Active Prosthetic Hand

Final Report

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EXECUTIVE SUMMARY

There is a large need for inexpensive prosthetic devices for amputees. This project focuses on the below the elbow amputees. The active prosthetic capstone provides below the elbow amputees with a replacement hand that provides a sense of touch to the user. The project is important because it give the user a new hand that make daily tasks easier. This project has many requirements presented by the project sponsor, Dr. Kyle Winfree. The prosthetic must be able to sense touch, easily activated, lightweight, adjustable size, comfortable, customizable control, and more. The project was inspired by the ENABLE projects that provide simple prosthetic devices for amputees. The ENABLE prosthetic are provided on their website and the CADs allow people around the world to build inexpensive and effective prosthetics. The hands on the site are customizable for the individuals. It is the teams goal to create a more advanced that can provide a sense of touch and more control to the user. It will continue to be inexpensive and will be added to the ENABLE site for people around the world.

To achieve these goals, the team analyses the needs and requirements to determine the most important factors. These were weighted against each other in a house of quality (HOQ). The flow of inputs and outputs were used to determine the needed elements of the device. The team designed many possible prosthetics. These were unique and biologically inspired. The most important factors were used to determine the best design. The final design that was chosen was similar to many of the competing designs. The final design was based on the ENABLE hand. The changes to the ENABLE hand include sensors to detect touch, bluetooth control, and vibrating motors. The hand is designed in Solidworks and also includes an altered thumb that has a large range of motion. The team also performed individual analysis of different aspects of the hand. These analyses include the percent infill, crossestional shape, arduino code, and thermoforming of plastic. The design will incorporate the results from these calculations. For example the design will incorporate a cross sectional area that has the smallest moment of inertia and include a code that will move the hand by the instruction of the user. The mechanical team is teamed with a group of Electrical Engineers. The Electrical engineers will aid the team to code the motors to move prosthetic fingers. This hand includes the bluetooth control from the toes and the sensors that respond to touch.

The prototype for this new hand utilizes the original ENABLE Hand with alterations. The hand has motors that move the fingers and control sensors on the toes that give the user the ability to control the hand. At the fingertips, there are pressures sensors that sense signals and vibrate to notify the user of touch.

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1 BACKGROUND

1.1 Introduction

As technology continues to advance, change, and adapt, so do the needs of the community that creates them. In the current age, one important issue that many face today is finding a functional below-elbow prosthetic that can be adjusted for amputees of all ages and sizes. Without such a device, individuals cannot complete daily tasks as quickly or as efficiently as people with two hands. Others have stated that having a prosthetic provides them with a sense of normalcy compared to without. This project approached this issue by creating an active prosthetic device for amputees in need. The objectives of the project were for the device to be affordable, scalable, and provide sensory and haptic feedback technology for the user. Upon completion, not only will this device be useful for amputees, but it was also be affordable and easy to build, allowing for a larger group of people to benefit from this design. The design will also benefit the sponsor as well, as the successful design can be used as a basis to be improved upon for customers in the future.

1.2 Project Description

The following is the original project description provided by the sponsor:

> "Everyday, you take your sense of touch for granted. Your sense of touch is critical to how you interact with the world. Imagine for a moment that you have lost your hand. Maybe from an accident, maybe from an infection, or maybe even as a congenital condition. For persons with prosthetics, touch becomes a complex issue. Those with amputations are often eligible for prosthetic devices. However, for a variety of reasons such as cost and technology, these devices are rarely actively driven and almost never provide the user with a direct sense of touch. This project will seek to address the limitations of existing prosthetic technologies, by leveraging rapid prototyping technologies such as 3D printed materials and inexpensive embedded architectures, and will result in an inexpensive, customizable, actively controlled, and haptic enabled prosthetic for children in the Northern Arizona (NAZ) area who have a below the elbow amputation. It is expected then that this resultant product will be utilized by children in NAZ, changing how they interact with the world around them."

2 REQUIREMENTS

The requirements for the prosthetic hand project were determined by the customer needs and the engineering requirements. The customer requirements were provided by our sponsor, Dr. Kyle Winfree. These requirements were ranked based on their importance. In addition, the customer needs were used to clarify the objectives of the project. The provided customer needs were broken down into measurable parameters to produce the engineering requirements. Each engineering/technical requirement were verified against measurable parameters and conditions in order to display their respective importance. The customer and engineering requirements were compared to one another using a house of quality. This was an important part of the design process because it informed the team which needs should be focused on to satisfy the customer and engineering requirements.

2.1 Customer Requirements (CRs)

The customer needs were presented to the team by their sponsor, Dr, Kyle Winfree. The provided customer needs were extensive. In order to reduce and simplify the needs, many were clumped together to form the main customer needs. The list of requirements provided by Dr. Winfree can be seen in the table below.

Table 2.1: List of all Customer Needs and the Overarching Categories of Customer needs

Customer Need	Overarching Need	Weights
Scalable	Scalable	3
Lightweight	No pain or discomfort or strain/Lightweight	3
Electromechanical control	Haptic sensing system	4
Sense of Touch	Haptic sensing system	4
Relay aspects of touch	Haptic sensing system	4
Rechargeable	Customization	3
Customized Hardware	Customization	3
Customized Software	Customization	3
Available for download of design file	Customization	3
Aesthetically pleasing	Aesthetically pleasing	1
Easy to clean	Easy to clean	2
Durable	Durable	4
Comfortable	No pain or discomfort or strain	4
Reliability	Reliability	4
Low Cost	Budget	4

After condensing the many needs, the following main overarching needs were developed. The description of each need is provided below, and the weights can be found in Table 2.1.

- Aesthetically pleasing
    - This need involved the appearance of the device. The Prosthetic should have a pleasant appearance. This will please the user. The hand should be and look professional. This need received a low ranking as it was not as vital to the prosthetic design as the other needs.

- No pain or discomfort or strain
    - The residual limb can be very sensitive. So, it is vital that the prosthetic hand should be comfortable for the user. If the hand causes pain or discomfort, then the individual will be unwilling to wear it. Thus, this was an extremely important requirement and as such was ranked highly.
- Scalable
    - The Prosthetic needed to be scalable. This is because each individual has different physical dimensions. In order for the device to be successful, it must have features that allow the dimensions to change for each unique residual limb. This was kept in mind when developing concepts and choosing designs. So, this need received a ranking of 3 out of 4.
- Customization
    - The customizability involved the hardware, software, and the design file. The client asked that the prosthetic hand be customizable to each person. This requirement was similar to scalability. By following this requirement the device can be manipulated in many ways, including the shape. The design CAD file should be replicable by other engineers and customers. Thus, the client will be able to change the sizes of the hand to fit individual amputees. The software for motors and signals should also be controllable by the user. Therefore, the arduino code should be manipulatable. Because of the many aspects involved this requirement was ranked highly.
- Easy to clean
    - This was not as vital as others which is why it received a low ranking. The hand must be easy to clean. Thus, the materials and shape of the prosthetic should allow the amputee to cleanse the device with standard cleaning tools and their one other hand.
- Light weight
    - It was important that the prosthetic hand be lightweight because the user needs to be able to lift it without struggling. The residual limb is a sensitive area. So, weight on the limb can cause pain. By keeping the device lightweight, it will increase the comfort to the amputee. This was why this need was ranked highly.
- Durable
    - The customer will be using the prosthetic as if it were their original hand. The average person pushes, pulls, and lifts many items. The human hand also endures many impact stresses. Therefore, the prosthetic device must be made of strong materials and shaped to support heavy loads. The device must also be reliable and functional. Choosing durable materials and design shapes will the recipient with the most reliable and functioning hand.
- Haptic sensing system

    - The prosthetic device will simulate the human hand by sensing touch. Within the human hand the nerves send signals that tell the human brain that the hand is gripping an object. The device will not be exactly like nerves but it can provide a response to touching an object. This response can be heat, vibration, visual, etc. The most favorable by the client was vibration because it was the least distracting and still sends the message. The arm also should be able to move by the command of the user. The arm actuation should be easy. Therefore, this customer need received a high ranking.
- Reliability
    - The prosthetic arm must be reliable. This means that the arm constantly works and responds to user input. The arm should not break or perform actions that were not specified by the user. This is important because the patient will be using the arm constantly. Thus, the arm must be reliable and received a ranking of 4.
- Budget
    - This device needs to be low cost. One of the main goal of the project is to provide individuals with affordable prosthetics. Most prosthetics are very expensive but this device is meant to be affordable. This is important to customers because if they can not afford to have the device it is not effective in providing many people with the devices they need. Hence, this requirement also receives a ranking of 4.

