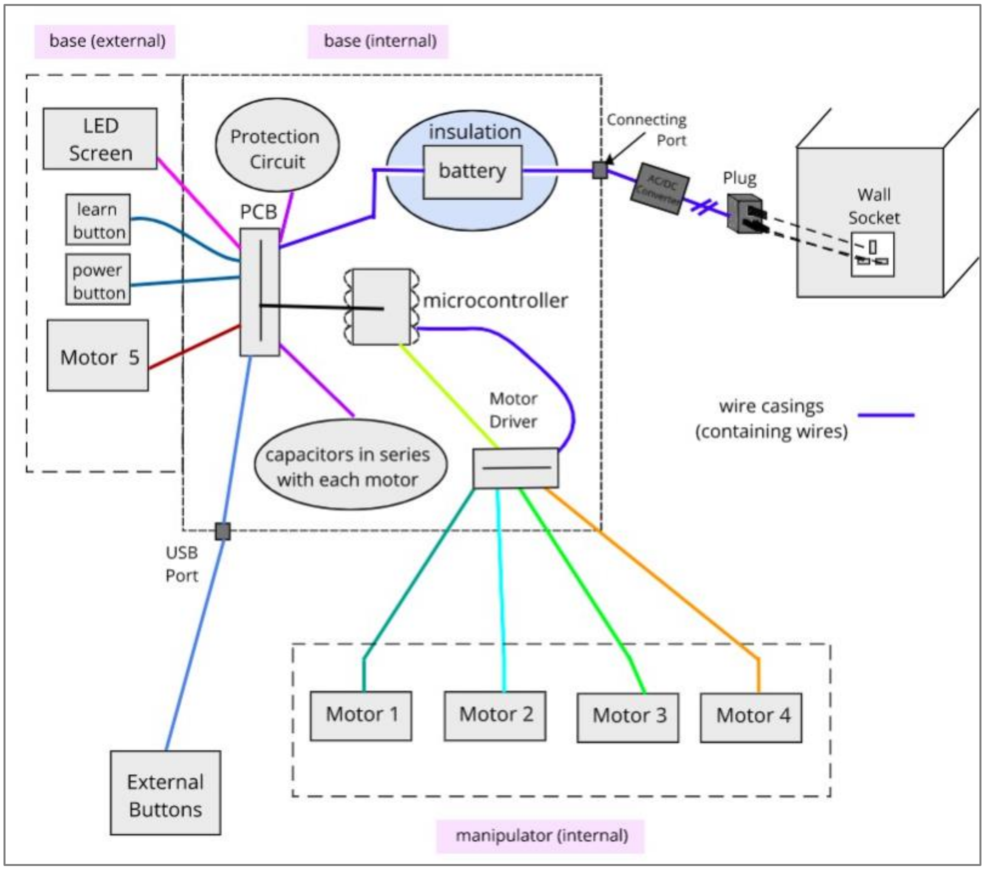


Figure 3.20: Schematic of the Base subsystem and its interfaces.

3.4.5.8 Plate Interfaces

Between the plate subsystem and the base, the plate's motor connects to the plate holder using the motor's servo horn. The servo horn is secure to the motor using one Phillip screw making it the internal physical interface between the servo horn and the motor. As for the servo horn, it is secure to the plate through four Phillip screws making them the internal physical interface between the plate holder and the servo horn. The plate holder is then connected to the plate using the lock-in-slot mechanism. *Figure 3.21* shows the schematic of the interfaces in the base. Based on the schematic, the N2 diagram for the plate subsystem was developed in *Figure F.4* in *Appendix F*.

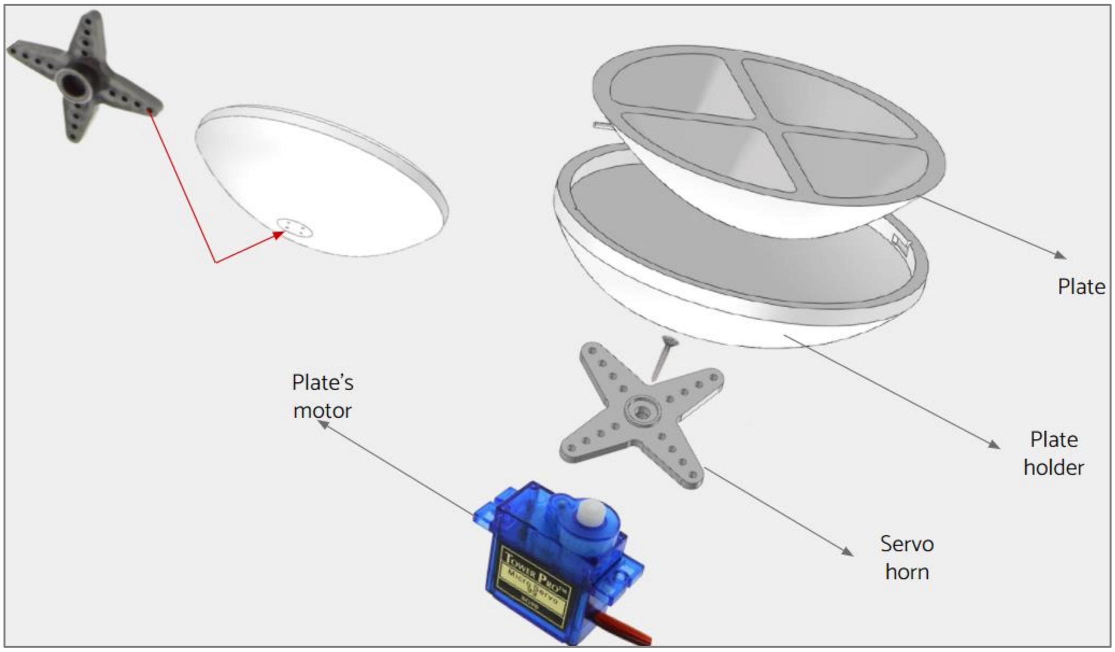


Figure 3.21: Schematic of the interfaces within the Plate subsystem.

3.4.5.9 Arm & Spoon Interfaces

There are five motors in the device, four for the arm and the last one is for the plate. The four motors are connected to the arm through extended jumper wires that can extend from the base to the arm. The arm base is secured to the base using six 6-32 UNC hex bolts. The arm base secures the first motor through a motor holder that is 3D printed onto the casing. The motor is secured using four 6-32 UNC Hex bolts to the motor holder. The motor is then connected to the gearboxes as supplied by the manufacturer. The gear box is secured to the waist joint with the same type of hex bolts mentioned above. Another motor gearbox system is attached to the waist joint in the slot provided and secured by four hex bolts. The Gearbox of the second motor is then connected to the

Lateral which is the first link with four hex bolts. The lateral is then secured to the third motor, except this one has no link but rather a servo horn. The servo horn is secured to the motor using a Phillip screw. The horn is then connected to the lateral using four hex bolts. The motor is secure to the second link through the use of hex bolts. On the other end of the second link, the fourth motor will be secure in a similar manner as the third one. The servo horn for the fourth motor – the spoon's motor – is screwed to the spoon connector. The spoon connecter connects with the spoon through the thread mechanism. The developed N2 Diagram is shown in *Figures F.5 and F.6* in *Appendix F.*

3.4.8 Final Design of Device

Figure 3.22 below shows the final device assembled after modifications and with the aforementioned dimensions. The different components are all assembled and ready for the next stage; simulation followed by manufacturing.

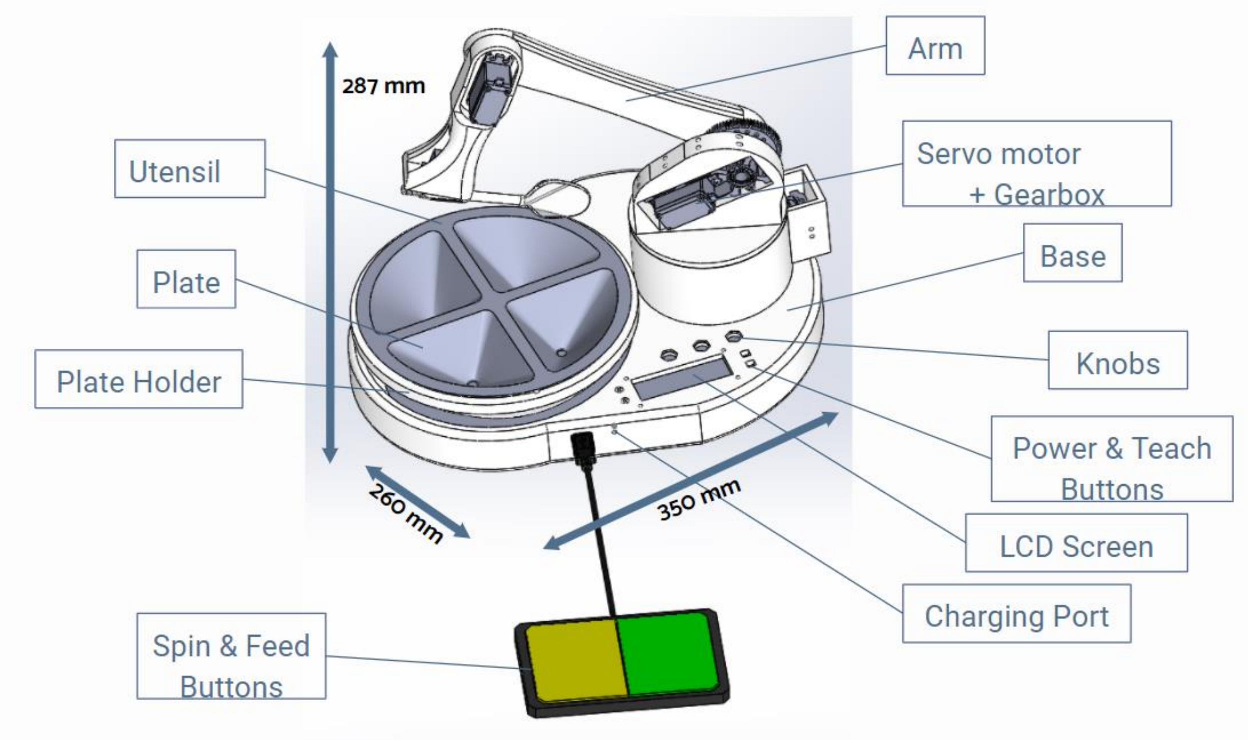


Figure 3.22: Finalized Device Assembled

3.4.9 Materials and Manufacturing

The manipulator is made up of multiple segments and joints, since this device is to be made with a time constraint, several rapid prototyping techniques as seen in *Table 3.10* were looked at and the best option was additive manufacturing.

Table 3.10: Relative Evaluation Matrix for the Rapid Prototyping Methods

Relative Evaluation	**Weight**	**Off the Shelf**	**Additive**	**Subtractive**
Cost	4	1	4	5
Dimension Precision	5	3	5	2
Longevity	3	5	5	3
Aesthetic	4	4	4	2
Durability	5	2	4	2
Score	105	60	**92**	57

There is a several set of criteria the prototype needs to meet, such as the precision in relation with to the CAD model, the aesthetic, the ease of assembly and so on. As seen in *Table 3.11* different options of additive manufacturing were evaluated, and material extrusion was found to be the most suitable option, also known as 3D printing.

Table 3.11: Relative Evaluation Matrix for Additive Manufacturing Methods

Relative Evaluation	**Weight**	**Binder Jetting**	**Directed Energy Deposition**	**Powder Bed Fusion**	**Material Extrusion (3D printing)**	**Material Jetting**	**Vat photo**
Cost	4	1	2	4	4	3	2
Accessibility	5	2	5	5	5	4	1
Accuracy	3	4	2	3	4	3	4
Finish	4	3	4	4	3	4	3
Simplicity	4	2	2	3	3	2	5
Duration to make	3	4	5	2	4	3	6
Score	115	58	78	84	**89**	74	75

Fused filament fabrication and fused deposition method are the two types of material extrusion, there is no difference between the two except for the historical terminology of the two terms. FDM/FFF is a process of 3D printing where a plastic filament is heated and extruded through a nozzle to build an object by depositing the melted material layer by layer. [19] There are several settings to look at when 3D printing, such as:

1. Layer thickness: This usually affects the resolution of the object being printed, the smaller the thickness, the higher the resolution, this can vary anywhere from 0.05 to 1 mm.
2. Infill density: It can vary anywhere from 0-100%, where 0% would make the part hollow while 100% makes it solid. The higher the infill density, the more time it would take to print and increases the density of the object being printed. An infill density of 20-25% is commonly used. Even though a 100% would result in the highest strength, time and weight remain a constraint.
3. Infill pattern [20]: Apart from infill density, the infill pattern also affects the strength of the part being printed. The different infill patterns are:
    a. Triangular: These lines go in three directions in the XY plane and only provides strength in two dimensions.
    b. Honeycomb (hexagonal): This consumes less material and has moderate strength; however, it does take time to print.
    c. Lines: This pattern keeps the object lightweight and is usually in one direction in the X or Y plane, however, it provides strength only in the XY plane. It has a faster print time as the printhead only travels in straight lines.

d. Grid: The grid pattern is similar to the lines except that it uses more material and is printed in both dimensions. However, it does provide more strength in the XY plane than that of the lines pattern.

e. Tri-hexagonal: This is nothing more than an assortment of triangular patterns creating a hexagon, it also provides strength in two dimensions.

f. Cubic: This pattern takes more time and material than the others creating stacked cubes placed at a 45-degree pattern in both the X and Y axes.

g. Gyroid: This infill pattern irregular curvatures that cross paths and is said to have a good balance between strength, material consumption, and print time.

h. Concentric: It uses the least amount of material and has a pattern of concentric lines.

4. Each material and printer have its own recommended nozzle temperature, speed, and diameter. As well as, heat bed temperature. A slower nozzle speed can also reduce warping.
5. The print orientation also matters because when 3D printing, it is better to consider the direction is being applied and print parallel to the layers as seen in *Figure 3.22*, as it would make the part stronger.

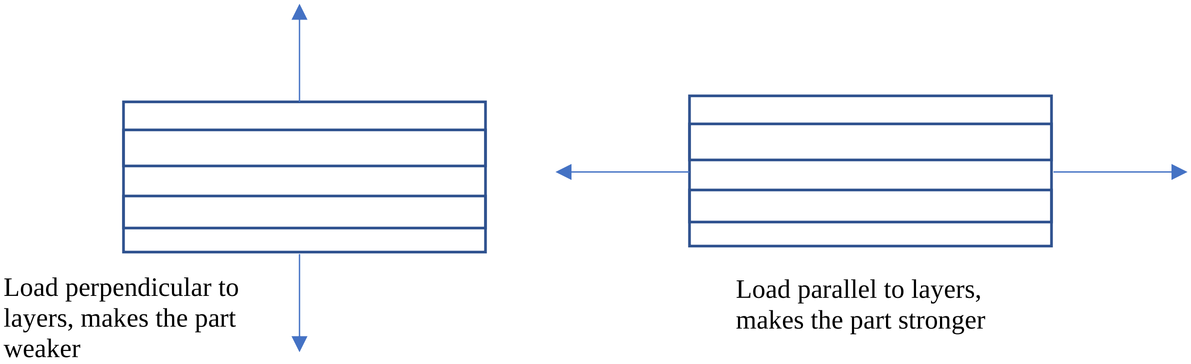


Figure 3.22: 3D Printing Layers Perpendicular vs. Parallel to the load

There are several characteristics to look at when selecting a 3D printer, such as the cost of the printer, material compatibility, user interface, heated bed, and safety features. FDM 3D printers can range anywhere between USD 150 - USD 1000. The material compatibility is important because some printers may not be able to provide the nozzle temperature or heat bed temperature needed for the material to melt or form nicely. The user interface also plays a major role in 3D printing, it needs to be easy to understand, practical, and be able to be compatible with SolidWorks files. As mentioned earlier, the heated bed temperature is very important to control as it controls how well the first few layers are formed and needs to make sure the object sticks in place and does not warp. Finally, one of the most important things is the safety features of the printer, such as a nozzle cooling feature, or include a temperature sensor that when the printer overheats, the printer shuts down. [21]

After doing some literature review on 3D printers, the two main printers that were looked at were the Ultimaker S5 and the Prusa I3 MK3S. The main difference between the two is that the Ultimaker S5 is a closed printer and this reduces mistakes when printing. The other differences between the two can be found in *Table 3.12.*

Table 3.12: Ultimaker vs Prusa I3 MK3S 3D printers

Property	Ultimaker S5 [29]	Prusa I3 MK3S [30]
Build Volume	330 x 240 x 300 mm	25 x 21 x 21 cm
Cost	5,995 USD	999 USD
Max. Travel Speed	24 mm^3/s	200 mm/s
Max. Nozzle Temperature	280	300 C
User Interface	Touch - Screen	LCD Screen
Material Compatibility	PETG & ABS Compatible	PETG & ABS Compatible

When it comes to selecting a material, one useful tool that can be used is GRANTA EDU Pack. This is done by selecting the mechanical properties the parts need to have to withstand their loads and perform their functions.

The parts need to withstand high mechanical properties such as the following: [22]

1. High tensile strength: This is important for structural, load bearing, and mechanical parts. It is the strength at which a material changes from an elastic to plastic deformation.
2. High young's modulus: This is important for the stiffness, it is the ratio of stress along and axis to strain, this determines the stiffness of a material.
3. High flexural strength: The segment can resist breaking when bent, it is the maximum bending stress that can be applied before it yields.
4. High hardness: The segment does not deform quickly; this is important because the device will be carried around, it is the resistance to indentation and ability to resist deformation.
5. Low density: This is measured as the mass per volume, this also affects the weight of the component.

The list of materials compatible with the Prusa 3D printer are shown in *Table 3.13* along with their mechanical properties, advantages, and disadvantages. The two selected materials that would work best based on their mechanical properties are Acrylonitrile Butadiene Styrene, also known as ABS, and Polyethylene terephthalate glycol, also known as PETG. ABS is an amorphous thermoplastic and is commonly used in 3D printing, as well as the making of interior components of automotive instrument panels and small home appliances. PETG is also an amorphous thermoplastic and is commonly used for medical devices and machine guards. Both ABS and PETG are recyclable but not biodegradable. [9]

Table 3.13: List of Materials Compatible with Prusa I3 MK3

Material	ρ(g/cm3)	E (MPa)	Tensile (MPa)	Flexural (MPa)	Price	Advantages	Disadvantages
ABS [23]	1.05	2140	52	65	USD 23/kg	Strong, high impact Harder than PETG	Resolution Poor fatigue resistance
PLA [24]	1.24	3310	110	-	USD 23/kg	Biodegradable, easy to print, can print all sizes	Brittle
PC blend [25]	1.22	1900	-	88	USD 54/kg	High impact & wear resistance	Larger models warp Susceptible to scratches
Woodfill [26]	1.15	3290	46	70	USD 38/600g	Easy to print, no warping, aesthetic	Prone to stringing
PETG - enhanced with carbon fiber [27]	1.32	4015	52.9	80	USD 62/500g	Strong, rigid, durable, easy to print Extra safe material Easy to sand	Not suitable for tiny parts Flexible Sensitive to temperature and humidity
Steelfill - [28]	3.13	-	23	30	USD 51/750g	Easy to print, no warping, aesthetic	Heavy

Table 3.14 show the constraints set on GRANTA EDU Pack. As seen in *Figure 3.23*, the material found is ABS, as expected, and its properties are found in *Table 3.13*. As such, ABS is selected as the initial material to work with, however it may take several tries to print and get it right, the main problem with it is warping due to the open printer.

Table 3.14: Mechanical Properties Constraints

Constraints	Must have a yield strength above 100 MPa Stiffness (young's modulus) above 10 GPa Compressive strength above 50 MPa Fatigue strength above 50 MPa Hardness above 30 HV
Objectives	Minimize Weight (density)
Free variables	Area
Material Index	$\frac{\sigma_f}{\rho}$ (slope = 1 and maximize it)

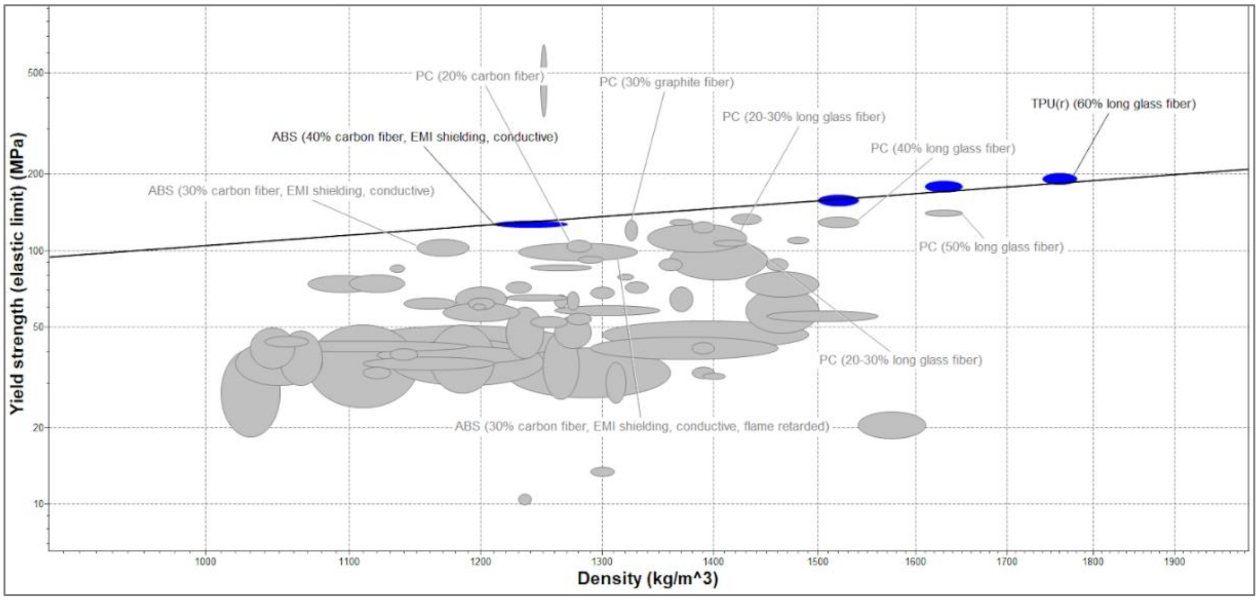


Figure 3.23: Yield Strength vs. Density using Granta EDUPack

When printing with an open-frame printer, ABS may need several tries to get it right due to warping where the plastic shrinks due to uneven cooling causing the cooler parts to contract. When warping occurs, the layers may rip apart. Therefore, the next best material to use that also meet the requirement is PETG which is easier to print and does not warp or shrink due to its low thermal expansion. PETG is considered food-safe however the print layers may carry numerous bacteria, therefore it would need to be covered with a special food-safe layer that seals the surface. The recommended settings when 3D printing with PETG are as follows:

- Nozzle Temperature: 230°C for the first layer and 240°C for the other layers
- Heated Bed temperature: 85 °C for the first layer and 90°C for the other layers
- Use a powder-coated print sheet.

Figure 3.24 shows the arm base that was printed using PETG on the Prusa I3 MK3 printer with the recommended settings. It can be seen that no warping occurred, however, there was some stringing that occurred but were easily removed.

Figure 3.24: Arm Base First Sample Printed

The base of the entire arm however does not fit the build volume of the Prusa I3 MK3 printer, therefore, other manufacturing options are considered such as subtractive manufacturing, where scrap material such as acrylic, wood, metal, or cardboard. *Table 3.15* shows the absolute evaluation of these materials, it can be seen that acrylic is the only one that passes the evaluation.

Table 3.15: Absolute Evaluation of the different materials that can be used with CNC laser-cutting

Material	**Strength**	**Weight**	**Insulation**	**Cost**	**Pass/Fail**
Acrylic	Pass	Pass	Pass	Pass	Pass
Wood	Pass	Fail	Pass	Pass	Fail
Metal	Pass	Fail	Fail	Fail	Fail
Cardboard	Fail	Pass	Pass	Pass	Fail

3.4.10 Controls

In order to map out a path for the arm to move through, forward and inverse kinematics are typically useful for manipulator control. This method of formulating the dynamics of the robotic arm provides the relation between joint velocities and end-effector velocities of a robot manipulator while considering any gravitational effects on the dynamics. In our manipulator, the end effector is the spoon.

The kinematics of the manipulator can be determined by the help of the Denavit – Hartenberg parameters [31]. The DH parameters are used to select reference frames for the manipulator. Also, they are useful for serial manipulators where a transformation matrix is used to represent the pose (position and orientation) of one body with respect to another. The matrix would then be used for both Forward and Inverse kinematics, which help map out the paths that the manipulator would follow. In other words, how the motors will actuate relative to each other to reach certain positions. In the case of this manipulator, we are considering three paths; hence, three positions for the spoon, also known as the end effector. First, the original position of the arm when the device is powered should be defined. The paths considered are:

1. The path the arm takes from original position to the plate.
2. The path the arm takes from plate to the patient’s mouth.
3. The path the arm takes from the patient’s mouth back to its original position.
4. The DH parameters are four main parameters and are generally defined as:
5. r - the distance between the current z-axis (zi-1) and the proceeding z-axis (zi) with respect to the proceeding x-axis (xi)
6. d - the distance between the current x-axis (xi-1) and the proceeding x-axis (xi), with respect to the current z-axis (zi-1).
7. α - the angle between the current z-axis (zi-1) and proceeding z-axis with respect to the proceeding x-axis (xi)
8. θ - the angle between the current x-axis (xi-1) and the previous x-axis (xi) with respect to the current z-axis (zi-1).

The manipulator is an articulated robot with 4 degrees of freedom as shown in *Figure 3.25*.

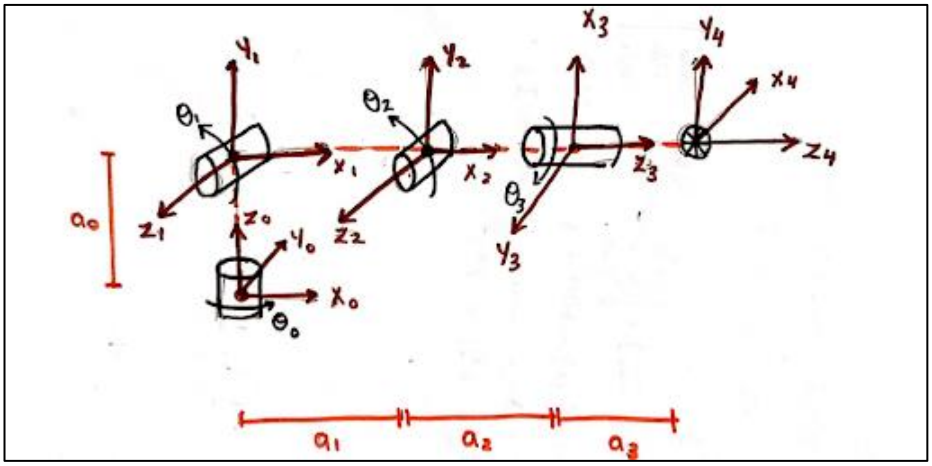


Figure 3.25: Manipulator Arm Kinematics

Table 3.16 shows the DH-parameters obtained for the manipulator, where a_0 and a_3 are imaginary links while a_1 and a_2 are lengths of real links.

Table 3.16: DH Parameters of the Manipulator Arm

Links	**r**	**d**	**alpha**	**theta**
0	0	a_0	90	θ_0
1	a_1	0	0	θ_1
2	0	0	90	$90+\theta_2$
3	0	0	0	$-90+\theta_3$

The development of the forward kinematics can be found in *Appendix E*. The inverse kinematics was completed on MATLAB to be integrated with the Arduino code that controls the position and speed of the spoon.

When it comes to actuating the motors and moving the arm, efficiently programming the Arduino controller is crucial. The flowchart shown in *Figure 3.26* details all of the decisions and actions that the microcontroller must check and execute when the device is turned on. First, the board needs to establish communication with the different libraries in use, such as VarSpeedServo, as well as define the objects and pins in use. The variables also need to be initialized in order to retrieve and use throughout the program.

The first main decision block checks if the teach button has been pressed; if so, the Arduino saves the resistances obtained from the potentiometer at the final position of the spoon and maps those values to motor angles. The Arduino stores those values for use later in the code to set the desired end effector position.

The next two decision blocks check if the plate and spoon are locked in place by using force sensors integrated into their locking mechanisms i.e. the program will not run until they lock. Physically, the spoon and plate are considered locked if the force sensor feels a non-zero force.

The feed decision block is then implemented where the Jacobian speed and angle equations previously determined from MATLAB are used to determine how much each motor angle should increment by, and at what speed. The incrementation loop ends once the desired position of the spoon end effector is reached.

The final decision block checks when the plate rotation button is pressed and rotates the plate 45 degrees when it is pressed. This allows the user to switch to a different section of the plate at any point.

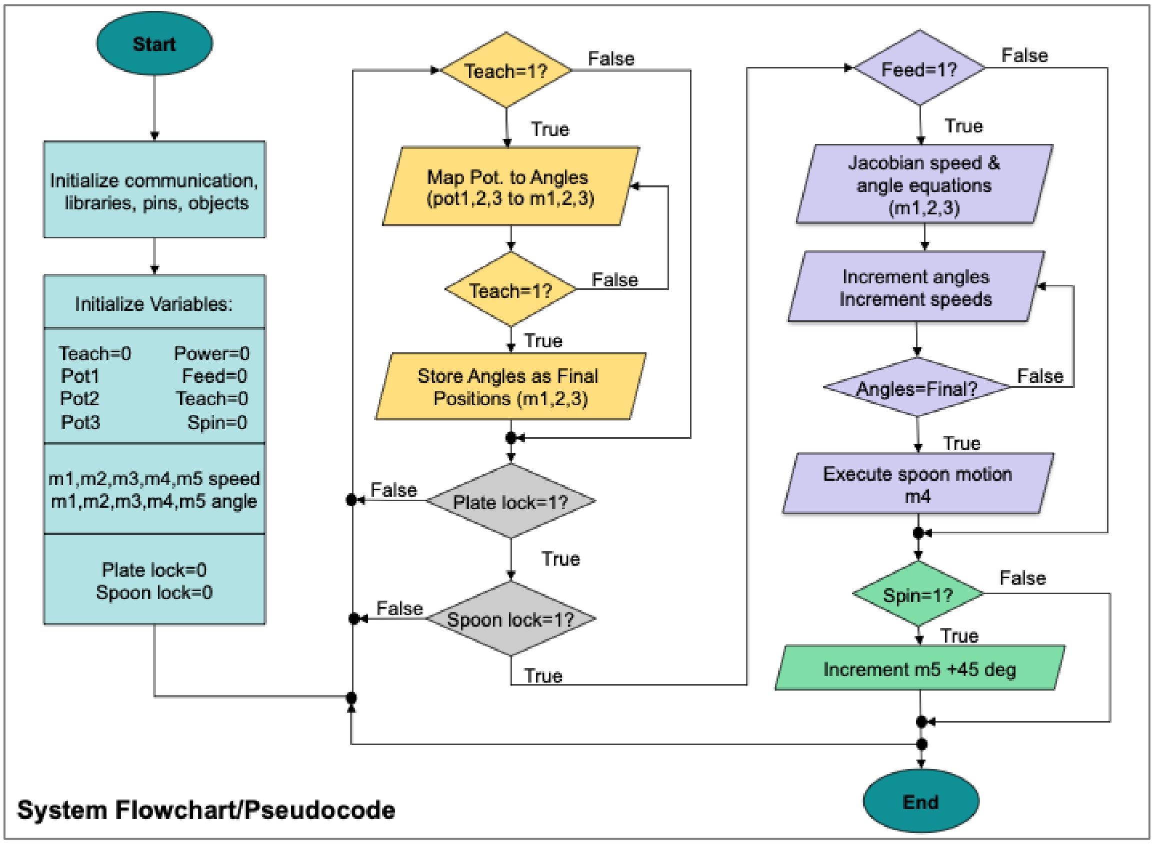


Figure 3.26: System Programming Flowchart

3.4.11 Cost Analysis

Cost analysis was looked at from two different points of views, prototype, and mass production. The prototype cost considers university resources as well as small batch size purchases. Mass production involves the entire cost the device would entail. Since the allocated budget given for the prototype is USD 1,096, *Table* 3.17 divided the system into subcomponents which will help in visualizing the cost analysis of the product. *Equation 3.1* shows the cost involved in building a prototype.

$$Prototype\ Project\ Budget = Cost\ of\ Manufacturing + Component\ Cost + Contingency\ Cost \qquad (3.1)$$

Table 3.17 provides each component’s availability in manufacturing, purchasing, and availability on campus at Texas A&M university at Qatar. The components which are to be manufactured using 3D printers are joints, base, external buttons, fittings, and a plate due to their specific dimensions for this project. The components such as a 6V battery, wires, microcontroller Arduino Board, and a PIR motion sensor are accessible on campus and will be used.

To better picture the cost it would take to purchase different components to build a prototype, the values of components such as buttons, screw and mounting kit, display screen, 6V battery, servo motor, microcontroller Arduino board, and a PIR motion sensor were discovered online. A robotic arm with similar specifications and functionality was found at 650 USD. Therefore, a rough estimate of purchasing different components to build the device is around 3,000 QR which does not exceed the project's budget. Regarding the mass production of the device, a study is to be conducted to achieve the finest option (manufacturing or purchasing or mix) to produce a larger batch size at an optimum price. A mix of manufacturing and purchasing the device is a possible solution to achieve that.

Table 3.17: Subsystem Cost Analysis

Subsystem Cost Analysis			
Component	**Manufacturing**	**Purchased**	**Campus Availability**
Joints	3D-printing	-	TBC
Base	3D-printing	-	-
Buttons	3D-printing	1.6	-
Plate	3D-printing	-	-
Servo Motor (Base/Shoulder/Elbow)	-	120.29 USD [19]	-
Servo Motor (Spoon/Plate)		31.86 USD [19]	-
Voltaat Arduino Ultimate Kit	-	54.67 USD [18]	-
Enclosure for Arduino UNO - Transparent	-	1.37 USD [18]	-
Voltaat Capacitor Kit 12 Values (120 Pack)	-	6.59 USD [18]	-
DS04-NFC Continuous Servo Motor	-	10.71 USD [18]	-
L293D Motor Drive Shield for Arduino	-	9.07 USD [18]	-
3-Pin Jumper Wire (Male to Female) 70 cm	-	1.37 USD [18]	-
3-Pin Jumper Wire (Male to Male) 70 cm	-	1.37 USD [18]	-
5A 5x20mm Fuse (5 pcs)	-	0.27 USD [18]	-
5x20mm Fuse Holder	-	0.27 USD [18]	-
Precision Potentiometer 10k Ohm	-	2.47 USD [18]	-
Potentiometer Knob (2 Pcs)	-	0.27 USD [18]	-
2x18650 Battery Holder with DC Jack	-	2.47 USD [18]	-
Lithium ion 3.7 V 3800mah rechargeable battery - 18650 Regular	-	6.04 USD [18]	-
3.7V Li-ion Battery Charger	-	9.34 USD [18]	-
PIR Motion Sensor	-	6.99 USD [7]	Available
Robotic Arm	-	650 USD [2]	-

Contingency cost was considered which involves the cost associated with unexpected events or potential scenarios which are not considered in the cost estimate of the device. This includes equipment maintenance, cost of replacement parts, and cost of fixing parts. In case of potential failure of any of the parts, supplies can be purchased from Voltaat Store located in the State of Qatar which offers electronic components, sensors, Arduinos, 3D printers, and more. [5] Contingency cost also includes fluctuations in currency values used to purchase items or utilities. It was seen to allocate 10-15% of the total budget to be reserved for contingency cost.

4. CONCLUSION

The need that this research project is trying to fulfil is to provide a means to assist people with upper body motor disabilities in feeding themselves without relying on any other human. The constraints of this research project are a budget of 4,000 QR, a time limit of six months to make it a marketable product and nine months to develop a prototype. In addition, the assistance should be achieved while safely feeding the patient without injury or malfunction at home or in a public setting.

By self-evaluating the preliminary design, it can be seen to have fulfilled the majority of the objectives set out in the need statement and need analysis. The device is portable with its current weight of 3.7087 kg which does not exceed the limit set of 5 kg; it can therefore be transported and used at home or in public settings. The device is seen to be autonomous with its four degrees of freedom, independence and different external interfaces that allow the user to have minimal assistance from the caregiver. The user is able to eat their meal without the assistance of anybody. The device is set out to be safe when operating and feeding the patient. The budget allocated for this project is USD 1,096, the current projected cost of completing the prototype is below the allocated budget USD 510.5 The material selection was finalized to be PETG which has a tensile strength of 52.9 MPa and accommodates for the weight of external forces and impact. In addition to its simplicity in 3D printing. The research project has faced some delays due to the pandemic. The final assembly along with the control's scheme of the device is in progress and the prototype is to be completed by May 2021.

Table 4.1 shows a summary on the performance requirements and whether or not they have been met. Those that are left empty are still being tested. The supplied voltage was tested by using a multimeter to measure the exact voltage supplied by the battery. For the transmission of electrical power and operating current will be tested using a multimeter. Once the device’s connections are safely finalized, the hours of storage will then be tested by running the device and timing it. In addition, the device will go through several checkups where the wires will be checked and ensure they are fully secured. The device’s power button will also act as a kill switch in the case of any electrical or mechanical issues. The spoon is currently being 3D printed; hence, its dimensions are yet to be studied if they met the requirements or not.

Table 4.1: Summary if the performance met the requirements

Subsystem	Performance Requirement	Performance met?
Power	Supply 7-8 V of electrical energy	Met: 7.36 V
	Transmit 60-70 W of electrical energy	TBD
	Store 7 Ah of energy storage rate	Met: 7.6 Ah
	Store 2 continuous hours of charge	TBD
	Operating current of 0.1-5 A, with a limit of 7.5A	TBD
	Isolate all electrically conductive components from parts that the user can touch	TBD
Manipulator Arm	Angular speed of the motors = 10-20 RPM	Angular speed: 17 RPM
	Arm must have a payload of 0.5 kg while the entire system must weigh 5kg.	Arm Payload: 0.55 kg Whole system: 1.8 kg
	Must have a horizontal and vertical reach of 30 cm.	H-reach: 30.1 cm V-reach: 30 cm
Motors (all must operate at a voltage of 4.8-7 V)	Motor 1 for the plate requires a torque of 0.000879 Nm	Provides a torque of 0.539 Nm
	Motor 2 for the arm base requires a torque of 4.069 Nm	Same motor and both provide a torque of 5.089 Nm
	Motor 3 for the waist requires a torque of 3.882 Nm	
	Motor 4 for the link requires a torque of 1.328 Nm	Provides a torque of 1.687 Nm
	Motor 5 for the spoon connector requires a torque of 0.102 Nm	Provides a torque of 0.539 Nm
Plate and Utensil	Plate must be divided into 4 sections and orient according to the patient Plate must hold 150-200 g of food	Met: 178 g
	Depth of the spoon of 3 cm & a diameter of 3-4 cm Spoon must hold 15-30 g of food	TBD
User-Interface	200 to 250 ms button’s response time	Met: 200 ms
	Have a readable screen with a suitable font size 12 points.	LCD screen size of 80x36x13.5 mm and font size of 12 points.

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APPENDIX A: FUNCTION STRUCTURE DIAGRAM

1. PMT transport food from the plate to the user

- 1.1 Deliver food to the patient's mouth
- 1.1.1 Secure a utensil
  - 1.1.1.1 Detect desire to insert utensil
  - 1.1.1.2 Accept utensil
  - 1.1.1.3 Detect utensil equipped
  - 1.1.1.4 Lock utensil in place
- 1.1.2 Eject a utensil
  - 1.1.2.1 Detect the desire to remove utensil
  - 1.1.2.2 Unlock the utensil from place
  - 1.1.2.3 Remove the utensil from the device
- 1.1.3 Secure a plate
  - 1.1.3.1 PMT detect desire to insert plate
    - 1.1.3.2 Accept plate
    - 1.1.3.3 Lock plate in place
    - 1.1.3.4 Stabilize plate
    - 1.1.3.4.1 Absorb shock
  - 1.1.3.5 Detect plate equipped
- 1.1.4 Eject a plate
    - 1.1.4.1 PMT detect the desire to remove plate
    - 1.1.4.2 Unlock plate from place
    - 1.1.4.3 PMT remove the plate from the device
- 1.1.5 Scoop the food
  - 1.1.5.1 Detect location of desired food on plate
      - 1.1.5.1.1 Detect location & orientation of utensil
      - 1.1.5.1.2 Detect position of plate
      - 1.1.5.1.3 Detect orientation of plate
      - 1.1.5.1.3 Detect location & orientation in front of mouth
      - 1.1.5.1.4 Create a path for the joints to reach desired location
      - 1.1.5.1.5 Hold utensil still in front of mouth for desired time

- 1.2 Protect the components (wires, actuators, joints)
- 1.2.1 Case the components (wires, actuators, joints)
- 1.2.2 Insulate from hazards (dirt, fire, water, etc.)