These rankings show that the main objectives for this project. These objectives were to create a prosthetic arm that is comfortable, durable, and has haptic sensing. These highly ranked needs were kept in mind as the concepts were developed and designs were chosen. In addition, these customer needs were used to cultivate the engineering/technical requirements.

2.2 Engineering Requirements (ERs)

The engineering/ technical requirements are measurable parameters that the prosthetic hand must complete. These were derived from the customer needs and were created in a way that makes them quantifiable. Each of the technical requirements that were generated have set units and sizes. This can be seen in Table 2.2.

Table 2.2: List of technical requirements, target value, units, and overarching customer need

Technical Requirements	**Target value**	**Overarching Customer Need**
Scalable Size	6-18 in	Scalable
Weight	1.72 lbs	Light weight No pain or discomfort or strain
Budget	$500	N/A
Material Properties	10 lbf	Durable Reliability
Force to actuate	< 5lbf	No pain or discomfort or strain Comfortable Light Weight
Force of Grip	2 lbs	Functionality Reliability
Number of Parts	< 100	Customization Rechargeable Hardware Software Downloadable Haptic systems

This table condenses the engineering requirements, their target values, units, and the customer need that it stemmed from. The table was a concise explanation of the technical requirements.
The technical requirements were as follows:

- Scalable Size
  - The active prosthetic must be able to change size to accommodate the customer need of scalability. The length of the forearm, fingers, and other parts of the hand must be adjustable to allow the device to be proportional to the amputee's body. The average human arm is 12 inches long. The individuals also have lost their limbs at differing locations along the arm. Thus, the size of the arm should be adjustable from approximately 6 to 18 inches. Similarly, the diameter of the human arm varies for each individual. The range for diameter should be between 1 and 3 inches. This can be achieved by creating Solidworks CAD drawings that accept dimensions while still keeping the hand at the proper proportions for functionality.
- Weight
  - The weight engineering requirement was derived from the lightweight customer need. The user needs to be able to lift it without struggling. The residual limb is a sensitive area. So, weight on the limb can cause pain. By keeping the device light it will increase the comfort to the amputee. The weight of the arm should not exceed the patient's ability of lifting. The average weight of a human arm is 1.72 pounds. This should not be exceeded by the prosthetic arm.
- Budget
  - The device should not cost more than $500 to create. One of the purposes of the project was to design a prosthetic that is affordable and functional. In order to do so, the materials to build the hand should not exceed the budget limit.
- Material Properties
  - The material properties were derived from the durability customer requirement. The arm needs to be strong enough to support the forces, torques, stresses, and strains of common uses. The material must be able to withstand at least 10 pounds of force. If the arm can withstand the dropping force of 10 pound, it should withstand the wear and tear of daily life. This will allow the user to grab lightweight items and perform simple tasks. Another material property is malleability. If the material is easy to shape it makes it easier for the construction of the device.
- Force to actuate
  - The arm actuation is the force required to activate the hand motion. The amount of force applied by the patient should not exceed 5 lbf. This parameter was derived from the need for the no discomfort. If the individual overexerts their

muscles this causes pain. Therefore, actions should be taken to keep the actuation smooth and easy for the user.

- Force of Grip
  - The hand must be able to grasp an item. This technical requirement stems from the customer need of functionality. If the prosthetic is not successful in grabbing an item then it is useless to the patient. The fingertips must be able to apply forces to close around and hold an object. The minimum force is 2 lbs. The figures must be able to support at least this weight and the arm must be able to handle of the torque caused by the weight and distance.
- Number of Parts
  - The number of parts should remain small in order to keep the cost and complexity of the design low. This allows it to be more customizable and fills the respective customer need. In order to keep the design simple and manipulatable, the number of parts should not exceed 100.

2.3 Testing Procedures

This section discusses the testing procedures for each of the engineering requirements. Each requirement is listed in the same order as above. These procedures will describe the methods to test scalability, weight, budget, material properties, force of actuation and grip, and number of part. Reliability and durability were directly related to the material properties as described below and therefore were not given their own testing procedure separate from material properties.

2.3.1 Scalable Size

Testing the scalability was done by printing more than one arm. The first arm was printed using the client's measurements, the second arm was printed using only the scale feature for the gcode converter. The second arm was scaled to the smallest team member's size. If the arm fits the team member and can still function as designed, then it was considered scalable.

2.3.2 Weight

Once the arm was printed and assembled it could be weighed using a scale from the WIL lab. The client's functioning arm will be measures as well and either weighed using a scale or a calculated estimation. The weights will then be compared and if the printed arm was less than five percent above the weight of the functioning arm then it qualifies for the weight requirement.

2.3.3 Budget

The budget was done using Excel. After the arm was fully assembled, the cost of all parts were added to the Excel spreadsheet, along with all identifiable information for each part, and the supplier. With all parts tabulated the end cost was calculated to $492 USD without shipping. Since all parts, both mechanical and electrical, are below $1000 USD, the product meets the budget requirement.

2.3.4 Material Properties

The material properties include strength, durability, and thermoformability. Strength was tested be tested using an impact load. This was done by releasing a mallet from a 90-degree angle that swung into thin and joint features of the prototype arm. The impact force was be calculated by the weight of the hammer and gravity. The number of impacts before fracture gave an estimate of the durability and strength of the arm. As for thermoformability, this was tested by applying a heat source to flat pieces of different plastics. Since the plastic can be formed with temperatures lower than 100 °C, the material meets the thermoformability requirement.

2.3.5 Force to actuate

Force of actuation was tested by adding pressure sensors to the inside of the prototype cuff. When the device was being actuated, the force exerted by the client on the device was be measured by the pressure sensor. The force can then be calculated by dividing the pressure readout by the area of the pressure sensor. Since the sensor required below 5 N to actuate the motors, the device was within the requirement.

2.3.6 Force of Grip

Similarly to the force of actuation, a pressure sensor was placed at the end of the fingertip between the thumb and first finger. The pressure was divided by the area of the sensor and used to calculate the force exerted by the grip. If the force exceeds 5 N, then the force of girp was within the requirement.

2.3.7 Number of Parts

When the final product was designed the number of parts was counted using the Excel sheet from the budget. If the number of parts does not exceed 100 pieces then the device was within requirements.

2.4 House of Quality (HOQ)

The House of Quality (HOQ) aided the team in computing the most important engineering/technical requirements. This was achieved by ranking the engineering requirements against themselves and the customer needs. The engineering requirements and customer needs were the same that were presented previously. The customer needs rank remains the same as do the target values for the technical requirements. This can be seen in the table below. Within the

HOQ the engineering requirements were given rankings for how well they fulfill the requirements. The rank of each was weighted by the importance of the respective needs. This was summed and displays to the team which engineering requirement was most important when designing the prosthetic.

Table 2.3: HOQ displaying the comparison of customer and engineering requirements.