- 1.3 PMT to move the arms in several directions
- 1.3.1 PMT move in rotational motion
  - 1.3.1.1 PMT rotate up-and-down (pitch motion)
    - 1.3.1.2 PMT rotate left-to-right (yaw motion)
    - 1.3.1.3 PMT rotate about vertical axis (roll motion)
- 1.3.2 PMT detect patient's mouth

            - 1.3.2.1 PMT to learn the distance from the plate to the patient's mouth
            - 1.3.2.2 PMT store desired orientation information
            - 1.3.2.3 PMT detect need to set desired utensil pause time
            - 1.3.2.3.1 PMT prompt user to input desired utensil pause time
            - 1.3.2.3.2 Accept user desired utensil pause time input
    - 1.3.3PMT store desired utensil time information

2. PMT to hold/carry the food

- 2.1 PMT hold the food in place
    - 2.1.1 PMT hold solid food
            - 2.1.1.1 Accommodate for softer foods
            - 2.1.1.2 Accommodate for harder foods
    - 2.1.2 PMT hold liquid food
        - 2.1.2.1 Accommodate for fluids
            - 2.1.2.1.1 Accommodate for various viscosities
            - 2.1.2.1.2 Accommodate for various temperatures
    - 2.1.3 PMT hold cold food
        - 2.1.3.1 Accommodate for direct contact with low and room temperature foods
    - 2.1.4 PMT hold hot food
            - 2.1.4.1 Accommodate for direct contact with high temperatures
            - 2.1.4.2 Accommodate for condensation
            - 2.1.4.3 PMT detect the temperature of the plate
    - 2.1.5 Accommodate for a variety of foods at once
        - 2.1.5.1 PMT separate the types of food
                - 2.1.5.1.1 PMT separate the types of food before the patient begins to eat
                - 2.1.5.1.2 PMT hold liquid, solid, cold, and hot foods at the same time
    - 2.1.6 Accommodate for convection
        - 2.1.6.1 Accommodate for hot convection
            - 2.1.6.1.1 PMT absorb heat
            - 2.1.6.1.2 Accommodate for forced hot convection
        - 2.1.6.2 Accommodate for cold convection
                - 2.1.6.2.1 PMT absorb cold air
                - 2.1.6.2.2 Accommodate for forced cold convection

- 2.2 PMT carry the food from the plate to the mouth
    - 2.2.1 PMT carry solid food steadily
            - 2.2.1.1 Accommodate for softer foods
            - 2.2.1.2 Accommodate for harder foods
        - 2.2.2 PMT carry liquid food steadily
        - 2.2.3 PMT carry cold food
        - 2.2.3.1 Accommodate for direct contact with low and room temperature foods
        - 2.2.3.2 Accommodate for freezing temperatures
    - 2.2.4 PMT carry hot food
            - 2.2.4.1 Accommodate for direct contact with high temperatures

2.2.4.2 Accommodate for condensation
2.2.4.3 PMT cool down hot food
2.2.4.4 Accommodate for boiling temperatures

3. PMT interface with user

3.1 PMT command the device
3.1.1 PMT store commands from the programming software.
3.1.2 PMT power the device
3.1.3 PMT feed the patient
3.1.4 PMT control the plate orientation
3.1.5 PMT store the latest position the device took

3.2 PMT provide a user-friendly interface.
3.2.1 PMT output the status of the device.
3.2.1.1 PMT to indicate whether the device is powered or not
3.2.1.2 PMT to indicate for errors.
3.2.1.2.1 PMT to indicate whether the device is overheated or not
3.2.1.2.2 PMT to indicate whether the plate is in locked position or not
3.2.1.3 PMT to indicate the battery percentage of the device
3.2.2 PMT simplify the control of the device
3.2.3 PMT accommodate for accessibility
3.2.3.1 PMT communicate with the device without the use of hand

3.3 PMT select desired food.
3.3.1 PMT categorize food on plate
3.3.1.1 PMT input food information
3.3.2 PMT to rotate the plate.
3.3.2.1 PMT actuate the rotation of the plate.
3.3.2.2 PMT prompt user to select desired food category

3.4 PMT set desired utensil position
3.4.1 PMT Control height/distance of utensil
3.4.1.1 PMT change utensil level
3.4.1.2 PMT prompt user to input desired utensil height
3.4.1.2.1 PMT Accept desired utensil position input
3.4.1.2.2 PMT store desired position information
3.4.1.2.3 PMT Detect height of utensil
3.4.1.3 PMT Apply force to lift utensil to desired height
3.4.2 PMT control orientation of utensil
3.4.2.1 PMT Detect orientation of utensil
3.4.2.2 PMT prompt user to set desired utensil orientation
3.4.2.3.1.1 PMT Accept user desired utensil orientation input
3.4.2.4 PMT store desired utensil orientation input
3.4.2.5 PMT Apply torque to rotate utensil to desired orientation

4. PMT Power the Device

4.1 Supply electrical energy
        4.1.1 PMT interface device with power supply
        4.1.2 PMT convert AC to DC
        4.1.3 PMT transmit power from main supply to interface
        4.1.4 PMT distribute electrical energy
        4.1.4.1 PMT convert electrical energy to mechanical energy
            4.1.4.1.1 PMT accept electrical energy
            4.1.4.1.2 PMT allow current flow in the presence of magnetic field
        4.1.4.2 Transmit mechanical kinetic energy to the manipulator
            4.1.4.2.1 PMT transmit translational kinetic energy to manipulator links
            4.1.4.2.2 PMT transmit rotational kinetic energy to manipulator joints

4.2 Store energy
    4.2.1 PMT contain electron/current flow
    4.2.2 Accept electrical energy input from the supply power
        4.2.2.1 Determine amount of current in storage
        4.2.2.2 Determine amount of current required to fill storage
        4.2.2.3 Allow required amount of current to flow into storage
        4.2.2.4 Stop current flow once required amount is exceeded

4.3 PMT condition electrical power
    4.3.1 PMT determine required power level
        4.3.1.1 PMT determine required force needed to execute task
        4.3.1.2 PMT determine time required to execute task
        4.3.1.3 PMT calculate the power required to be delivered
    4.3.2 PMT regulate current
        4.3.2.1 PMT detect the current level
            4.3.2.2 PMT determine the required current level to produce desired power
            4.3.2.3 PMT increase/decrease current level
    4.3.3 PMT convert voltage
            4.3.3.1 PMT determine required voltage input to device
            4.3.3.2 PMT determine input voltage from power supply
            4.3.3.3PMT convert voltage from supply to required input voltage to device
    4.3.4 PMT rectify frequency
            4.3.4.1 PMT categorize type of current flow
            4.3.4.2 PMT detect the need for rectification
            4.3.4.3 PMT perform needed rectification

4.4 PMT maintain safety of device and user
    4.4.1 Break circuit during current overflow
            4.4.1.1 PMT detect the current level

        - 4.4.1.2 PMT know the current limit of the circuit
        - 4.4.1.3 PMT compare current limit to the real-time current level
        - 4.4.1.4 PMT break circuit when the current limit is higher than the real-time current level
- 4.4.2 PMT isolate manipulator from circuit
- 4.4.3 PMT protect against overheating
    - 4.4.3.1 PMT dissipate heat in the system
    - 4.4.3.2 PMT absorb heat generated from the system
    - 4.4.3.3 PMT minimize friction in the manipulator
- 4.4.4 Insulate electrically conducting parts from user

APPENDIX B: DEFINITION OF TERMS

Affordable	The total cost of the device must not exceed QR 4000, as requested by the customer.
Amputation	Removal of limb due to trauma, illness or from birth.
Arthrogryposis	Patient has stiff joints and cannot bend their arms.
Assist	Help aid the patient in eating food on their own with the constraints of their physical disability.
Broken Bones	A breakthrough a part or all of the bone.
Feeding	The action of delivering solid or liquid food from a plate or bowl to a point in front of the patient's mouth for them to consume it at their own will and pace.
Home	Place of residence.
Independently	Freedom of the patient to control their eater device on their own when eating and eat at their own pace. This term does not encompass independently setting up, cleaning, and packing the device without the help of another person.
Joint	The part of the robot that allows motion.
Link	Stiff/flexible beam/rod/frame that connects the joints together.
Lifespan	The expected service life of a robot - how long before its motors are worn out such that the performance, power efficiency, and physical components have degraded.
Malfunction	The device fails to function as programmed, or desired. Could cause a safety hazard.
Manipulator	A device that helps carry out a function without a physical interaction by the operator. It is a robot arm made up of joints and links.
Muscular Dystrophy	Muscles are weak which results in a loss of muscle mass.
Myopathy	Muscle fiber does not function properly (normally).

Public setting	Signifies that the device is portable and can be used on many types of tables and surfaces. It also means that the device is easy to move between different locations such as in schools, hospitals, and restaurants.
Prismatic joints	A joint that constricts motion of one link to translational motion along a single axis.
Revolute joints	A joint that constricts the motion of two links to rotational motion only.
Safely	Without causing injuries to the patient. Injuries may include but are not limited to poking the patient with the utensils, electrocution from a power source, spilling hot or cold food contents on the patient, and injuries from sharp objects.
Spinal Cord Injuries	Damage to the vertebrae, ligaments, or disks of the spinal column. Causes weakness or complete loss of muscle function.
Spinal Muscular Atrophy	Genetic disorder that causes weakness in muscles used for movement.
Suitable	Appropriate for patients with upper body motor disabilities.
Autonomy	Defined as the ability to function independently with minimizing the control of a caregiver.
Degrees of Freedom	The number of modes or directions a mechanical device or system can move in.

APPENDIX C: STATIC CALCULATIONS

Table C.1: Center of Mass Calculations for Motor 1.

Components	x (cm)	m (kg)	mx (cm*kg)
spoon + food	0	0.0248	0
spoon holder	4.25	0.0633	0.2690
wrist joint	5.8	0.193	1.1204
		xbar (cm)	**4.94**

Table C.2: Center of Mass Calculations for Motor 2.

Components	x (cm)	m (kg)	mx (cm*kg)
spoon, food, spoon holder, wrist joint	10	0.281	2.813
shoulder joint	2.5	0.903	2.258
		xbar (cm)	**4.28**

Table C.3: Center of Mass Calculations for Motor 3.

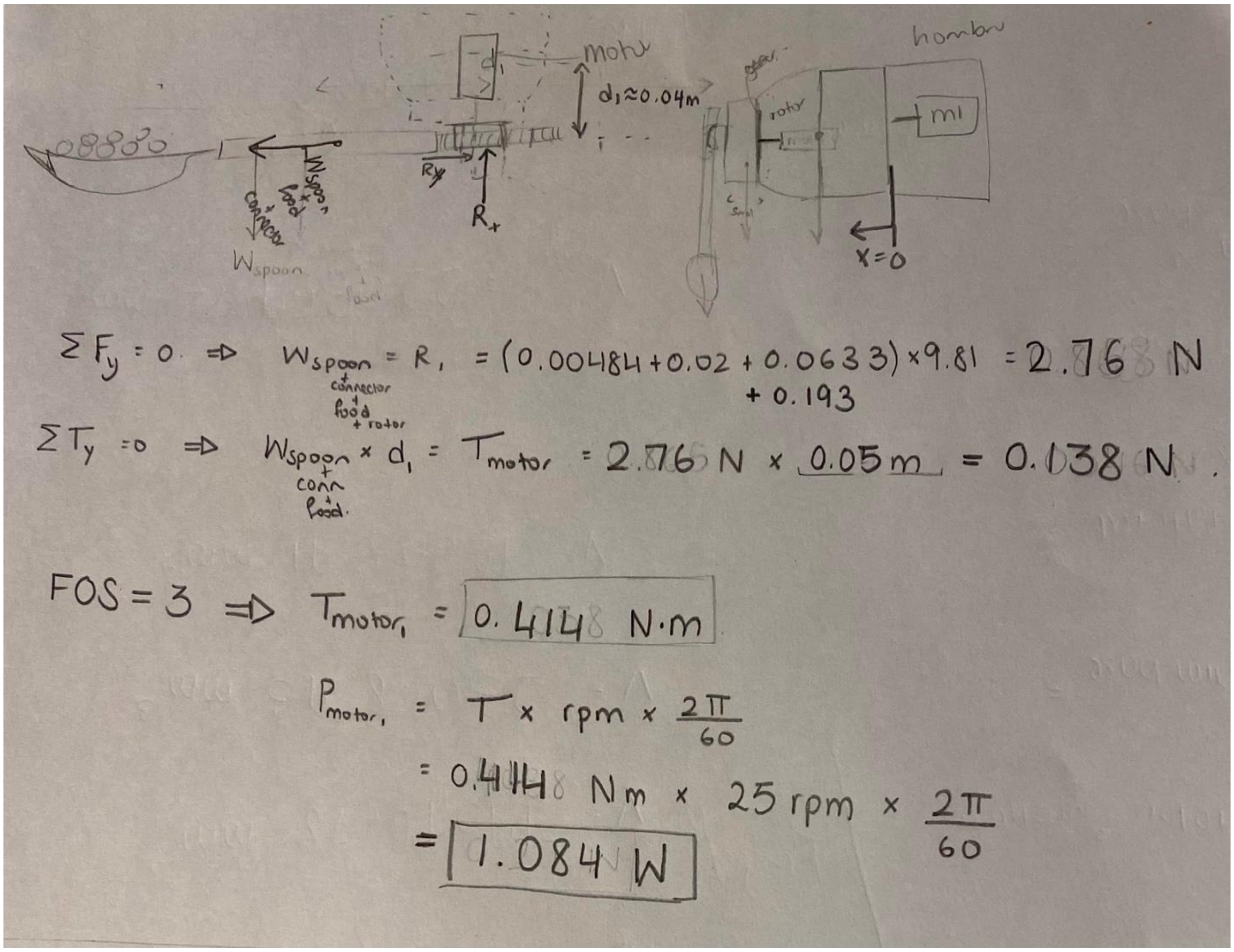
Components	x (cm)	m (kg)	mx (cm*kg)
spoon, food, spoon holder, wrist joint, elbow joint	19.3	1.185	22.863
laterals x2	7.5	0.324	2.431
		xbar (cm)	**16.8**

Table C.4: Center of Mass Calculations for Motor 4.

Components	x (cm)	m (kg)	mx (cm*kg)
spoon, food, spoon holder, wrist joint, elbow joint, lateral x2	19.55	1.509	29.50
shoulder joint	0	0.903	0
		xbar (cm)	**12.2**

Table C.5: Maximum Density, Volume, and Maximum Mass of Components Used in Calculations

Component	Max. Density (kg/m3)	Volume (mm3)	Mass (kg)
Spoon	1540	3140.28	0.00484
Plate	9800	76107.63	0.746
Base	10,000	220859.72	2.209
Spoon connection	10,000	6330.35	0.063
Shoulder joint	10,000	90332.15	0.903
Elbow joint	10,000	90332.15	0.903
Wrist joint	10,000	19316.78	0.193
Arm Base	10,000	23068.93	0.231
Lateral 1	10,000	16203.91	0.162
Lateral 2	10,000	16203.91	0.162



$$\Sigma F_y = 0 \Rightarrow W_{spoon + connector + food + rotor} = R_1 = (0.00484 + 0.02 + 0.0633 + 0.193) \times 9.81 = 2.76 \text{ N}$$

$$\Sigma T_y = 0 \Rightarrow W_{spoon + conn + food} \times d_1 = T_{motor} = 2.76 \text{ N} \times \underline{0.05 \text{ m}} = 0.138 \text{ N}$$

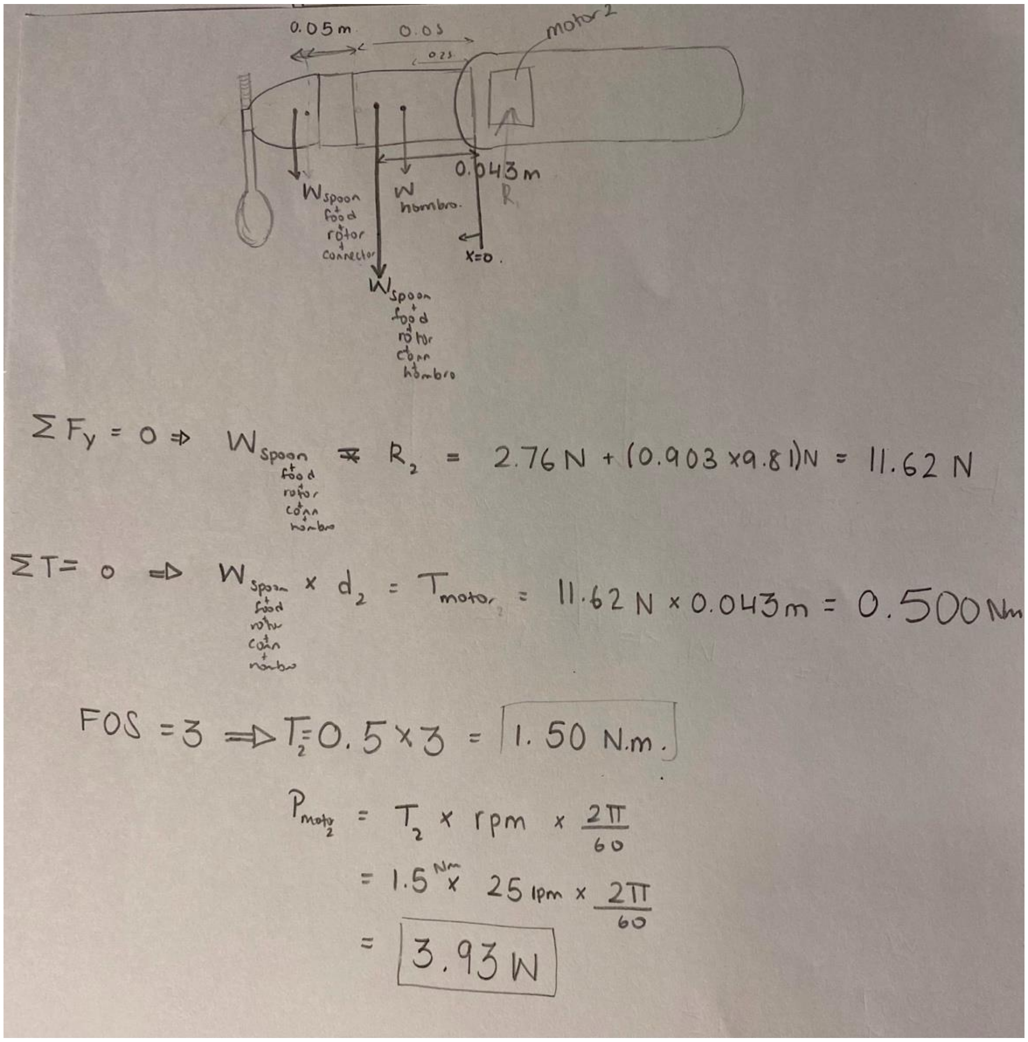
$$FOS = 3 \Rightarrow T_{motor_1} = \boxed{0.414 \text{ N} \cdot \text{m}}$$

$$P_{motor_1} = T \times rpm \times \frac{2\pi}{60}$$

$$= 0.414 \text{ Nm} \times 25 \text{ rpm} \times \frac{2\pi}{60}$$

$$= \boxed{1.084 \text{ W}}$$

Figure C.1: Motor 1 power calculation.



$$\Sigma F_y = 0 \Rightarrow W_{spoon+food+rotor+conn+hombro} \cancel{=} R_2 = 2.76\,N + (0.903 \times 9.81)\,N = 11.62\,N$$

$$\Sigma T = 0 \Rightarrow W_{spoon+food+rotor+conn+hombro} \times d_2 = T_{motor_2} = 11.62\,N \times 0.043\,m = 0.500\,Nm$$