System QFD

Project: An Active Prosthetic Device
Date: September 16, 2018
Input areas are in Blue

Legend
A E-Nable Hands
B Animal 3D printed Prosthe
C Prosthetic that feels pain

		Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip	Number of Parts
1	Scaleable Size							
2	Weight							
3	Budget							
4	Material Properties			-3				
5	Force to actuate	3	-3		3			
6	Force of Grip				3	9		
7	Number of Parts	3	3	-3				

	Customer Needs	Customer Weights	Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip	Number of Parts	1 Poor	2	3 Acceptable	4	5 Excellent
			Technical Requirements							**Customer Opinion Survey**				
1	Aesthetically pleasing	1	9	0	3	0	0	0	1			ABC		
2	No pain or discomfort or strain	4	3	9	0	3	9	6	3	C		B	A	
3	Scalable	3	9	3	3	3	3	0	6		C	B	A	
4	Customization	3	9	3	3	1	3	6	6			C	AB	
5	Easy to clean	2	0	0	1	3	0	0	3		ABC			
6	Light weight	3	3	9	1	9	1	0	6		C	B	A	
7	Durable	4	1	3	0	9	1	3	3		C	AB		
8	Haptic sensing system	4	0	0	9	0	9	9	0	AB				C
9														
10														
11														

	Scaleable Size	Weight	Budget	Material Properties	Force to actuate	Force of Grip	Number of Parts
Technical Requirement Units	in	lbs	$	lbs	lbf	lbs	#
Technical Requirement Targets	6_18	1.72	500	10	<5	2	<100
Absolute Technical Importance	88	93	62	93	97	90	85
Relative Technical Importance	5	2	6	2	1	3	4

Table 2.3 shows the HOQ. This HOQ was successful in computing and ranking the most important technical requirements relative to the customer needs. According to the calculations, the most important engineering requirement was the force to actuate. As stated in the engineering

requirement section, the force to actuate was important because the patient should not strain their muscles to move the prosthetic. Therefore, the team will make the ease of motion a priority. During design generation, devices should include ways to decrease the force needed to move the arm. Similarly, during concept selection the final design chosen should be actuated using the target force, 5 lbs. The other main engineering requirements to consider during concept generation and selection were weight and material properties.

The engineering requirements were also plotted against themselves. Most requirements have positive or no correlation with the others. However, some requirements contradict one another. Thus, the team must decide which requirement was more important and compromise or forego the other. An example of this was budget vs material strength and number of parts. Since the material strength in highly ranked and important, the budget may need to be altered to accommodate the best materials. It was better to have a higher cost and quality prosthetic than a prosthetic that was non-functional. This will be important during concept design and selection. By defining the customer needs the team was successful in derving engineering requirements. These were analysed using the HOQ to rank the most important requirements.

3 EXISTING DESIGNS

In order to begin the concept generation in the design process, existing designs was evaluated and compared to determine characteristics that were important in order to meet customer requirements. This section contains details of the benchmarking research process, system level benchmarks, subsystem level benchmarks, and flow charts of problem decomposition which were used to determine necessary components while researching quality benchmarks. The system level existing designs relate directly to below elbow prosthetics, while the subsystem existing designs relate to aspects or characteristics the prosthetic will need to contain.

3.1 Design Research

To start researching existing designs, the team looked at volunteer chapters of Enable [1] in order to consider the current design that is easily printed for anyone. While researching benchmarking, the team was looking for qualities that met the customer requirements. The specific characteristics used as reference were means of secure attachments, mechanisms for motion, and types of feedback sensing to the user. These characteristics were most important to the final design because the active prosthetic needed to be able to grip onto things in order to be usable, the user needed to be able to control the motion of the arm in an easy and logical manner, and the prosthetic needed to be active so that the user can feel a sense of touch or motion.

When benchmarking, the team conducted web searches of prosthetics for below elbow amputees that had the specific characteristics the team was looking for. This was done through web searches and meetings with the client in order to gain recommendations on areas of research. Most designs researched involved nerve connections and high budgets, something not suitable for the Capstone team. One of the criteria important when evaluating quality benchmarks were estimating the cost of production as well as the market cost of the design. Part of this project was to design an active prosthetic that is affordable and makeable for almost anyone, anywhere in the world. Thus, the team evaluated the cost of the benchmark. The team also evaluated the mechanism for motion; whether the prosthetic was actively controlled by a motor or controlled by motion. Finally, the team made sure to research existing active prosthetics in order to determine probable sensors to use and how the feedback would reach the user.

3.2 System Level

This section discusses organizations and their products that relate to affordable prostheses. The organizations selected were e-NABLE, Open Bionics, and Limbitless Solutions. Organizations were selected instead of individual products, because each of these institutions specialize in making unique prosthetic hands and arms, and all of the products meet at least one or more of the customer requirements.

3.2.1 e-NABLE: "Enabling the Future [1]"

e-NABLE is a world-wide community of volunteers that design, fabricate, and assemble 3D printed prosthesis [1]. This description is important because it shows that e-NABLE's designs meet five of the customer needs. First, it states that the arms are 3D printed, which meets one of the customer requirements. Since the group includes volunteers from around the world, it can be assumed that these arms are easy to build, affordable, scalable, and customizable. This was insinuated because volunteering means that no one is being paid for their time and that resources are likely donated or out of pocket. Also, volunteers do not always share the same skills, therefore these design must be easy to build. The designs are given to both children and adults so they must be scalable. Finally, since this is a worldwide community, the designs must be customizable to fit with different sizes, interests, and cultures. All of these traits are displayed in Figure 3.1.

Figure 3.1: Volunteer scouts assembling unique e-NABLE hands [1].

There were some customer requirements not met by these designs. These designs are mechanically actuated by the elbow but the customer requires active actuation. In addition, there was no haptic feedback for object sensing, which was another customer requirement [1]. The hand systems designed by e-NABLE meet many but not all customer requirements. Therefore, they were a good example for benchmarking.

3.2.2 Open Bionics: "Turning Disabilities into Superpowers [2]"

Open Bionics' prostheses are 3D printed and use active actuation. Each arm is uniquely made for the recipient, and the company uses shells over the prosthesis to create aesthetically pleasing arms. In Figure 3.2, the bionic arm is shown with an intricate pattern designed by the company called the Handala cover. The colors for this cover can be changed and there arm more covers available by request.

Figure 3.2: Bionic arm with Handala cover [2].

The Bionic arms meets three of the customer requirements and one customer need. The requirements were to be 3D printed, actively actuated, and customizable. The customer need that was satisfied was aesthetically pleasing. However, the arms do not give any indication that they were scalable or if each arm must be redesigned for the recipient. The arms were significantly cheaper than average prostheses but still cost about £5000 or $6523 USD and the covers cost more than a typical e-NABLE hand at £400 or $522 USD [2]. These prices continue to make the arm unaffordable to low income clients.

3.2.3 Limbitless Solutions: "Creating Hope with 3D Printed Limbs [3]"

Limbitless Solutions is much like e-NABLE. They have volunteers around the world that create custom arms at no cost to the recipient [3]. These arm meet the same five customer requirements as e-NABLE but they are also actively controlled. Figure 3.3 shows three customized designs from Limbitless Solutions.

Figure 3.3: Arms provided by Limbitless solutions [3].

While this organization's hands appear to meet the majority of the customer requirements, they do not meet one of the most important requirements of including haptic feedback. The goal of this project was to not only meet but exceed these benchmarks and give the recipient a sense of touch.

3.3 Functional Decomposition

The functional decomposition of the prosthetic hand begins with a black box model. The model focuses on the inputs and outputs that lead to the hand closing and gripping an item. The hand grasping an item was the main function of the prosthetic. After these inflows and outflows were determined, the process diagrams for specific flow were detailed. This breaks down the action of gripping objects into subsystems. These subsystems were customized hardware and software, electronic control, arm actuation, and sensing touch. The process diagram includes details on how the flows changed at each step to perform the action of grabbing. These models and diagrams show the team that in order for the prosthetic to be successful, every change in the flow must be considered for energy, materials, and signals.

3.3.1 Black Box Model

The Black Box Model was important because it displays the required material, energy, and signals needed to perform a task. This was the most important customer need. The main task that the prosthetic hand executes was to close the hand and grip items. The Black Box Model also presents the outputs of material, energy, and signals from the action. This model was advantageous because it simplifies the customer needs to the inputs and outputs. The figure below shows the Black Box Model that aided in the decomposition of the prosthetic hand. It displays the inputs and outputs necessary for closing the prosthetic and gripping and item.

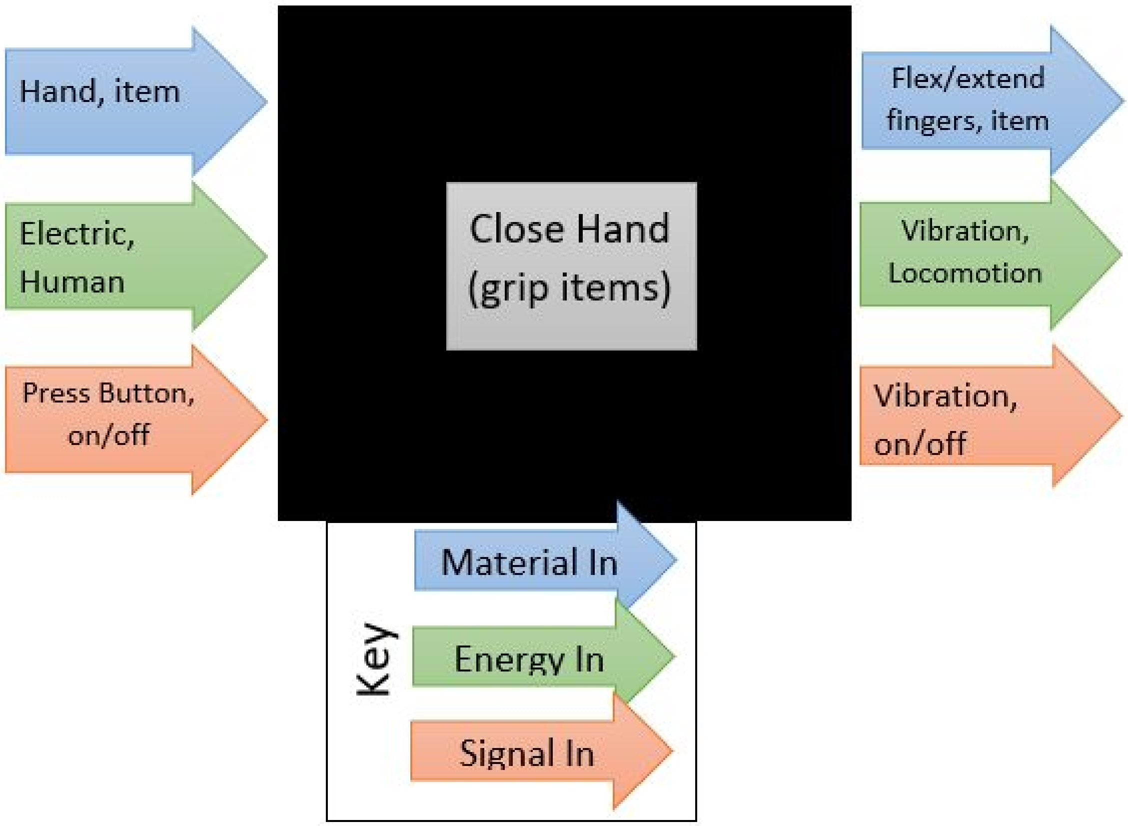


Figure 3.4: Black Box Model

The material inputs to grip items include the hand and an item. The hand is required to turn on and activate any switches. The item was needed because it will be gripped when the hand closes. These inputs and the other inputs can be viewed in the figure above. The energy input includes the electric and human energy. The electricity will supply energy to the motor to actuate the arm and the motors that vibrate the sensors. The signals that are sent in are pressing buttons and viewing on/off switches. Pressing the button will send a message to the motors and the hand will move. The on/off indicates whether the motors are on or off. Knowing the required inputs helps the team because it provides a basic understanding of what will needed in the conceptual and final designs.

The outputs of the Black Box Model re flexed/extended figures, the item, vibration, locomotion, and on/off. The item remains a material throughout the process. The energy is changed from the inlet into vibration and locomotion. This means that the hand will change position and the figures are flexed or extended. The vibration also was an output signal because it vibrates against the human skin to notify the user of the action that has been performed. By knowing the outputs the team will be aware of how the hand should respond. The final design will include a vibration signal, locomotion, and electricity.

3.3.2 Work-Process Diagram

The Process Diagram was a useful tool that breaks down the flow between inputs and outputs of the system. Each of the flows performs a task that was needed for completing a customer need. Unlike the black box model, these diagrams show how the flows change in order to perform the task at hand. The subsystems that were analyzed were customized hardware and software, electronic control, arm actuation, and sensing touch. The figures for each and explanations are available below. Each provides unique flows and demonstrates that the completion of the action was dependent on more than the materials, signals, and energies that enter and exit.

The first process diagram breaks down the process to customize the hardware. A customer requirement was that the device design must be replicable. This allows the user to create the device on their own without the need of a trained engineer to build it. In order to do this, the user will be provided a CAD file that can be changed to the desired dimensions. The figure below shows the flow from computer signal to customized hardware.

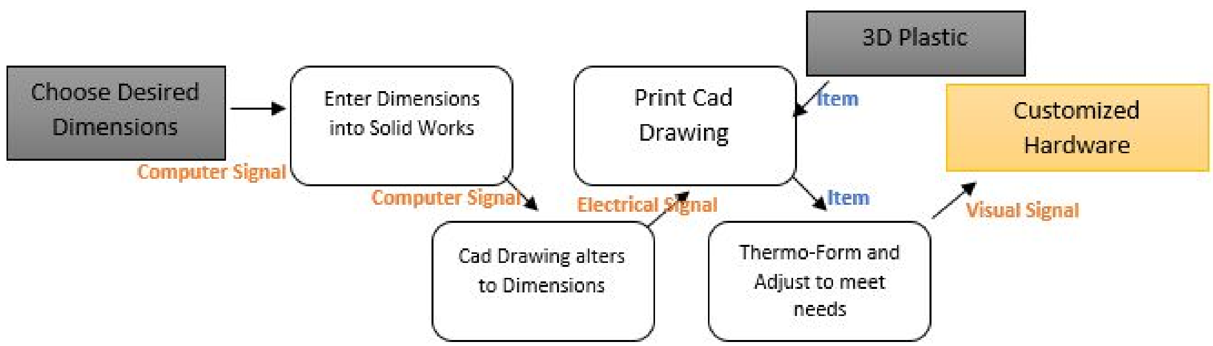


Figure 3.5: Process Diagram for Customized Hardware

The chosen dimensions were sent through a series of computer signals to electrical signals. The process also involves a 3D printer and the plastic to build the design. Thus, for the need to be met, the CAD files will need to be available and changeable. In addition, the 3D printer must have the proper signal and plastic that allows the hand to be printed and thermo-formed. The result is the visual signal that the hand is the appropriate size and shape. Each step of this process was important to consider when designing the active prosthetic.

The second subsystem was to give the hand a sense of touch. This process involves the passing of many signals. Below is the process diagram showing how the flow travels.

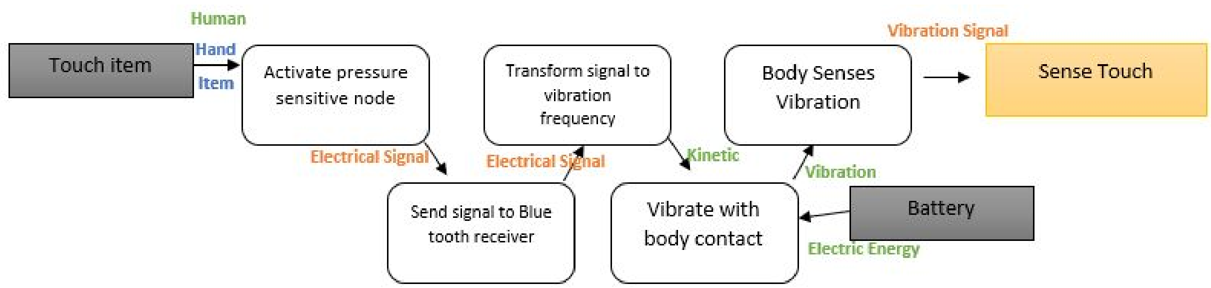


Figure 3.6: Process Diagram for Sense of Touch

This process begins with the prosthetic hand touching an object. At the fingertips, there are pressure sensors that send a bluetooth signal to the battery powered vibrators. The battery energy changed to a vibration and kinetic energy. The vibration on the skin sends a signal to the nerves of the user. Thus, the hand stimulates the sense of touch. This process requires batteries, sensors, emitters, and receivers.

The next subsystem was to customize the software. The code was designed to perform different actions and grip types. The flow diagram can be viewed below in the figure.