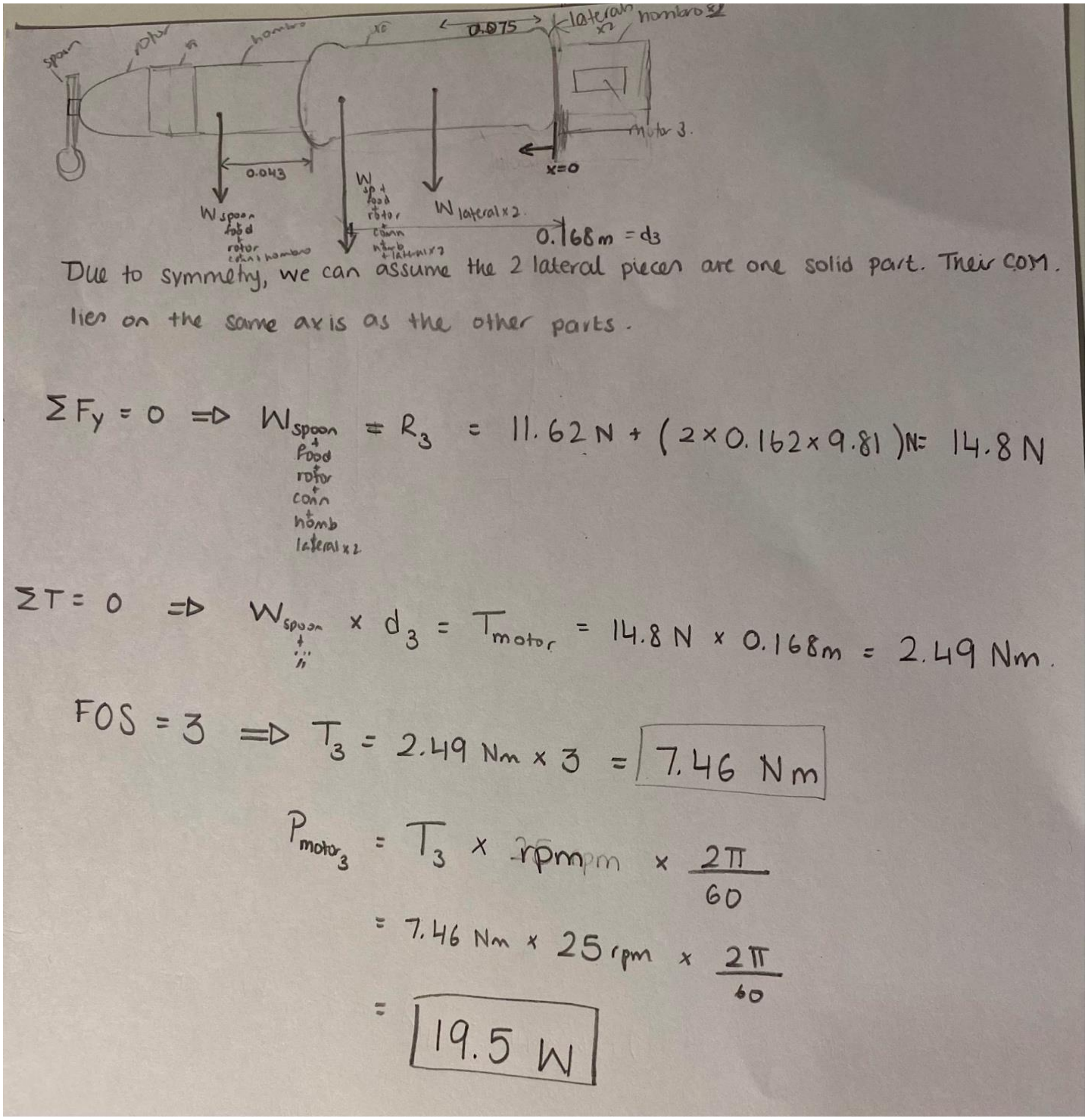
$$FOS = 3 \Rightarrow T_2 = 0.5 \times 3 = \boxed{1.50\ N.m.}$$

$$P_{motor_2} = T_2 \times rpm \times \frac{2\pi}{60}$$

$$= 1.5^{Nm} \times 25\,rpm \times \frac{2\pi}{60}$$

$$= \boxed{3.93\,W}$$

Figure C.2: Motor 2 power calculation.



Due to symmetry, we can assume the 2 lateral pieces are one solid part. Their COM. lies on the same axis as the other parts.

$$\Sigma F_y = 0 \Rightarrow W_{\substack{spoon \\ + \\ food \\ + \\ rotor \\ + \\ conn \\ + \\ homb \\ lateral \times 2}} = R_3 = 11.62\,N + (2 \times 0.162 \times 9.81)\,N = 14.8\,N$$

$$\Sigma T = 0 \Rightarrow W_{\substack{spoon \\ + \\ \vdots}} \times d_3 = T_{motor} = 14.8\,N \times 0.168m = 2.49\,Nm.$$

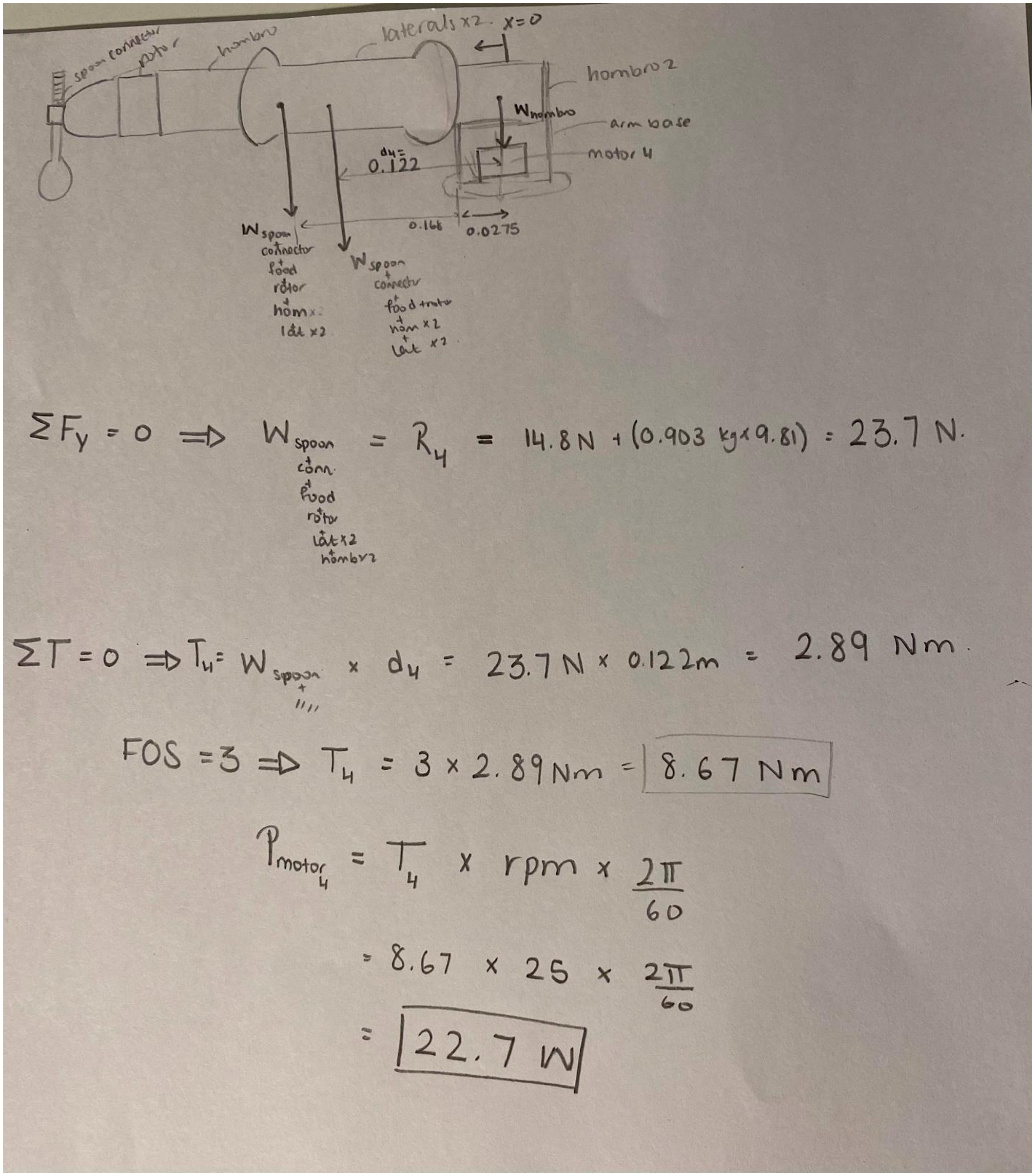
$$FOS = 3 \Rightarrow T_3 = 2.49\,Nm \times 3 = \boxed{7.46\,Nm}$$

$$P_{motor_3} = T_3 \times rpm \times \frac{2\pi}{60}$$

$$= 7.46\,Nm \times 25\,rpm \times \frac{2\pi}{60}$$

$$= \boxed{19.5\,W}$$

Figure C.3: Motor 3 power calculation.



$$\Sigma F_y = 0 \Rightarrow W_{\substack{spoon\\ + conn.\\ + food\\ rotor\\ + lat x2\\ + hombro x2}} = R_4 = 14.8\,N + (0.903\,kg \times 9.81) = 23.7\,N.$$

$$\Sigma T = 0 \Rightarrow T_4 = W_{\substack{spoon\\ +\\ ''''}} \times d_4 = 23.7\,N \times 0.122\,m = 2.89\,Nm.$$

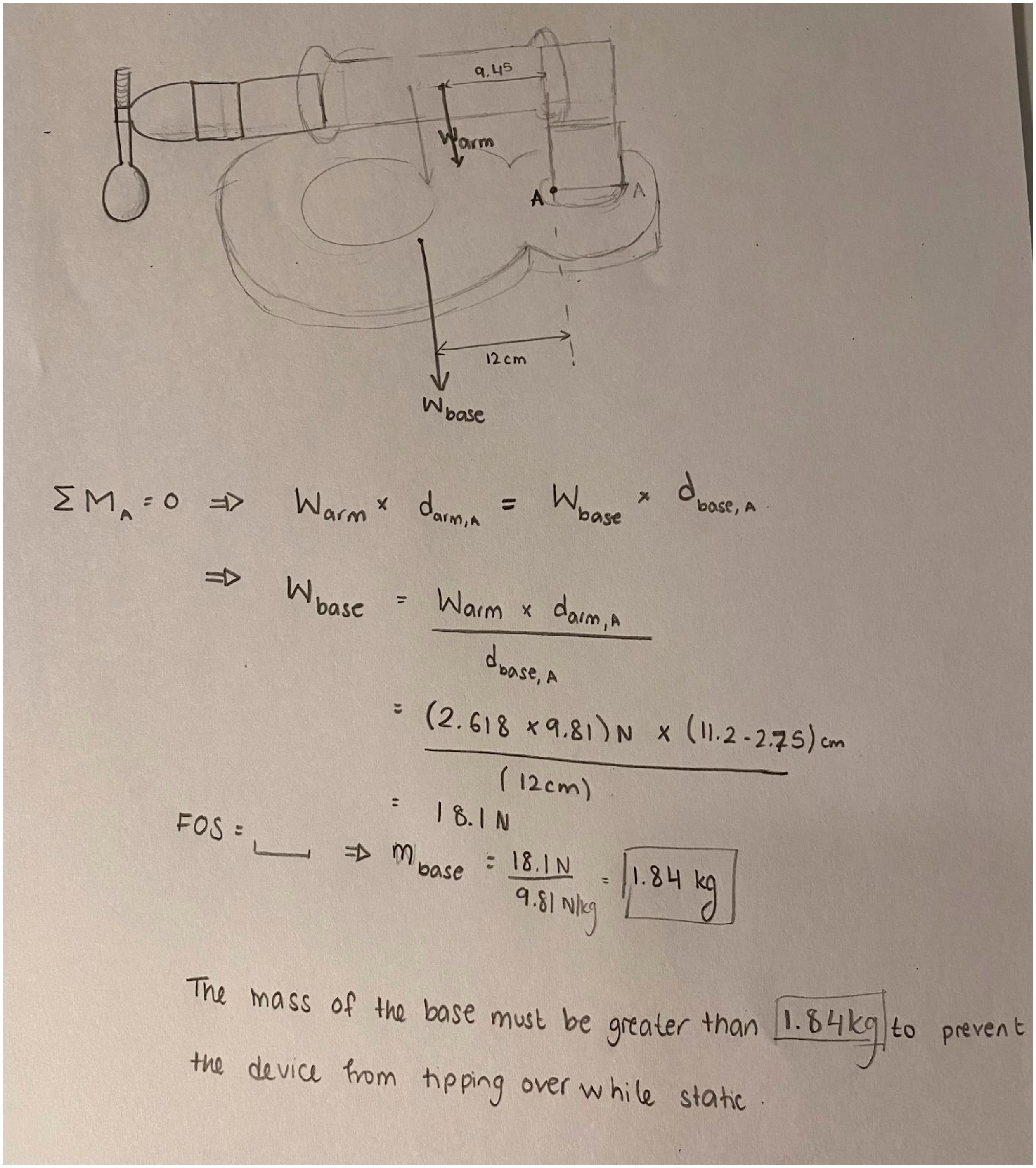
$$FOS = 3 \Rightarrow T_4 = 3 \times 2.89\,Nm = \boxed{8.67\,Nm}$$

$$P_{motor_4} = T_4 \times rpm \times \frac{2\pi}{60}$$

$$= 8.67 \times 25 \times \frac{2\pi}{60}$$

$$= \boxed{22.7\,W}$$

Figure C.4: Motor 4 power calculation.



$$\sum M_A = 0 \Rightarrow W_{arm} \times d_{arm,A} = W_{base} \times d_{base,A}$$

$$\Rightarrow W_{base} = \frac{W_{arm} \times d_{arm,A}}{d_{base,A}}$$

$$= \frac{(2.618 \times 9.81)\,\text{N} \times (11.2 - 2.75)\,\text{cm}}{(12\,\text{cm})}$$

$$= 18.1\,\text{N}$$

FOS = ___ $\Rightarrow m_{base} = \frac{18.1\,\text{N}}{9.81\,\text{N/kg}} = \boxed{1.84\text{ kg}}$

The mass of the base must be greater than $\boxed{1.84\text{kg}}$ to prevent the device from tipping over while static.

Figure C.5: Device equilibrium calculation

APPENDIX D: FAILURE MODES AND EFFECTS ANALYSIS

Item	Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes of Failure	Occurrence	RPN	Recommended actions
Arm	To deliver food to the patient’s mouth	Links wear out/break	The manipulator, as a whole, will fail to deliver food to the user.	9	Exceeding the arm's payload or deliberate interaction	5	45	Set a high payload of the arm
		Joints wear out/break						
		Damage to utensil	Result in harm to the patient	8		3	24	Include alternative utensils. Use a material with high fracture toughness for the utensils
Actuators	Provides rotational motion to the arm (Actuates the arm)	The motor itself spins instead of the shaft or along with the shaft	The arm does not actuate or move. The plate does not rotate. the system as a whole fails.	8	The shaft isn’t secured to the links firmly.	3	24	Secure the shafts firmly with the motor and run tests before marketing
		Excessive vibrations of the motor		5	Motor functions at a frequency that is out of range	2	10	Supply encoders that will manage the speed and in turn control the frequency range
		Motor stops working		8	The robot arm's payload had been exceeded	4	32	Set a high payload of the arm.
Switches	To provide manual commands to the device	Button doesn't send out commands	The system overall fails in functioning. The user loses control over the device --> Inability to feed	8	Damage to the switch that is below the button	4	32	Improve the damage tolerance of the switch.
		Switches are not properly protected	Spark or damage to the switches	9	Diodes malfunction.	2	18	Install a multimeter to track the diodes regularly
LCD Display	Display the status of the device	Damage to the screen	Does not provide the status of the device. The patient wouldn't know if the utensils and plates are fully secured.	7	Impact force on plate (falling, hitting, etc.)	7	49	Add a screen case & ensure no gaps into the base’s internal parts.
		Screen does not work			Food spillage on the screen	8	56	

Plate	To act as a container to hold the food for the user	Breaks/Chips	The plate is no longer functional	6	Exposed to impact or being dropped	6	36	Manufacture the plate from a material with high fracture toughness and high service temperature.
		Melts or deforms over time	The food becomes poisonous or not edible	8	The material used for the plate has a service temperature below that of the hot food served	3	24	
Battery (Power source)	To supply the device with power to function.	Overheats	Causes a fire or explosion. Damages surrounding components	10	Overcharging or fast charging the battery	8	80	Provide voltage and current regulators.
		Battery stops working	The system loses power supply overall	10	Battery ages	7	70	Replace the battery every 3 years
Plate	to contain the different food items	Plate breaks or shatters into pieces	Spilling of food; Inability to contain food	9	Impact force on plate (falling, hitting, etc.)	4	36	Select a material for the plate with a high fracture strength; increase the surface area of the plate and its thickness
					Plate experiences temperatures below its ductile to brittle transition temperature	3	27	Select a material that undergoes ductile failure with a low ductile to brittle transition temperature in order to avoid a brittle failure that shatters the plate
			Injuries to patient from sharp pieces	6	Impact force on plate (falling, hitting, etc.)	4	24	Select a material for the plate with a high fracture strength; increase the surface area of the plate and its thickness
					Plate experiences temperatures below its ductile to brittle transition temperature	3	18	Select a material that undergoes ductile failure with a low ductile to brittle transition temperature in order to avoid a brittle failure that shatters the plate
		Pieces of plate chip off	Injuries to patient from sharp pieces (or mixed in with food)	4	Impact force on parts of the plate	6	24	Select a material that undergoes ductile failure in order to avoid a

			Spilling of food or leaking of liquids in plate	9			54	brittle failure that shatters the plate
		Some material melts	Injures to patient if they ingest some of the material (choking, poisoning, abrasion)	9	The food or dishwasher environment is at a temperature higher than the plate's service temperature		0	Ensure that the maximum service temperature of the plate is higher than the temperature of the food or the inside of a dishwasher
			Spilling of food or leaking of liquids in plate			3	0	
		Plate emits toxic chemicals or substances	Health hazard to patient (poisoning, choking, etc.)	10	The material of the plate is toxic or becomes toxic when heated or microwaved	2	20	Select a nontoxic and microwave safe material for the plate
		Plate becomes deformed	Spilling of food or leaking of liquids in plate; plate becomes unusable	9	Heat warps the shape of the plate	2	18	Ensure that the maximum service temperature of the plate is higher than the temperature of the food or the inside of a dishwasher + add a safety factor
			Plate becomes unable to rotate, limiting the user's selection of food	8		2	16	
		Plate adheres to the food	Utensil becomes unable to lift food off the plate; device cannot feed	4	Protein reacts with surface of the plate under heat	1	4	Ensure that the material selected does not react with proteins under heat; add recommendation in user manual to warn against heating the plate under a direct flame
			Plate cannot be cleaned; plate becomes unusable	6		5	30	
Utensil	to hold the bite of food to be carried from the plate to the user's mouth	Utensil breaks	Spilling of food; Inability to contain food	8	Impact force on utensil (dropping, hitting, pushing, etc.)	8	64	Select a material for the utensil with a high fracture strength; increase the thickness of the utensil
					Utensil experiences temperatures below its ductile to brittle transition temperature	3	24	Select a material that undergoes ductile failure with a low ductile to brittle transition temperature to avoid a brittle

								failure that shatters the plate
			Injuries to patient from sharp pieces	8	Impact force on utensil (dropping, hitting, pushing, etc.)	8	64	Select a material for the utensil with a high fracture strength; increase the thickness of the utensil
					Utensil experiences temperatures below its ductile to brittle transition temperature	3	0	Select a material that undergoes ductile failure with a low ductile to brittle transition temperature to avoid a brittle failure that shatters the plate
		Some material chips off of utensil	Injuries to patient from sharp end of utensil (or mixed in with food)	5	Impact force on parts of the utensil	8	40	Select a material with high fracture strength (to protect against impact); include extra set of utensils in case
			Spilling of food or leaking of liquids in plate	4		8	32	
			Imbalance in utensil system (center of mass shifts)	3		8	24	
		Some of the utensil material melts or deforms	Injures to patient if they ingest some of the material (choking, poisoning, abrasion)	9	The food or dishwasher environment is at a temperature higher than the utensil's service temperature	3	27	Ensure that the maximum service temperature of the utensil is higher than the temperature of the food or the inside of a dishwasher
		Utensil emits toxic chemicals or substances	Health hazard to patient (poisoning, choking, etc.)	9	The material of the utensil is toxic or becomes toxic when heated or microwaved	3	27	Select a nontoxic and microwave safe material for the utensil
		Utensil bends	Inability to set comfortable position for utensil	3	Impact force on utensil (dropping, hitting, pushing, etc.)	8	24	Select a material for the plate with a high fracture strength; increase the surface area of the plate and its thickness

					Excessive torque applied on one end of the utensil due to the weight of the food	2	6	Perform stress and torque calculations to ensure the weight of the food and other external forces remain within the yield limit of the selected material
					Cyclic loading and unloading of food on the utensil (fatigue)	4	12	Select a material with adequate fatigue strength and fatigue life
			Imbalance in utensil system (center of mass shifts, loads are unevenly distributed, risk of breakage)	5	Impact force on utensil (dropping, hitting, pushing, etc.)	4	20	Select a material for the plate with a high fracture strength; increase the surface area of the plate and its thickness
					Excessive torque applied on one end of the utensil due to the weight of the food	3	15	Perform stress and torque calculations to ensure the weight of the food and other external forces remain within the yield limit of the selected material
					Cyclic loading and unloading of food on the utensil (fatigue)	5	25	Select a material with adequate fatigue strength and fatigue life
		Utensil Fixture	Utensil slipping from the clamp	9	Excessive food weight applied and unloading of food on the utensil	4	36	Come up with a secure mechanism to hold the spoon whilst rotating and lifting foods
Power Supply	to provide the system with energy to store and use	Power supply does not provide electricity	Inability to charge the device	8	Electricity cuts off; plugs are faulty	3	**24**	Include charging indicator; if a power outlet is faulty, the user can use another one
		Power supply delivers too much current	Components of the device become fried (microcontroller, circuit components, etc.)	9	Current fluctuations in power supply	4	**36**	Integrate a fuse or circuit breaker into the electrical system

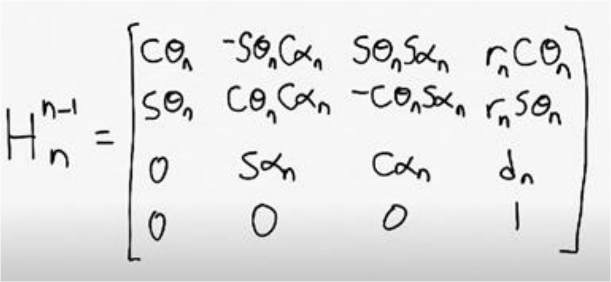
		Power supply inaccessible	Inability to charge the device	5	Device is being used outdoors or in a space without power outlets	5	**25**	Recommend charging the device prior to use in spaces without power outlets in the user manual; accommodate for long enough battery time to complete meals without charging
Battery	to store the energy provided by the main power supply for use in the system	Battery dies	Unable to use device until it is recharged or replaced	5	Out of charge or permanently damaged battery	7	**35**	Install indicators and alerts for low battery; include battery life recommendations in device documentation/user manuals
		Battery life deteriorates	Shorter times in between charging device (extra hassle for the user)	4	Old battery or battery is charged and recharged too often	5	**20**	Ensure the service life of the battery chosen can outlive that of the device or ensure that the battery chosen can be replaced
		Battery Overheats	Unable to deliver power		Short circuit or overcurrent			Add insulation to
		Battery does not store/supply required amount of energy	Battery cannot be used at its maximum efficiency	7	Battery does not have enough capacity to store and supply required amount of energy	3	**21**	Choose a battery that has the required amount of storage capacity
					Disconnections between the wiring to and from the battery	3	**21**	Ensure that the wire connection points are secured strongly; reinforce wire to component interfaces with adhesives, locks, etc.
Wiring	to deliver power to different components and connect them	Wire gets cut	Power does not deliver to all components, device cannot function	9	Wire is too stretched out or the wire is too weak to resist pulling forces on it	5	**45**	Reinforce the wires with strong casing, stronger materials, or a thicker wire diameter as well as a long enough wire not to be stretched.

		Wire gets disconnected from its respective interface			Wire to component interface is too weak to hold together or resist pulling forces on it	5	**45**	Ensure that the wire connection points are secured strongly; reinforce wire to component interfaces with adhesives, locks, etc.
		Wire not long enough to connect different components	Wire gets stretched out and cut/disconnected or cannot connect to the different components, not allowing power to be distributed throughout the system	9	Chosen length of wire is too short, or long enough when the device is static but cannot account for the movement of the manipulator arm	4	**36**	Select a length of wire that is longer than required to account for dynamic movements in the system and a factor of safety
		Wires not connected correctly	Power does not deliver to all components; power is incorrectly distributed between components (can damage electrical and mechanical components)	10	Incorrectly designed circuit	3	**30**	Implement system design checks, simulations for the electrical circuit, and adequate circuit testing during the physical testing stage
					Confusion between the wires when making the physical connections	3	**30**	Color code the wires on both the circuit design and the physical wire casings to prevent wiring confusion
Circuit Components (resistor, voltage regulator, etc.)		Break	Circuit becomes open; most functions of the device become unavailable (no power delivery)	8	Impact force on device	7	**56**	Utilize parallel circuits (in case one resistor fails, another one in parallel can keep the circuit closed
		Do not perform their function correctly	Some or all functions of the device become unavailable	8	Incorrectly designed circuit	3	**24**	Implement system design checks, simulations for the electrical circuit, and adequate circuit testing during the physical testing stage
					Confusion between the wires when making the physical connections	3	**24**	Color code the wires on both the circuit design and the physical wire casings to prevent wiring confusion

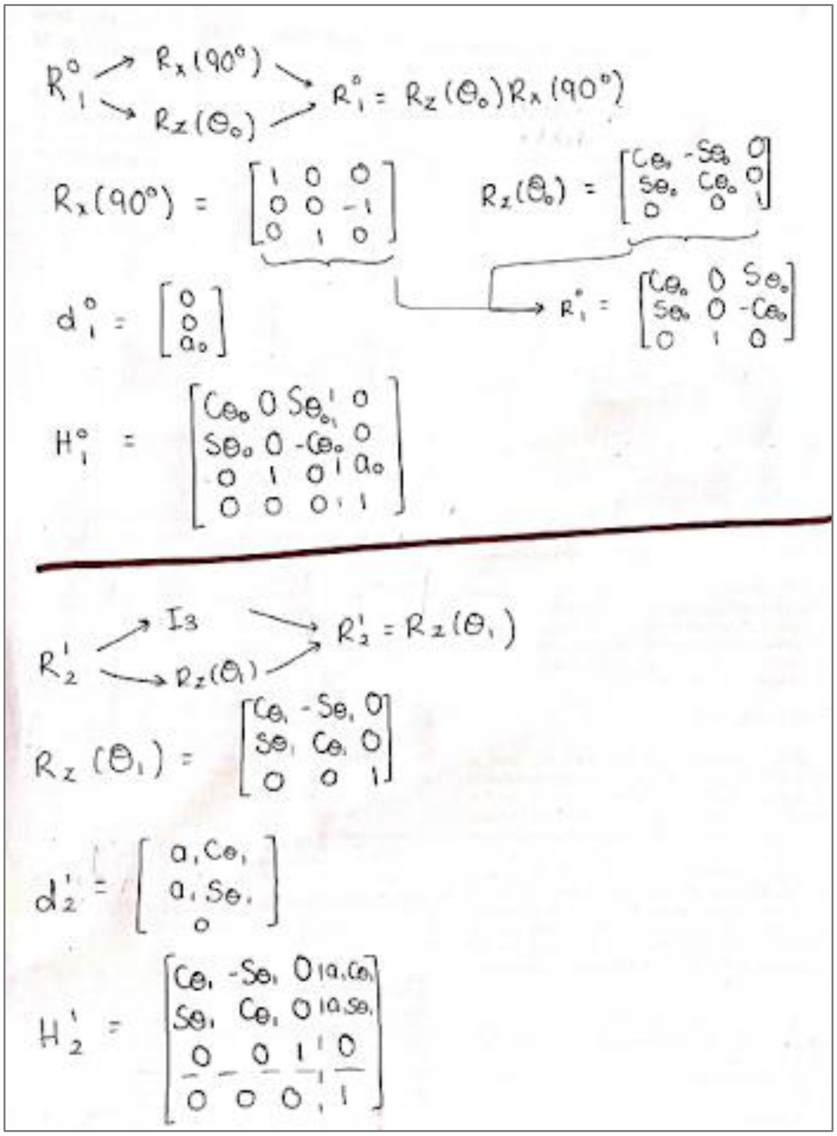
		Disconnect from the circuit	Circuit opens; Power cannot deliver to components; device cannot function	7	Wire to component interface is too weak to hold together or resist pulling forces on it	4	**28**	Ensure that the wire connection points are secured strongly; reinforce wire to component interfaces with adhesives, locks, etc.
Microcontroller	to store and execute tasks given by the programmer and user	Breaks	Device cannot accept commands; inability to use device	7	Harsh handling of the device or dropping the device	7	**49**	Ensure that the microcontroller is secure enough in the device to handle impact; ensure that the microcontroller has good solder quality
		Memory Stack Overflow	Hardware failure; device cannot accept commands; inability to use device	7	Variable greater than the stack size is allocated	5	**35**	Ensure that every variable allocated is within the microcontroller's defined stack size
		Crashes/Freezes	Device cannot accept commands temporarily; inability to use device temporarily	5	Unstable voltage source or constant disruptions in the power source	3	**15**	Install dynamic voltage stabilizers; increase the diameter of the power source and device conductor (interface)
					Electrical interference induced from relays and motors	6	**30**	Add or increase electrical insulation using an operational amplifier for example
		Does not deliver all of the required signals	Some or all functions on the device become inaccessible	6	Low quality solder joints on microcontroller	4	**18**	Choose a microcontroller that had a high process quality during its manufacturing
					The microcontroller is old (aging)	3	**18**	Ensure the life of the the microcontroller chosen can outlive that of the device
					Incorrect wiring in the circuit	5	**30**	Color code the wires on both the circuit design and the physical wire casings to prevent wiring confusion and adequate circuit testing during

Plug	to interface the power supply with the device	Wires disconnect from plug	Power cannot deliver to components; device cannot function	7	Wire to component interface is too weak to hold together or resist pulling forces on it	4	**28**	Ensure that the wire connection points are secured strongly; reinforce wire to component interfaces with adhesives, locks, etc.
		Plug breaks			Harsh handling of plug or impact on plug; material not strong enough to absorb impact	7	**49**	Select a material for the plug that has high strength; increase the thickness of the components in the plug
		Plug does not interface with power supply			Disconnection in the wires or the prongs are too short	3	**21**	Ensure that the prongs and wire connections are designed and manufactured according to Qatar's electrical standards
		One or more prongs bend or break	Device cannot interface with power supply; Power cannot deliver to components; device cannot function	8	Prongs are too flexible and/or too weak	3	**21**	Select a material for the plug that has high strength and high stiffness; increase the thickness of the components in the plug

APPENDIX E: FORWARD KINEMATICS



$$H_n^{n-1} = \begin{bmatrix} C\theta_n & -S\theta_n C\alpha_n & S\theta_n S\alpha_n & r_n C\theta_n \\ S\theta_n & C\theta_n C\alpha_n & -C\theta_n S\alpha_n & r_n S\theta_n \\ 0 & S\alpha_n & C\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



$$\begin{tikzcd} & R_x(90^\circ) \arrow[dr] & \\ R_1^0 \arrow[ur] \arrow[dr] & & R_1^0 = R_z(\theta_0) R_x(90^\circ) \\ & R_z(\theta_0) \arrow[ur] & \end{tikzcd}$$

$$R_x(90^\circ) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \qquad R_z(\theta_0) = \begin{bmatrix} C\theta_0 & -S\theta_0 & 0 \\ S\theta_0 & C\theta_0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$d_1^0 = \begin{bmatrix} 0 \\ 0 \\ a_0 \end{bmatrix} \qquad R_1^0 = \begin{bmatrix} C\theta_0 & 0 & S\theta_0 \\ S\theta_0 & 0 & -C\theta_0 \\ 0 & 1 & 0 \end{bmatrix}$$

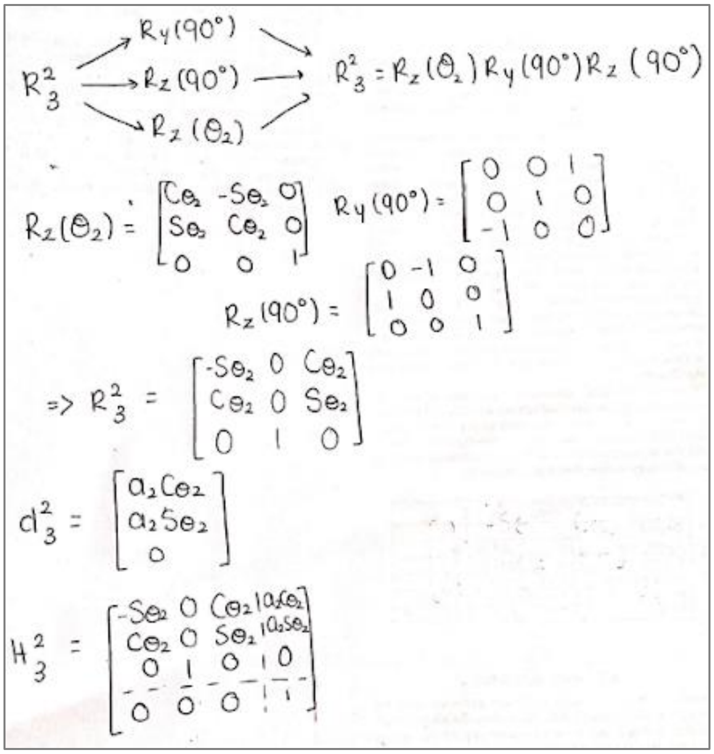
$$H_1^0 = \left[\begin{array}{ccc|c} C\theta_0 & 0 & S\theta_0 & 0 \\ S\theta_0 & 0 & -C\theta_0 & 0 \\ 0 & 1 & 0 & a_0 \\ 0 & 0 & 0 & 1 \end{array}\right]$$

$$\begin{tikzcd} & I_3 \arrow[dr] & \\ R_2^1 \arrow[ur] \arrow[dr] & & R_2^1 = R_z(\theta_1) \\ & R_z(\theta_1) \arrow[ur] & \end{tikzcd}$$

$$R_z(\theta_1) = \begin{bmatrix} C\theta_1 & -S\theta_1 & 0 \\ S\theta_1 & C\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$d_2^1 = \begin{bmatrix} a_1 C\theta_1 \\ a_1 S\theta_1 \\ 0 \end{bmatrix}$$

$$H_2^1 = \left[\begin{array}{ccc|c} C\theta_1 & -S\theta_1 & 0 & a_1 C\theta_1 \\ S\theta_1 & C\theta_1 & 0 & a_1 S\theta_1 \\ \hline 0 & 0 & 1 & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$



$$\begin{tikzcd}
 & R_y(90^\circ) \arrow[dr] & \\
R_3^2 \arrow[ur] \arrow[r] \arrow[dr] & R_z(90^\circ) \arrow[r] & R_3^2 = R_z(\theta_2)\,R_y(90^\circ)\,R_z(90^\circ) \\
 & R_z(\theta_2) \arrow[ur] &
\end{tikzcd}$$

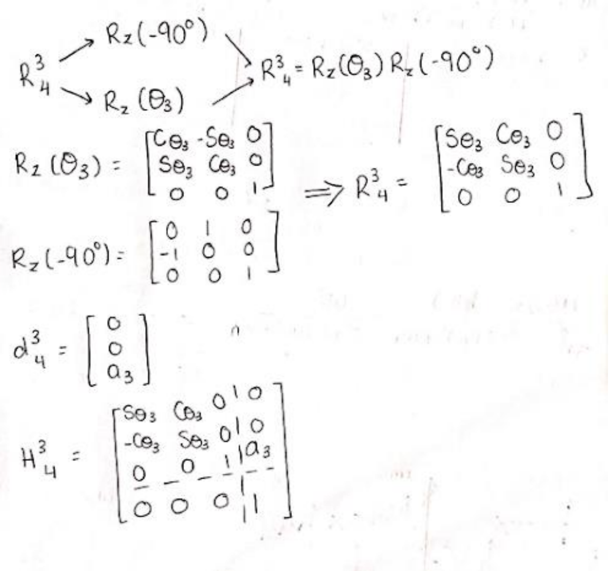
$$R_z(\theta_2) = \begin{bmatrix} C\theta_2 & -S\theta_2 & 0 \\ S\theta_2 & C\theta_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad R_y(90^\circ) = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

$$R_z(90^\circ) = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\Rightarrow R_3^2 = \begin{bmatrix} -S\theta_2 & 0 & C\theta_2 \\ C\theta_2 & 0 & S\theta_2 \\ 0 & 1 & 0 \end{bmatrix}$$

$$d_3^2 = \begin{bmatrix} a_2 C\theta_2 \\ a_2 S\theta_2 \\ 0 \end{bmatrix}$$

$$H_3^2 = \left[\begin{array}{ccc|c} -S\theta_2 & 0 & C\theta_2 & a_2 C\theta_2 \\ C\theta_2 & 0 & S\theta_2 & a_2 S\theta_2 \\ 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$



$$\begin{tikzcd}
 & R_z(-90^\circ) \arrow[dr] & \\
R_4^3 \arrow[ur] \arrow[dr] & & R_4^3 = R_z(\theta_3)\,R_z(-90^\circ) \\
 & R_z(\theta_3) \arrow[ur] &
\end{tikzcd}$$

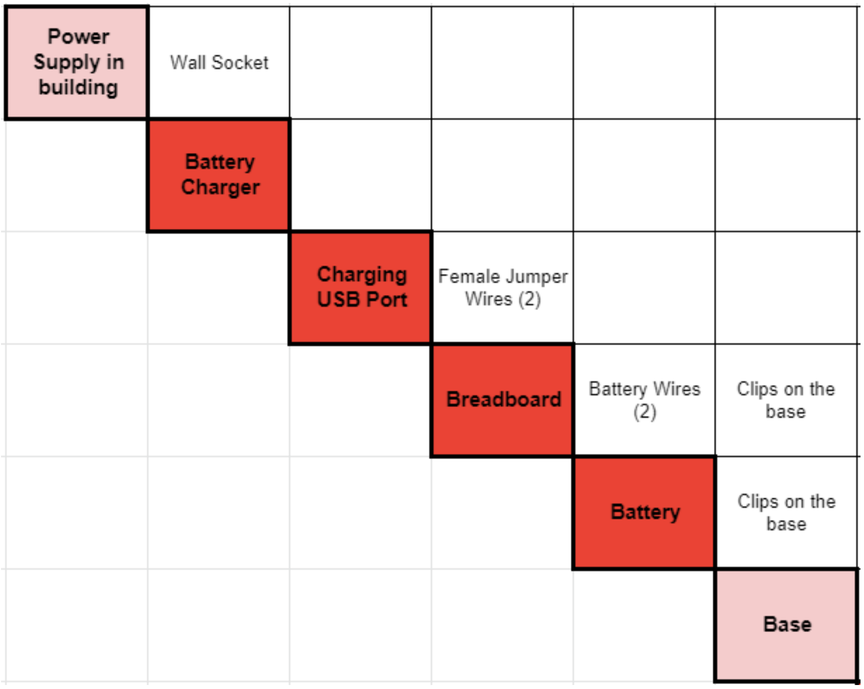
$$R_z(\theta_3) = \begin{bmatrix} C\theta_3 & -S\theta_3 & 0 \\ S\theta_3 & C\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \Rightarrow R_4^3 = \begin{bmatrix} S\theta_3 & C\theta_3 & 0 \\ -C\theta_3 & S\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_z(-90^\circ) = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$d_4^3 = \begin{bmatrix} 0 \\ 0 \\ a_3 \end{bmatrix}$$