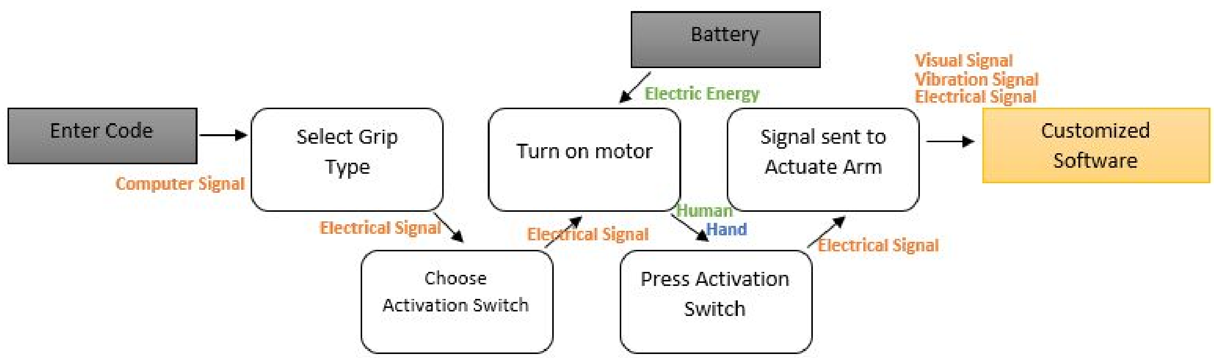


Figure 3.7: Process Diagram for Customized Software

This subsystem takes the coded signal and that signal was sent to a battery powered motor that actuates the arm. To complete the task, the team will need to include motors, batteries and switches. This was considered during concept selection and generation.

The electronic control was the fourth subsystem. The flow can be seen below.

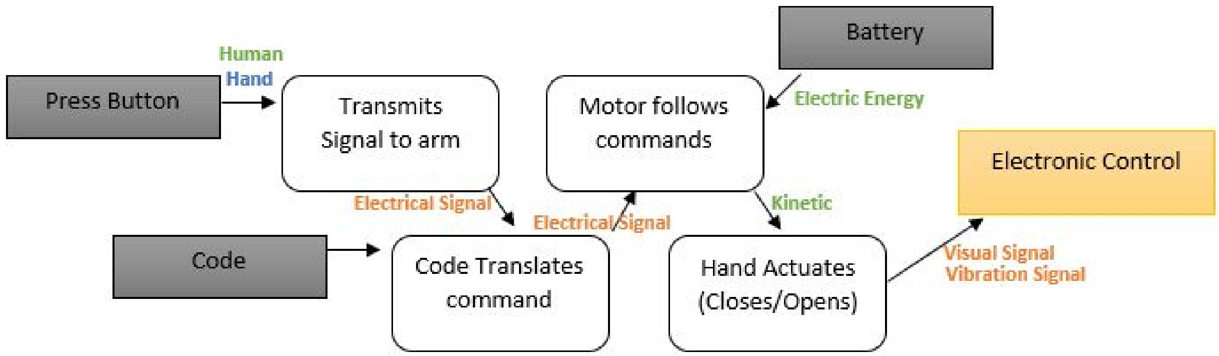


Figure 3.8: Process Diagram for Electronic Control

The electronic control requires code, button pressing and a battery as inputs. The button sends a signal to control the motor and actuate the hand. The energy from the battery become the motion of the arm. Therefore, a battery and code are needed to do the action.

The final subsystem was the arm actuation. This actuation can work separately or in tandem with the electronic control. The elbow bends and a series of kinetic energy transfers are sent through the arm and it is actuated. This can be seen below.

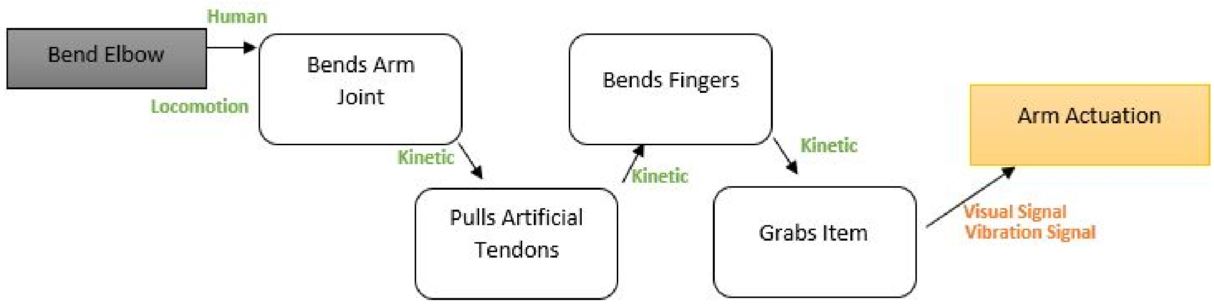


Figure 3.9: Process Diagram for Arm Actuation

This process diagram can be aided and linked to the electronic control because the electronic control also moves the arm and fingers. The electronic control will reduce the amount of work needed by the user. This was important to consider during the design of the arm.

The Process diagrams above aid the team by determining the many steps needed to complete a task. The needs will help determine if the design will fulfill the needs of the customer. For the prosthetic hand will be transmitters, receivers, batteries, motors, switches, codes, and adaptable solidworks drawings. All of these aspects will aid in creating a prosthetic hand that fulfills the needs of the user.

3.4 Subsystem Level

This section covers designs that could satisfy three different subsystems of the active prosthesis. These subsystems were haptic feedback, actuation for gripping, and attachment. Each of theses subsystems were important to the functionality of the design in order to meet the customer needs and requirements.

3.4.1 Haptic Feedback: Giving the User a Sense of Touch

Haptic Feedback was one of the most important subsystems because it was one of the main customer requirements. Different types of haptic feedback include tactile vibration, warming, and pressure. All of these types of user feedback can be shown or made similar to existing products.

3.4.1.1 Tactile Vibration: Cell Phone and Game Controller Vibration

Tactile vibration is used in everyday objects such as cell phones and video game controllers as a method of informing the user of some input [4]. This vibration can be used in the prosthetic design to notify the user that they are touching something. Vibrations could even intensify with increased grip as they are done in gaming controllers.

3.4.1.2 Warming: Electric and chemical Warmers and Gloves

Temperature feedback was not often addressed in prosthetics but could be implemented much like electric and chemical hand warmers. Since chemical warmers are for one time use, electric hand warmers may be more applicable to the prosthetic design [5]. This should be easier to implement in an active device since an energy source will already be needed. This energy source could cause a small heat pad to warm up with current when objects that are warmer are detected.

3.4.1.3 Pressure Sensing: Inflatable Pads

Inflatable pads such as blood pressure cuffs can be used to provide force feedback [6]. The tighter the grip on an object the tighter the pressure cuff can inflate. This could allow the user to pick up more delicate or heavier objects by informing them of the strength of their grip.

3.4.2 Actuation: Gripping Objects

Actuation was a necessity to any semi-function prosthesis. There were many solutions to actuation but they were often hard to implement into the device and usually cause the device to be more expensive and heavier. The listed solutions here are elbow actuation, motor actuation, and pressure actuation. Actuation in this subsystem was defined as what makes the prosthetic grip and not what starts or controls the gripping process. This subsystem was a key component to the functionality of the active prosthesis.

3.4.2.1 Elbow: Mechanical Actuation

Some bench marked designs mentioned previously use mechanical actuation from the elbow to grip objects. This forces the user to bend their elbow in order to actuate the device and can be uncomfortable and difficult to position the hand to grip an object. Though this in not an ideal actuation and does not satisfy the active prosthesis requirement, it is an important solution to making prostheses more affordable and lightweight. This actuation could still be used in parallel to another form of actuation that could result in a better gipping force while keeping the assisted actuation lightweight and inexpensive.

3.4.2.2 Motor: Electrical Actuation

Motor actuation would satisfy the need for the prosthetic to be active. This would increase the weight of the prostheses but is commonly used in myoelectric prostheses such as the bionic arms. This also increases the cost, however can be made affordable with gear systems and mechanical leverage.