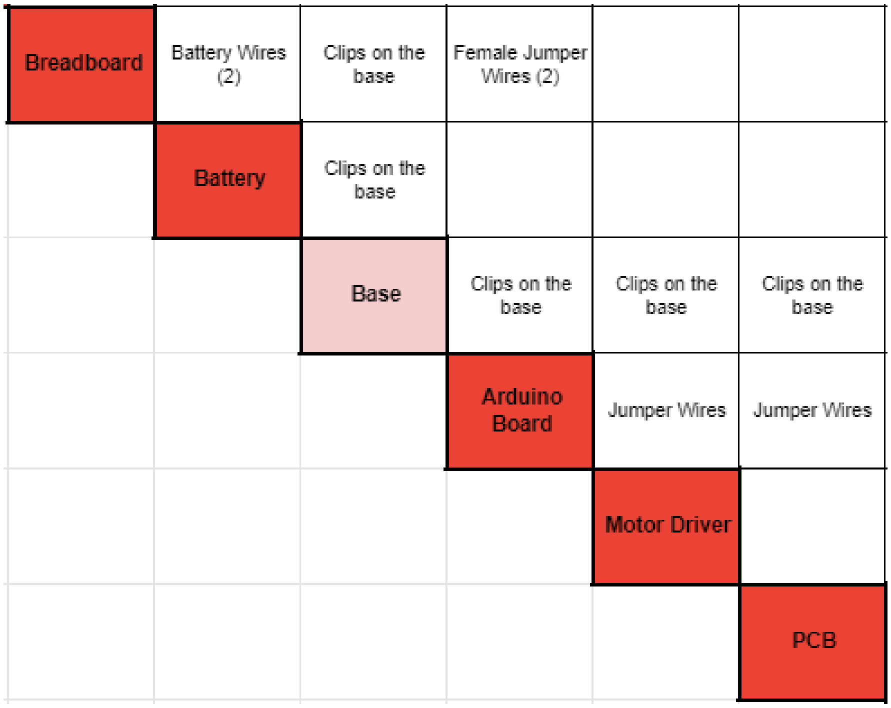
$$H_4^3 = \left[\begin{array}{ccc|c} S\theta_3 & C\theta_3 & 0 & 0 \\ -C\theta_3 & S\theta_3 & 0 & 0 \\ 0 & 0 & 1 & a_3 \\ \hline 0 & 0 & 0 & 1 \end{array}\right]$$

APPENDIX F: N2 DIAGRAMS



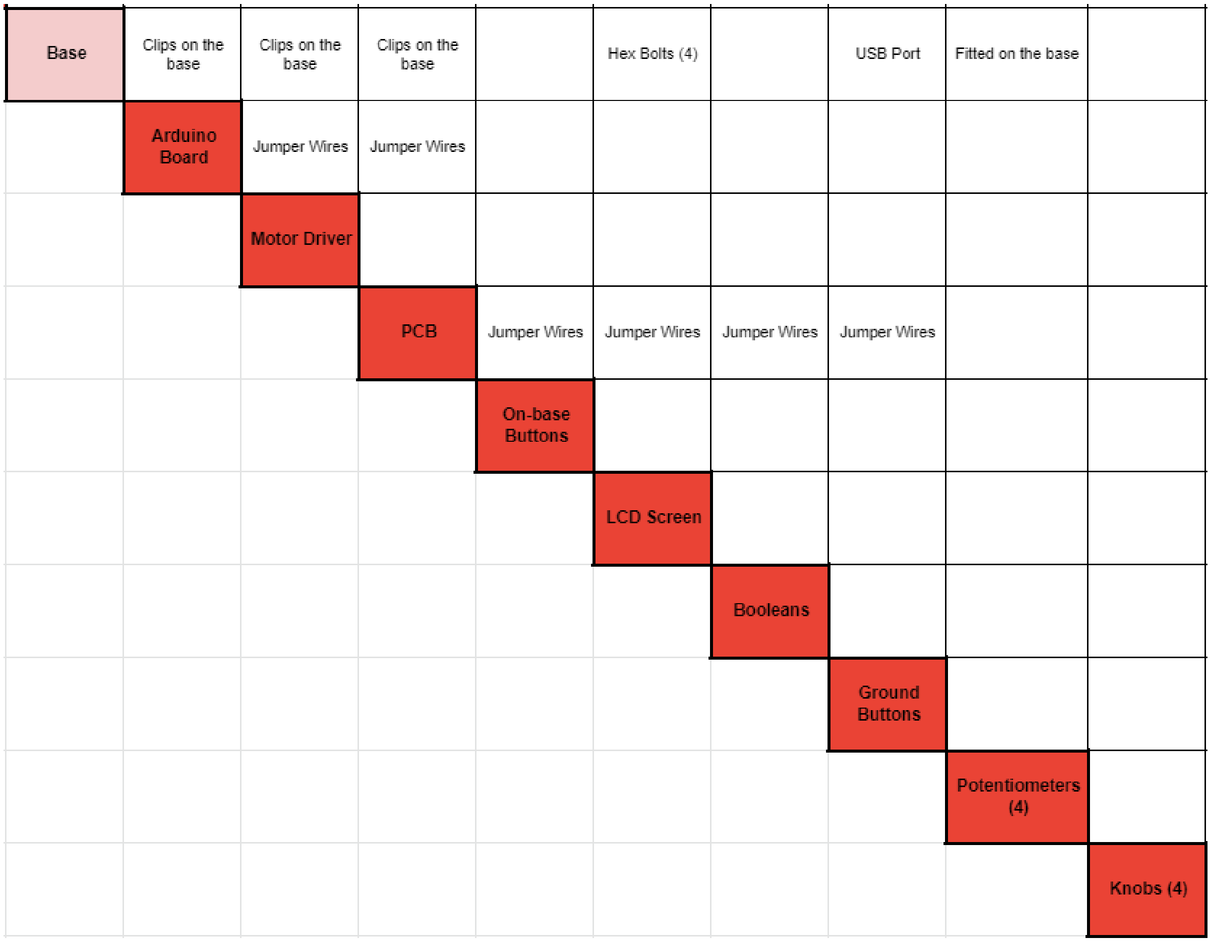
Power Supply in building	Wall Socket				
	Battery Charger				
		Charging USB Port	Female Jumper Wires (2)		
			Breadboard	Battery Wires (2)	Clips on the base
				Battery	Clips on the base
					Base

Figure F1: N2 Diagram for the Power supply subsystem



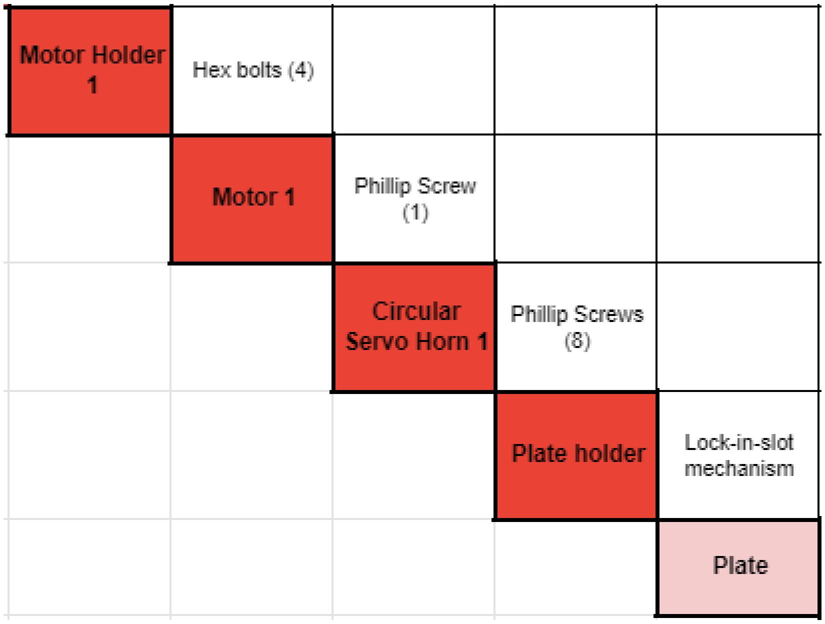
Breadboard	Battery Wires (2)	Clips on the base	Female Jumper Wires (2)		
	Battery	Clips on the base			
		Base	Clips on the base	Clips on the base	Clips on the base
			Arduino Board	Jumper Wires	Jumper Wires
				Motor Driver	
					PCB

F.2: N2 Diagram for the Base subsystem part 1



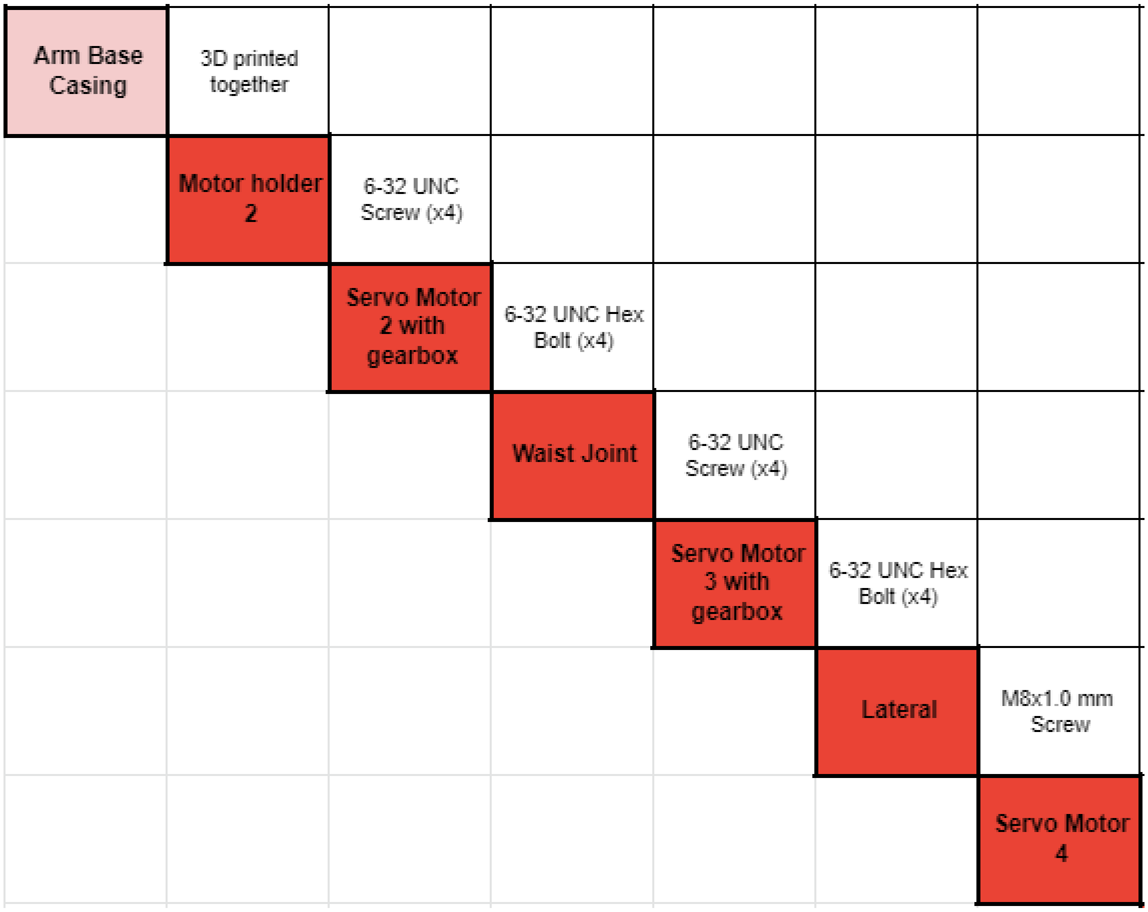
Base	Clips on the base	Clips on the base	Clips on the base		Hex Bolts (4)		USB Port	Fitted on the base	
	Arduino Board	Jumper Wires	Jumper Wires						
		Motor Driver							
			PCB	Jumper Wires	Jumper Wires	Jumper Wires	Jumper Wires		
				On-base Buttons					
					LCD Screen				
						Booleans			
							Ground Buttons		
								Potentiometers (4)	
									Knobs (4)

F.3: *N2 Diagram for the Base subsystem part 2*



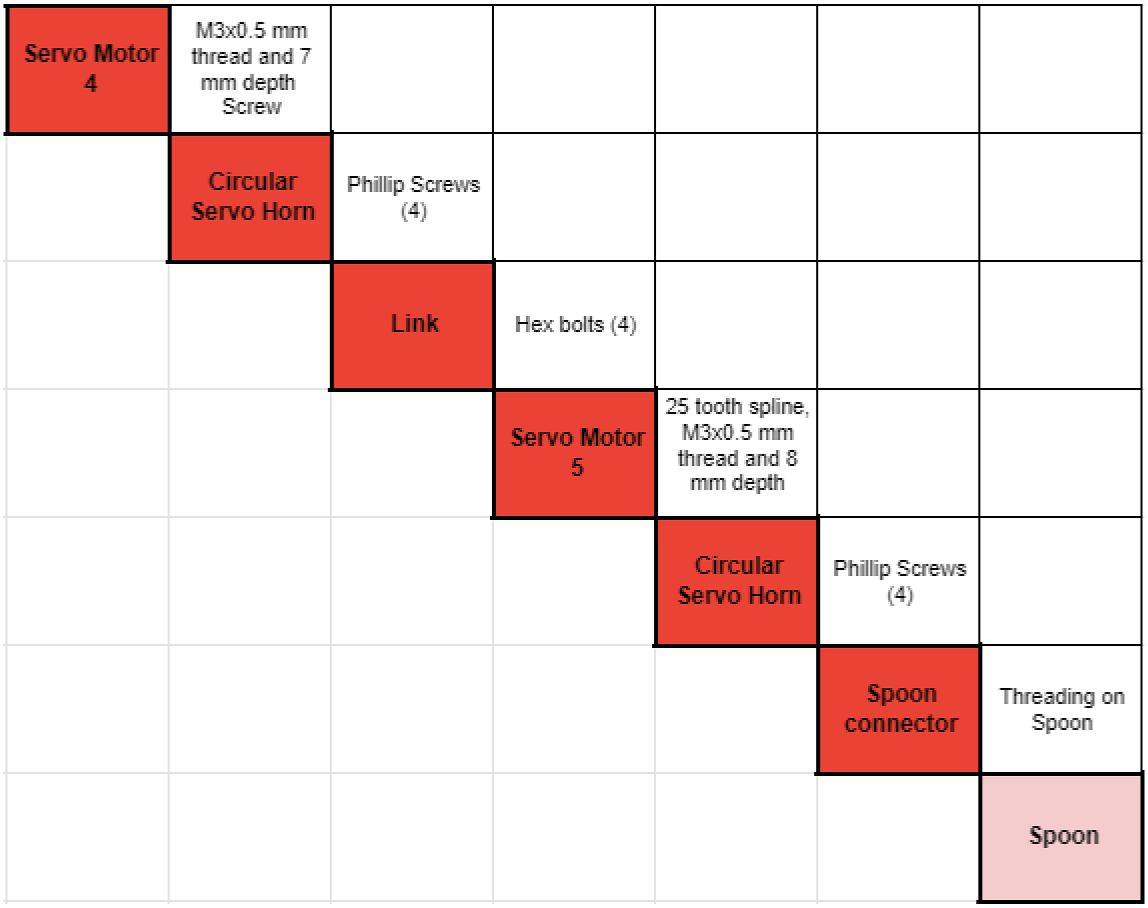
Motor Holder 1	Hex bolts (4)			
	Motor 1	Phillip Screw (1)		
		Circular Servo Horn 1	Phillip Screws (8)	
			Plate holder	Lock-in-slot mechanism
				Plate

F.4: *N2 Diagram for the Plate subsystem part 2*



Arm Base Casing	3D printed together					
	Motor holder 2	6-32 UNC Screw (x4)				
		Servo Motor 2 with gearbox	6-32 UNC Hex Bolt (x4)			
			Waist Joint	6-32 UNC Screw (x4)		
				Servo Motor 3 with gearbox	6-32 UNC Hex Bolt (x4)	
					Lateral	M8x1.0 mm Screw
						Servo Motor 4

F.5: N2 Diagram for the Arm & Spoon subsystem part 1



Servo Motor 4	M3x0.5 mm thread and 7 mm depth Screw					
	Circular Servo Horn	Phillip Screws (4)				
		Link	Hex bolts (4)			
			Servo Motor 5	25 tooth spline, M3x0.5 mm thread and 8 mm depth		
				Circular Servo Horn	Phillip Screws (4)	
					Spoon connector	Threading on Spoon
						Spoon

F.6: N2 Diagram for the Arm & Spoon supply subsystem part 2

APPENDIX G: FAULT AND EVENT TREES

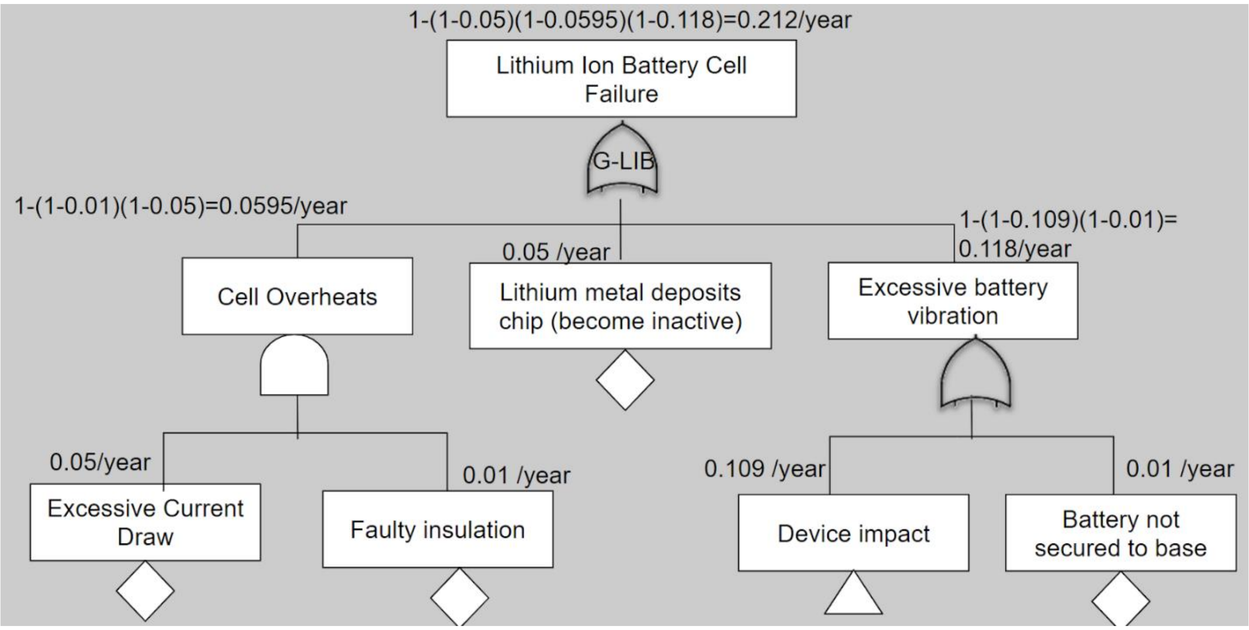
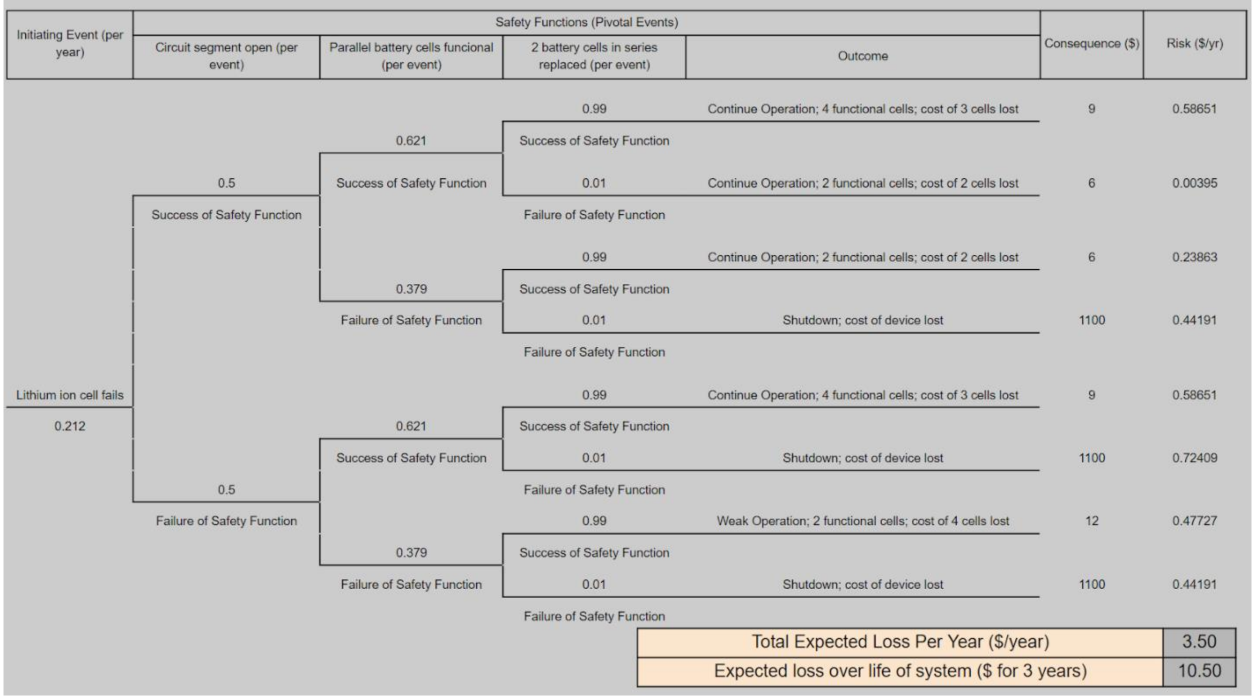


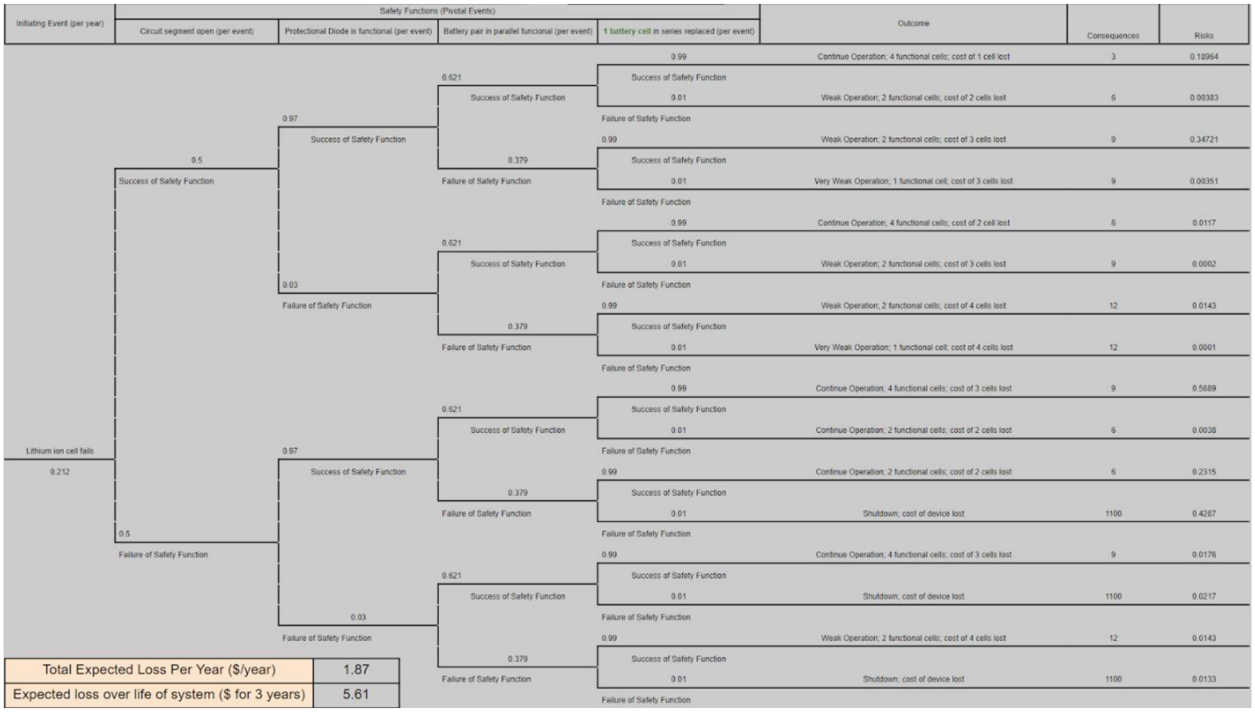
Figure G.1: Lithium Ion Battery Fault Tree



Initiating Event (per year)	Safety Functions (Pivotal Events)				Consequence ($)	Risk ($/yr)
	Circuit segment open (per event)	Parallel battery cells funcional (per event)	2 battery cells in series replaced (per event)	Outcome		
Lithium ion cell fails 0.212	0.5 Success of Safety Function	0.621 Success of Safety Function	0.99 Success of Safety Function	Continue Operation; 4 functional cells; cost of 3 cells lost	9	0.58651
			0.01 Failure of Safety Function	Continue Operation; 2 functional cells; cost of 2 cells lost	6	0.00395
		0.379 Failure of Safety Function	0.99 Success of Safety Function	Continue Operation; 2 functional cells; cost of 2 cells lost	6	0.23863
			0.01 Failure of Safety Function	Shutdown; cost of device lost	1100	0.44191
	0.5 Failure of Safety Function	0.621 Success of Safety Function	0.99 Success of Safety Function	Continue Operation; 4 functional cells; cost of 3 cells lost	9	0.58651
			0.01 Failure of Safety Function	Shutdown; cost of device lost	1100	0.72409
		0.379 Failure of Safety Function	0.99 Success of Safety Function	Weak Operation; 2 functional cells; cost of 4 cells lost	12	0.47727
			0.01 Failure of Safety Function	Shutdown; cost of device lost	1100	0.44191

Total Expected Loss Per Year ($/year)	3.50
Expected loss over life of system ($ for 3 years)	10.50

Figure G.2: Lithium Ion Battery Event Tree



Outcome	Consequences	Risks
Continue Operation; 4 functional cells; cost of 1 cell lost	3	0.18964
Weak Operation; 2 functional cells; cost of 2 cells lost	6	0.00383
Weak Operation; 2 functional cells; cost of 3 cells lost	9	0.34721
Very Weak Operation; 1 functional cell; cost of 3 cells lost	9	0.00351
Continue Operation; 4 functional cells; cost of 2 cell lost	6	0.0117
Weak Operation; 2 functional cells; cost of 3 cells lost	9	0.0002
Weak Operation; 2 functional cells; cost of 4 cells lost	12	0.0143
Very Weak Operation; 1 functional cell; cost of 4 cells lost	12	0.0001
Continue Operation; 4 functional cells; cost of 3 cells lost	9	0.5689
Continue Operation; 2 functional cells; cost of 2 cells lost	6	0.0038
Continue Operation; 2 functional cells; cost of 2 cells lost	6	0.2315
Shutdown; cost of device lost	1100	0.4287
Continue Operation; 4 functional cells; cost of 3 cells lost	9	0.0176
Shutdown; cost of device lost	1100	0.0217
Weak Operation; 2 functional cells; cost of 4 cells lost	12	0.0143
Shutdown; cost of device lost	1100	0.0133

Total Expected Loss Per Year ($/year)	1.87
Expected loss over life of system ($ for 3 years)	5.61

Figure G.3: Lithium Ion Battery Design Change Fault Tree

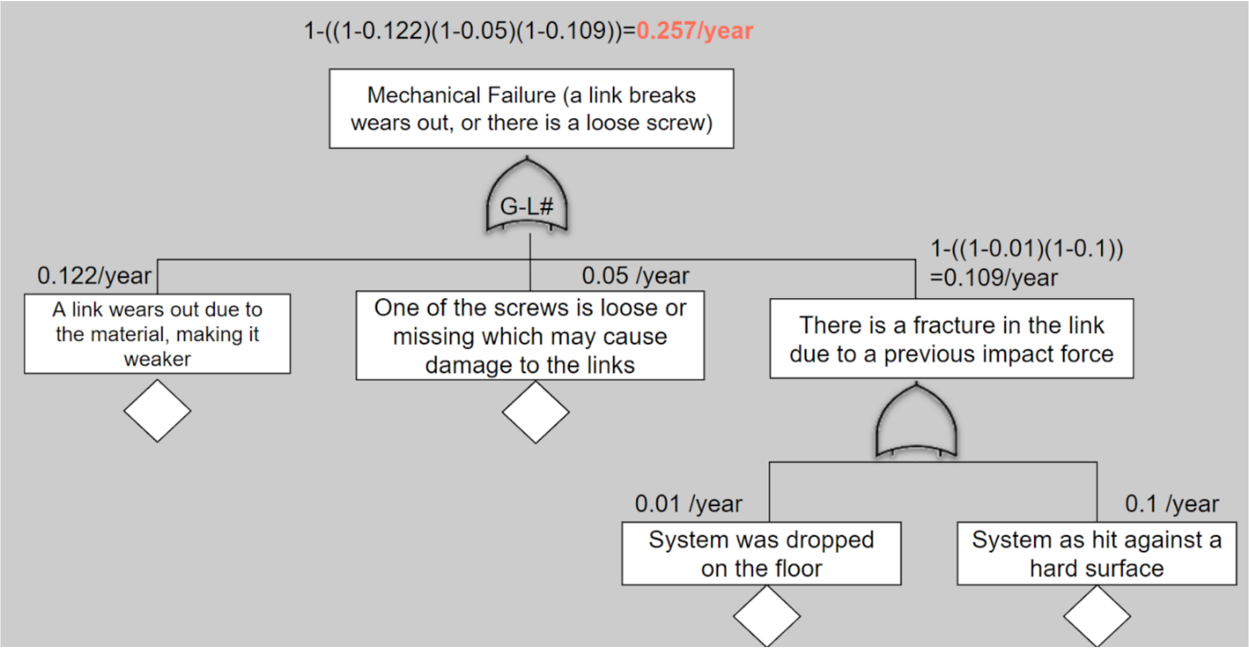
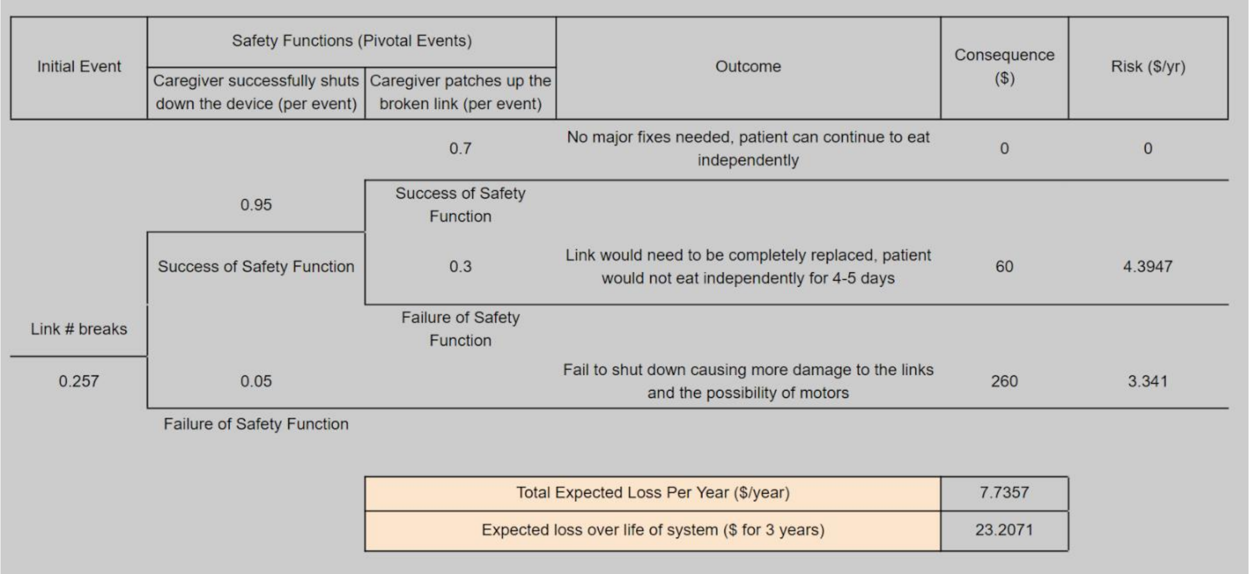


Figure G.4: Link Failure Fault Tree



Initial Event	Safety Functions (Pivotal Events)		Outcome	Consequence ($)	Risk ($/yr)
	Caregiver successfully shuts down the device (per event)	Caregiver patches up the broken link (per event)			
Link # breaks 0.257	0.95 Success of Safety Function	0.7 Success of Safety Function	No major fixes needed, patient can continue to eat independently	0	0
		0.3 Failure of Safety Function	Link would need to be completely replaced, patient would not eat independently for 4-5 days	60	4.3947
	0.05 Failure of Safety Function		Fail to shut down causing more damage to the links and the possibility of motors	260	3.341

Total Expected Loss Per Year ($/year)	7.7357
Expected loss over life of system ($ for 3 years)	23.2071

Figure G.5: Link Failure Event Tree

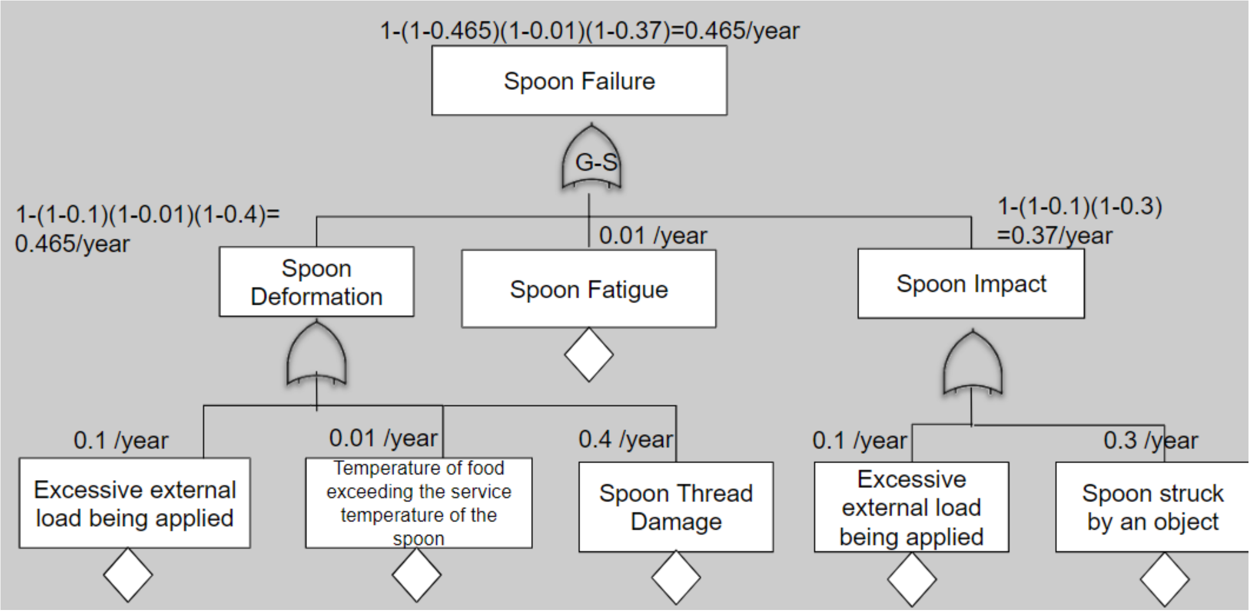
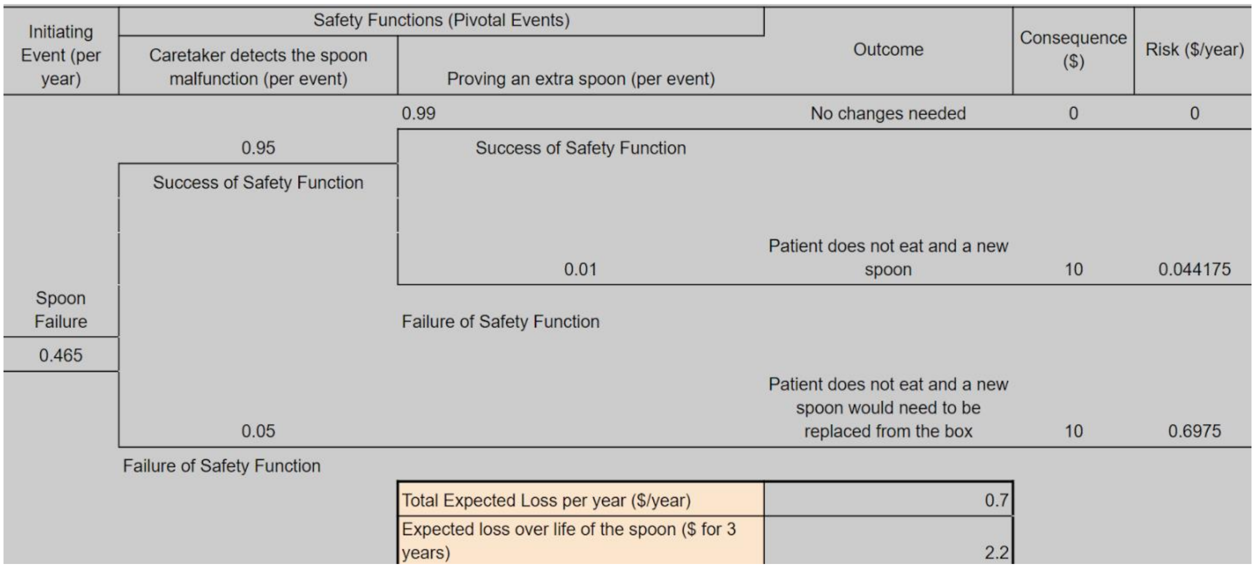


Figure G.6: Spoon Fault Tree



Initiating Event (per year)

Safety Functions (Pivotal Events)

Caretaker detects the spoon malfunction (per event)

Proving an extra spoon (per event)

Outcome

Consequence ($)

Risk ($/year)

Spoon Failure

0.465

0.95

Success of Safety Function

0.99

No changes needed

0

0

Success of Safety Function

0.01

Patient does not eat and a new spoon

10

0.044175

Failure of Safety Function

0.05

Patient does not eat and a new spoon would need to be replaced from the box

10

0.6975

Failure of Safety Function

Total Expected Loss per year ($/year)	0.7
Expected loss over life of the spoon ($ for 3 years)	2.2