3.4.2.3 Pressure: Pneumatic or Fluid Actuation

Increasing and decreasing pressure through a series of tubes can also be used for actuation. This was shown in productions that use pneumatic pistons or fluids to mechanically control and actuate different parts of a machine. Using hydraulics as a form of actuation could weight but may lower the cost of the system.

3.4.3 Attachment: Securing the Device to the User

Attachment of the device was another necessary component to a functional device. If the device does not properly attach then it cannot be used by the recipient for its intended purpose; being a prosthetics arm.

3.4.3.1 Cuff: Device Formed to Wrap Around User

Nearly all of the benchmarked designs use a cuff to engage the users arm. Though these cuffs often have additional properties that assist with securing the device, the cuff continues to be the most practical form of attachment. Cuffs allow the users arm to held in the device and add to the appearance that it is an extension of the arm and not a separate object.

3.4.3.2 Hook and Loop: Using Hook and Loop to Secure Attachment

The benchmarked system e-NABLE uses hook and loop attachment to secure their cuffs to the arm. Hook and loop makes the arm easy to attach and detach using one hand as needed. It also allows for adjustability for comfort and alignment to the arm. Hook and loop was a relatively inexpensive method for attachment.

3.4.3.3 Strings: Securing with Ties or Laces

Much like the laces of a shoe, strings allow the attachment to be adjusted and secured over an area of the appendage. This could be very comfortable as it can be tightened and loosened where needed and is also very inexpensive and easily replaced. However, strings would be very difficult for the user to adjust and attach on their own. It could also wear or cut off circulation to certain areas of the arm if not attached properly, which was why it was important the user be able to adjust their attachment on their own.

4 DESIGNS CONSIDERED

After researching existing designs, the team generated concepts by setting a deadline and having each member generate five concepts. This method was chosen due to each team member having unique ideas they wanted to contribute to the generation process, and the alternative methods limited the individual abilities of the team members to include these ideas. It was more beneficial for each member to come up with five ideas, and then meet as a team and evaluate and discuss the ideas. If there were aspects of different concepts that work well together, the team combined those characteristics or discussed the ability to combine them into a singular design.

4.1 Design 1: Adaptation

This design was similar to one of the existing designs because the arm is made up of connecting 3D printed parts, and wire or string was threaded on the back of the arm and through the elbow attachment. The threading imitated tendons and allows for the fingers to close when the wearer moved the remainder of their elbow. Changes to the design included a motor attachment at the elbow to help control the movement of the threaded wire, as well as sensors at the fingertips and feedback at the elbow. Advantages of this design included scalability of the design for different sized users as well as easy assembly of parts, but disadvantages included the weight of the prosthetic being too taxing on the user.

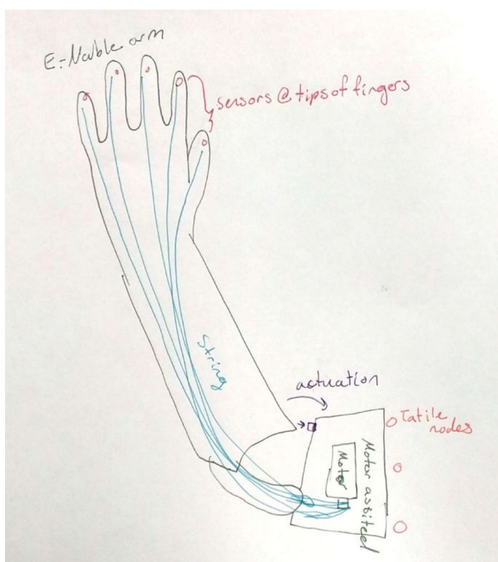


Figure 4.1: Adaptation Arm

4.2 Design 2: Customizable Skeleton

This design used a cup and upper arm band for attachment to the amputee, and the arm was a thin skeleton with skeletal fingers. Wires for the sensors at the fingertip traveled up within the tube of the forearm. The forearm was thin like a skeleton to allow for customization, for different curved coverings can be 3D printed and clipped on to the arm. This arm allowed for comfortable support and customizability with its design, but lacked mechanical motion. Advantages of this design were the customizability and the containment of the sensors and wires. Disadvantages were the grip strength due to not having a palm of the hand, and the motor control.

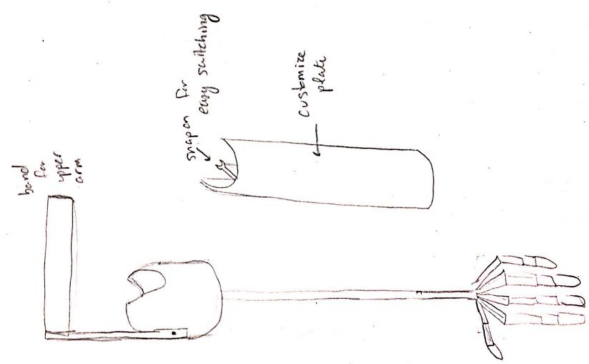


Figure 4.2: Customizable Skeleton Arm

4.3 Design 3: Capt’n Crabby

This design was modeled after a crab claw. The 3D printed active prosthetics would be marketed as a toy, meaning the aesthetic can range from humanoid to fun. As the user moved their elbow, the claw would open and close accordingly. This design was intended for a younger recipient due to the crab claw appearance, but can give the wearer a unique prosthetic and fun outlook on their condition. Advantages of this design were the aesthetic and customizability, but disadvantages included the lack of sensors and weight of the design.

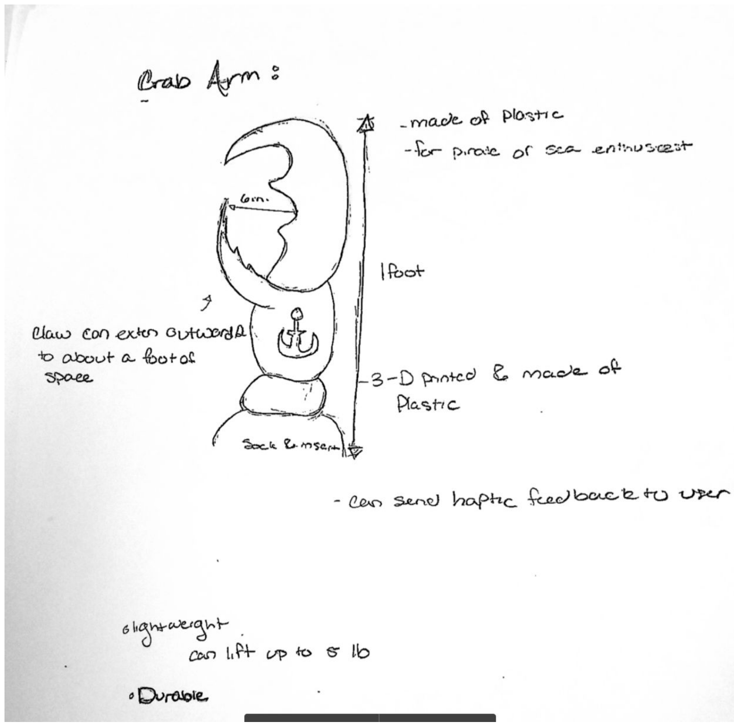


Figure 4.3: Crab Arm

4.4 Design #4: Drawstring Tendons

The Drawstring Tendons Arm design utilized strings/wires that pull the fingers closed. This was similar to how tendons were pulled to move fingers in the human body. Thus, the name for this design was derived. The design also included a frame that was lightweight and minimalistic. This was advantageous because it was easier for the user to lift the arm. However, it lost durability due to this. The prosthetic was attached to the arm with a velcro strap. It was wrapped around the residual limb and is adjustable to the proper size of the arm.

Figure 4.4: Drawstring Tendons Arm

4.5 Design 5: Faux Flesh

The Faux Flesh was a sleeve made out of a material that was to be determined, but the material would be sewn in the form of a forearm and hand. This glove would then be slipped over a skeleton of a prosthetic arm, which would be similar to the Customizable Skeleton base design. The material sleeve was advantageous because it would improve the grip while also making the arm look more realistic, and should be easy to clean because the sleeve could be removed for washing, but disadvantages included ease of assembly and durability.

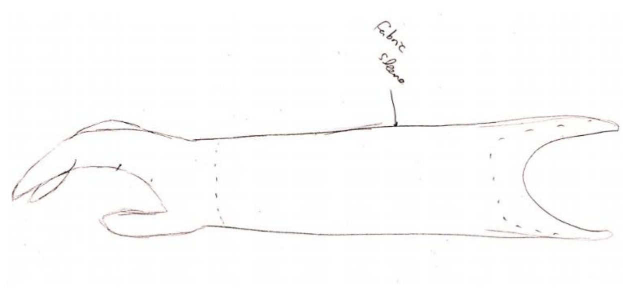


Figure 4.5: Fabric Sleeve over Skeleton Arm

4.6 Design 6: Foot Control

The idea behind this design was for the motion control of the fingers to be controlled by sensors on the foot. When the user clinched his/her toes, the fingers on the prosthetic would also clinch.

The physical design of the prosthetic was similar to the Adaptation arm, with the main modification being the actuation provided by movement of the toes. Advantages of this design included more control over movement as well as ease of assembly, but disadvantages were in the reliability of the sensors on the foot.

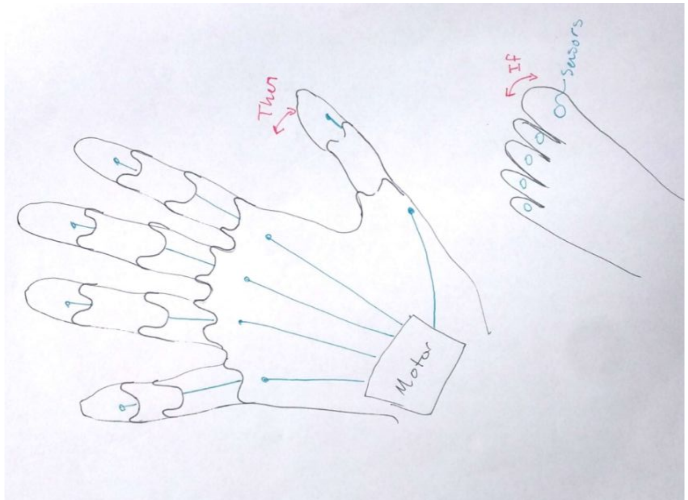


Figure 4.6: Foot Controlled Sensors

4.7 Design 7: Shape Memory

Shown in Figure 1 of Appendix B, the Shape Memory hand had a nitinol skeleton. Nitinol has shape memory and returns to its original shape when heated. Thus, it got its name from this feature. The design also had a glove like covering that made it more aesthetically pleasing. The hand was attached to the residual limb with a strap. The disadvantage of this design were that fingers do not open without assistance. It would not be easily controlled by the user due to the necessity of temperature difference to get the wire to move.

4.8 Design 8: Cool Hand Squid Man

Shown in Figure 2 of Appendix B, Cool Hand Squid Man was modeled after the tentacle of a squid. This design was a long arm of varying diameters that took the shape of a tentacle, and it had suckers on the end to improve grip. It also had sensors along the inside of the arm to grab objects of varying sizes. This design's sensing capabilities allowed the arm to automatically close when a receiver picks up the shape or weight of an object within range. Advantages of this design included the aesthetic and the grip, but disadvantages included the motor control.

4.9 Design 9: Clip-o-Grip

Shown in Figure 3 of Appendix B, the Clip-o-Grip was an arm made of several components that could be clipped together to form the full functioning prosthetic. The battery for the sensors and motors were stored on the back of the hand of the prosthetic, and each finger included a sensor. Advantages of this design included customizability, but disadvantages included ease of assembly and reliability of the sensors.

4.10 Design 10: Vine Grab

Shown in Figure 4 of Appendix B, the Vine Grab was an arm made up of five tubes full of pressurized fluid. As the fluid pressure changed with the motion of the arm, the five vines moved in order to grasp things around it. Each vine also had sensors located at designated areas. The advantages of this design included the grip strength and sensor reliability, but disadvantages included the active control and probability of creating a functioning model.

The remaining ten designs generated were shown in Figures 5-14 of Appendix B.

5 DESIGN SELECTED

After the designs were created, they had to go through a series of evaluations to determine which design is the most useful, durable, and aesthetically pleasing design. The design chosen would be able to provide haptic feedback and sense touch for the user. In order to determine which design met or even exceeded the need and requirements, all 20 designs were evaluated using a Pugh chart and the final 5 used a Decision Matrix. Once this was completed, the final design was chosen. This section includes the selection and justification of the final design.

5.1 Rationale for Design Selection

The requirements for the active prosthetic device were for it to provide haptic feedback and sensing capabilities as well as be scalable and customizable for multiple users. It would also need to be comfortable, secure, and easy to build for the user. No design met all of the criteria but several were advantageous in different fields. Based on the criteria, all designs were narrowed to one final selection. After the evaluations were completed, the final design was chosen to be the Foot Controlled design. This was mainly due to its advantages of control, customization, and haptic sensing abilities, which were the most important requirements of this project. The justifications can also be seen from the Pugh chart and the final Decision Matrix in tables 5.1.1 and 5.1.2 respectively.

For the first part of the design selection, all 20 designs were placed into a Pugh chart. The designs were weighted against the following chosen criteria: Aesthetically pleasing, no discomfort, scalable, customization, easy to clean, lightweight, durable, and included haptic sensing ability. The adaptation model was chosen as the datum due to the fact that it was similar to an already working model and met all criteria of the project. Each design was judged on whether they were less than, met, or exceeded the ability of the datum for each criteria. Once all designs were evaluated, it was clear that the Foot Control met all requirements for the device compared to the datum, which gave the design a total of 0. This design along with the Customizable Skeleton, Datum, We Got You Covered, and the Drawstring Tendons were selected for further analysis in the Decision Matrix.

Table 5.1.1: Pugh Chart

CRITERIA	Clip-o-Grip	Need-Forearm-Muscles	Customizable Skeleton	Faux Flesh	Visible Nerves	Foot Control	Vine Grab	Pincer	Adaptation (DATUM)	The Blob
Aesthetically Pleasing	S	-	+	+	+	S	+	-	D	+
No Pain/Discomfort/Strain	-	+	S	S	S	S	-	-		S
Scalable	S	-	-	-	-	S	S	-	A	-
Customizable	S	S	+	+	-	S	-	-		-
Easy to Clean	-	+	S	S	-	S	+	-	T	-
Light Weight	S	+	+	+	S	S	-	+		-
Durable	S	-	-	-	-	S	S	-	U	+
Haptic Sensing System	S	-	-	-	S	S	-	-		-
Total +	0	3	3	3	1	0	2	1	M	2
Total -	2	4	3	3	4	0	4	7		5
Total S	6	1	2	2	3	8	2	0		1
Total	-2	-1	0	0	-3	0	-2	-6	DATUM	-3

CRITERIA	The Claw	We Got You Covered	Cap'n Crabby	You Can Toucan	Cool Hand Squid Man	Vacuum Hands	Drawstring Tendons	Shape Memory	Magnetic Fingertips	Bendy Fingers and Lace Up
Aesthetically Pleasing	-	+	+	+	S	+	S	+	+	+
No Pain/Discomfort/Strain	S	S	S	S	-	-	S	-	-	+
Scalable	-	-	S	S	+	S	S	-	-	S
Customizable	-	+	-	-	+	-	S	-	-	-
Easy to Clean	-	S	+	+	-	+	S	S	S	-
Light Weight	-	+	-	-	S	-	S	-	-	-
Durable	+	-	+	+	-	+	-	+	+	S
Haptic Sensing System	-	-	-	-	S	-	S	-	-	-
Total +	1	3	3	3	2	3	0	2	2	2
Total -	6	3	3	3	3	4	1	5	5	4
Total S	1	2	2	2	3	1	7	1	1	2
Total	-5	0	0	0	-1	-1	-1	-3	-3	-2

The Decision matrix gave the ability to weigh certain criteria to determine the best design of the final 5. Part of the previous criteria were weighted along with new additional properties such as being easy to build, actively controlled, and having a secure attachment. Once these additional criteria were added and weighed on its importance, it is clear why the Foot Controlled option was selected.