Figure G.7: Spoon Event Tree

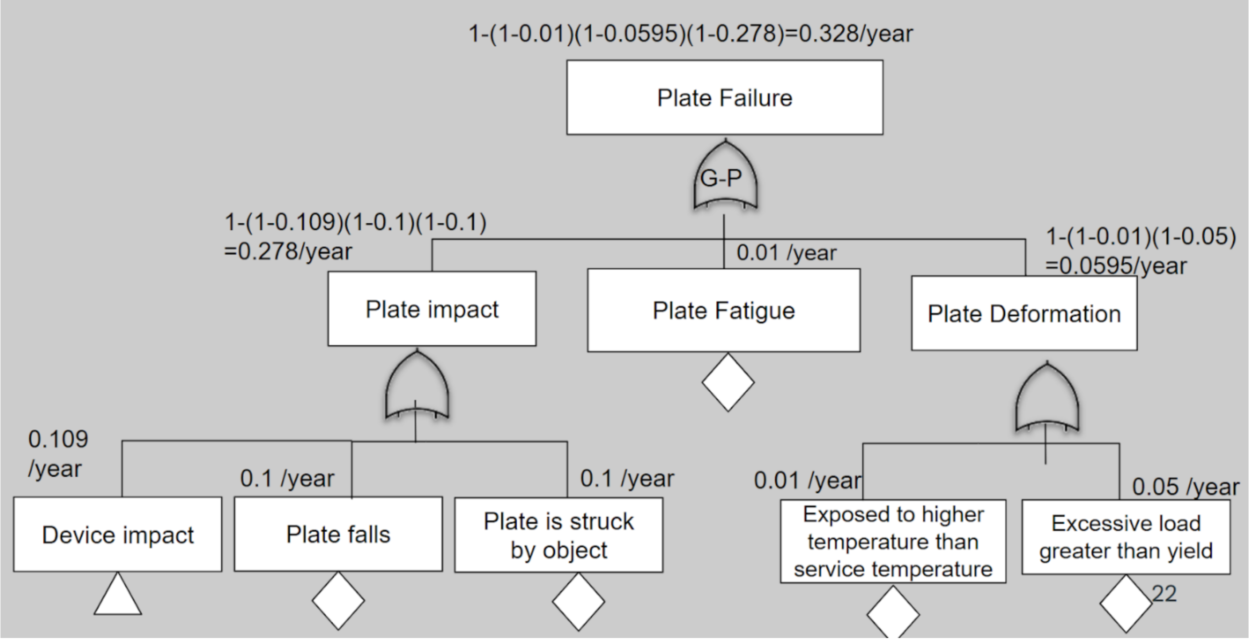


Figure G.8: Plate Fault Tree

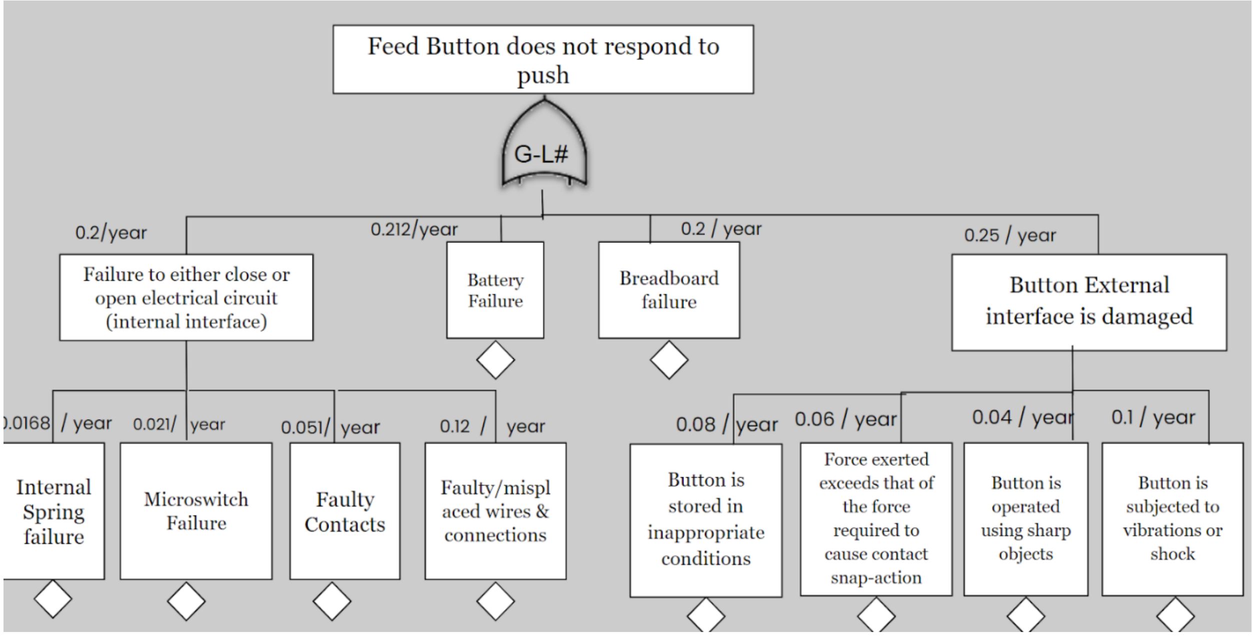


Figure G.9: Feed Button Fault Tree

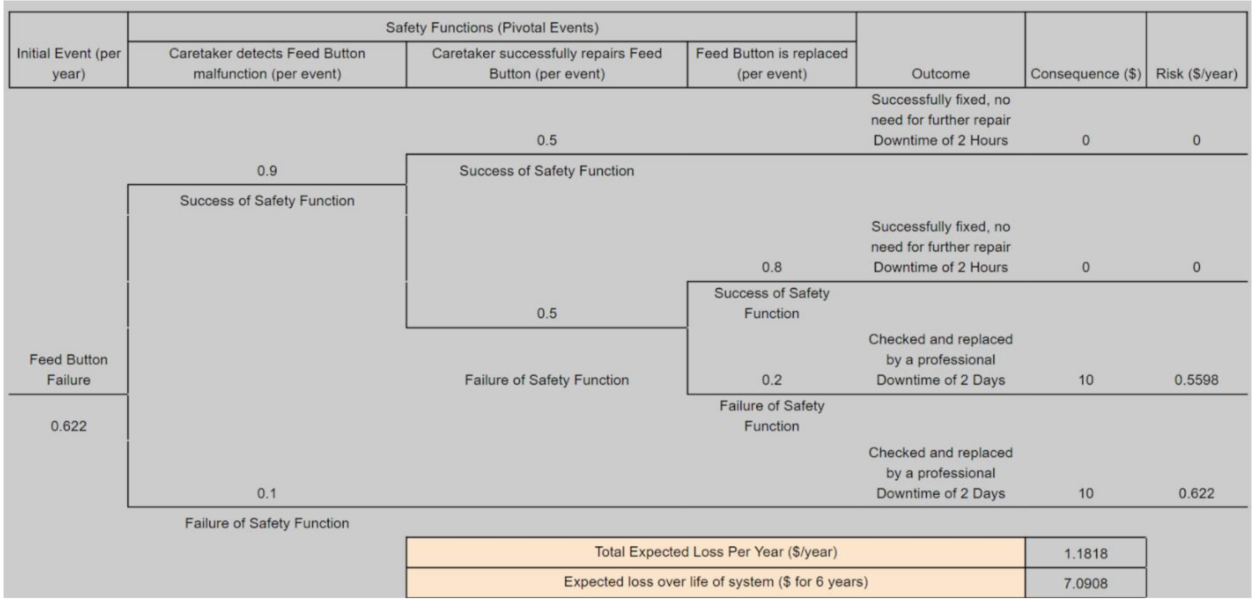


Figure G.10: Feed Button Event Tree

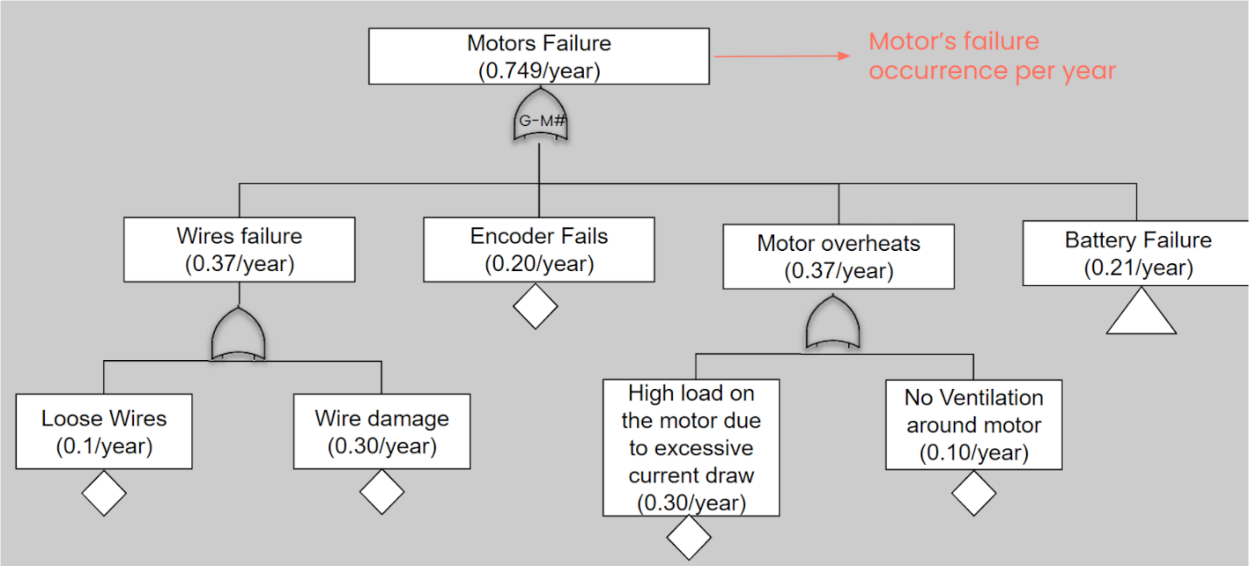


Figure G.11: Motors Fault Tree

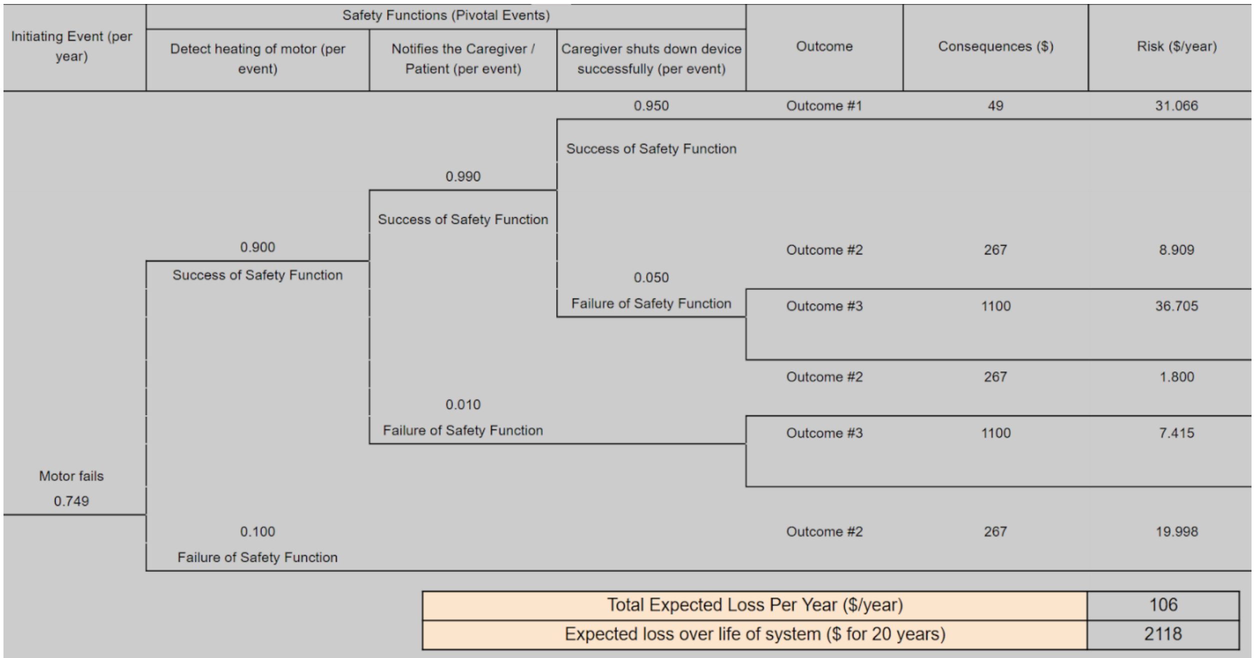


Figure G.12: Motors Event Tree

APPENDIX H: ENGINEERING DESIGN DRAWINGS

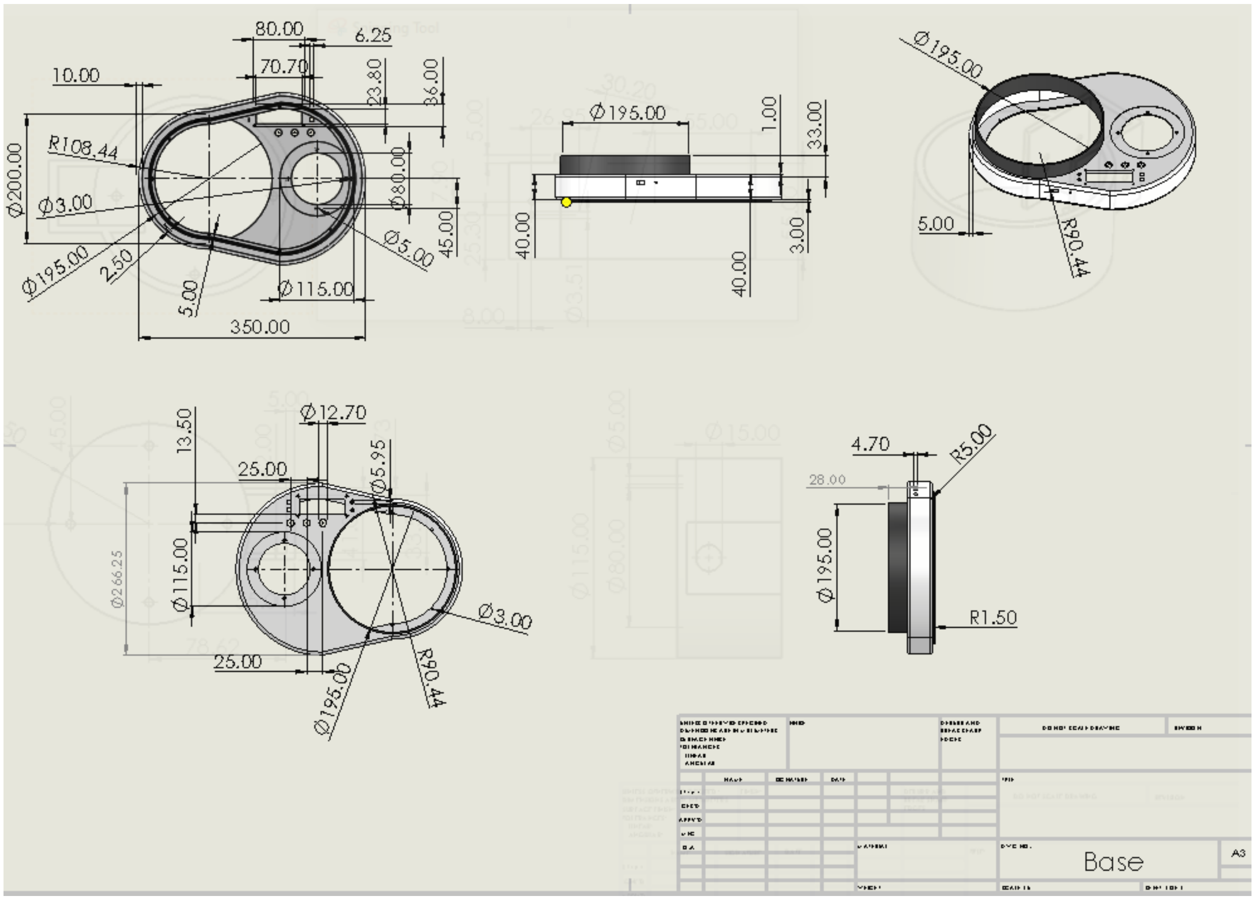


Figure H.1: Base Engineering Drawings

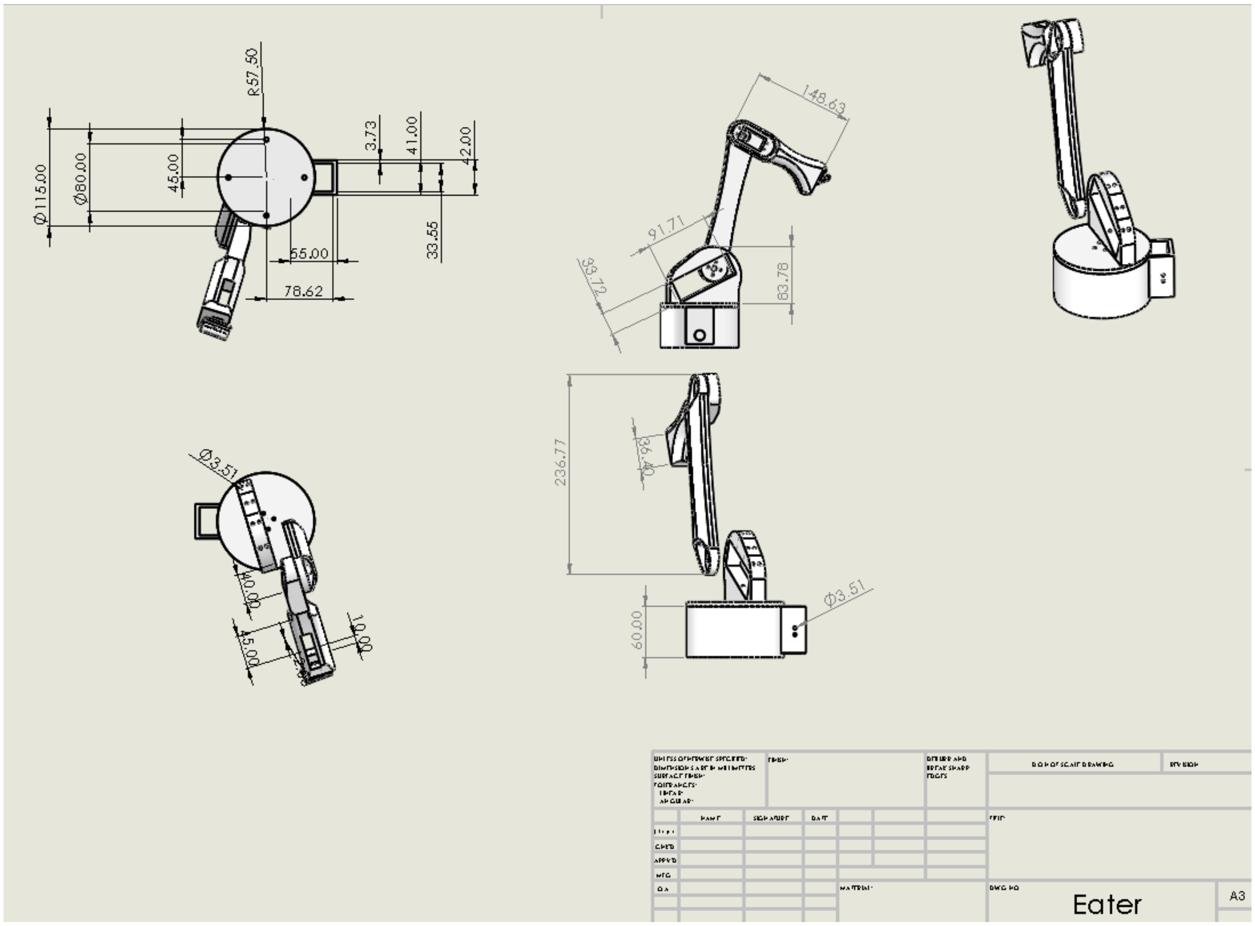


Figure H.2: Arm Base Engineering Drawings

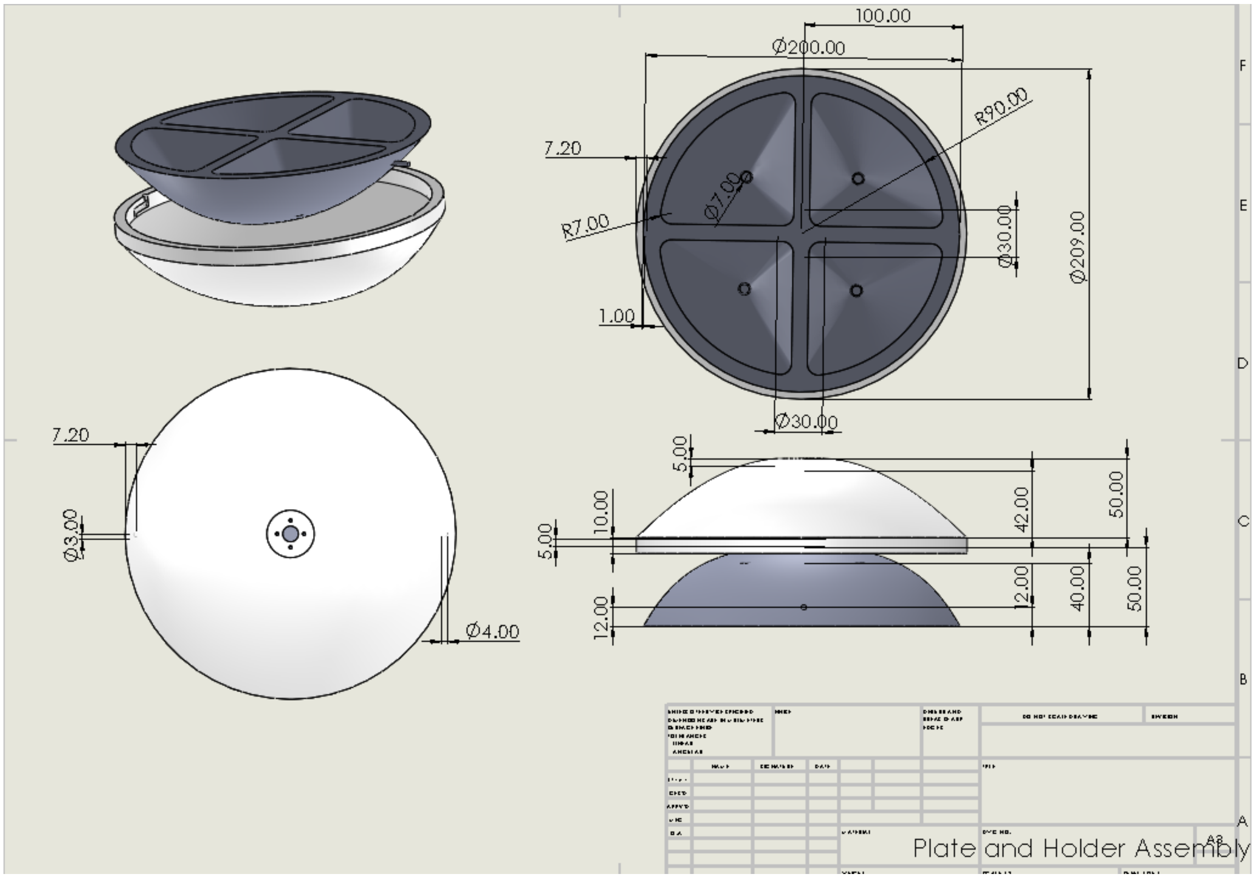


Figure H.3: Plate and Plate Holder Engineering Drawings