Table 5.1.2: Decision Matrix

		Adaptation		We Got You Covered		Foot Control		Customizable Skeleton		Drawstring Tendons	
Criteria	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight	Raw Score	Weight
Secure Attachment	0.1639344262	3	0.4918032787	3	0.4918032787	3	0.4918032787	3	0.4918032787	1	0.1639344262
Durability	0.131147541	3	0.393442623	3	0.393442623	3	0.393442623	1	0.131147541	1	0.131147541
Haptic Sensing	0.1475409836	5	0.737704918	3	0.4426229508	5	0.737704918	1	0.1475409836	3	0.4426229508
Active Control	0.131147541	3	0.393442623	3	0.393442623	5	0.6557377049	1	0.131147541	1	0.131147541
Comfortable	0.1147540984	3	0.3442622951	5	0.5737704918	3	0.3442622951	3	0.3442622951	1	0.1147540984
Easy to Build	0.08196721311	1	0.08196721311	1	0.08196721311	1	0.08196721311	3	0.2459016393	1	0.08196721311
Scalable	0.09836065574	3	0.2950819672	1	0.09836065574	3	0.2950819672	1	0.09836065574	3	0.2950819672
Ability to Grip	0.06557377049	1	0.06557377049	3	0.1967213115	1	0.06557377049	1	0.06557377049	3	0.1967213115
Customization	0.01639344262	5	0.08196721311	1	0.01639344262	5	0.08196721311	3	0.04918032787	1	0.01639344262
Light Weight	0.04918032787	3	0.1475409836	3	0.1475409836	3	0.1475409836	5	0.2459016393	5	0.2459016393
Total	1		3.032786885		2.836065574		3.295081967		1.950819672		1.819672131

The Foot Controlled design met all previously mentioned requirements, but it was advantageous in that its haptic feedback and customization were better than most other designs. The design even surpassed the adaptation model because it provides more control for the user. This design still had disadvantages by being more difficult to build and having a weaker grip ability. Some possible fixes were to add better gripping material or to simplify the design. These disadvantages were improved as the design is created and adjusted for ultimate customer satisfaction.

5.2 Design Description

Before prototyping of the arm could begin, analytical analyses had to be done in order to mathematically determine what the arm needed to withstand in order to meet customer and manufacturing needs. There were a variety of different aspects and parameters to consider in order to have a well working and consistent design. Each parameter and physical barriers of the design were tested using experimental procedures, code prototypes and consistent calculations.

5.2.1 Percent Infill Analysis

When it came to determining the most efficient and durable way to manufacture the prosthetic arm, the percent infill of material needed to be evaluated. By examining the percent infill, the durability of the arm would be maximized. It was found that a 40% infill optimized the durability of the 3D printed arm. In order to pick an optimum percent infill, the volume of a segment of 3D printed material with varying percent infills was used to calculate the weight the segment can withstand under yield strength. The weight was compared to the yield strength to visualize a fracture point. This process was repeated with different percent infills to determine the one that lasts the longest before fracture. This analysis was important in order to help reduce funding by lowering the mass of the 3D printed part, as well as ensure the arm is lightweight and durable.

The modulus of elasticity (E) and the density (ρ) of PLA were found to be 3.5 GPa and 1.3 g/cm^3 [7]. The force was set to withstand a minimum of 5 pounds. The cross sectional area was estimated to be 45.6 cm^2 for the analysis. Using equation 1, the stress was calculated using these inputs.

$$\sigma = \frac{F}{A} \tag{1}$$

Using the calculated stress of 4868.4 Pa and the found modulus of elasticity reduced to Pascals, equation 2 was used to calculate the strain which was found to be 1.3909e-6. .

$$\sigma = E\varepsilon \tag{2}$$

The dimensions of the tested segment were set using a thickness of 1.2 mm, which was standard for the nozzle used for 3D printing. Figure 5.2.1 shows a diagram of the rectangular segment and the dimensions used. The percent infill (p_{infill}) varied between 0.05 and 1 in increments of 0.5. The volume calculated using equation 3 was 167.143 cm^3. These dimensions were picked because the cross sectional area of the rectangular section was approximate to the resulting circular cross sectional area. A rectangular shape was assumed for these calculations because if a differential section of the curved surface of the arm was taken, the differential would also be rectangular.

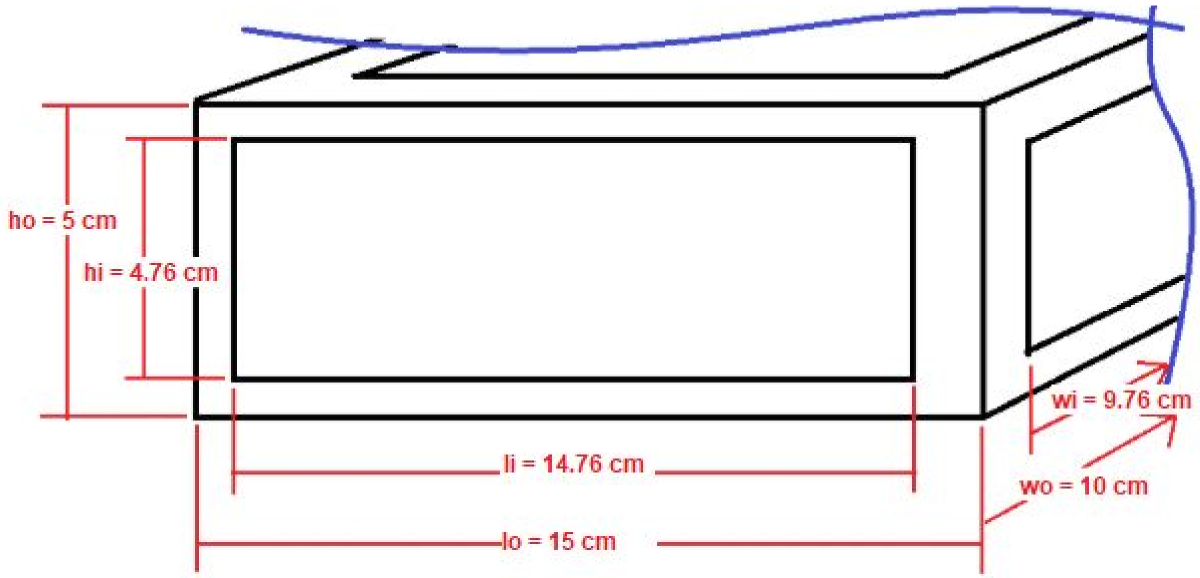


Figure 5.2.1: *Segment Schematic*

$$V = l_o w_o h_o - l_i w_i h_i (1 - p_{infill}) \tag{3}$$

Taking this volume and the calculated density, the mass was found using equation 4. This mass was 217.285 grams.

$$m = V\rho \tag{4}$$

Using mass and the gravitational constant, the weight was found to be 212940.1 gcm/s^2 or 0.021294 N using equation 5.

$$W = mg \tag{5}$$

Using equation 6 to calculate the yield strength at 0.2% offset from the original stress-strain graph, the resulting yield was 9.7363 N/m^2

$$\sigma_y = 0.002\varepsilon E \tag{6}$$

The weight was then compared to the yield strength times the area in order to make the units equal to each other, shown in equation 7.

$$W = \sigma_y A \tag{7}$$

The resulting yield strength times area is 0.044 N. This means the weight needed to be less than 0.044 N in order to resist permanent deformation under stress. This process was repeated for the other percent infills. Once all percent infills were analyzed, it was determined that 40% infill was the most efficient arm design, shown in table 5.2.1.

Table 5.2.1: Results of % Infill

% infill Input	Weight (N)
0.05	0.01256
0.1	0.01693
0.15	0.02129
0.2	0.02566
0.25	0.03003
0.3	0.0344
0.35	0.03877
0.4	0.04313
0.45	0.0475
0.5	0.05187
0.55	0.05624
0.6	0.06061
0.65	0.06497
0.7	0.06934
0.75	0.07371
0.8	0.07808
0.85	0.08245
0.9	0.08681
0.95	0.09118
1	0.09555

5.2.2 Material Thermoforming Ability

In order to make a durable, malleable, and well-functioning arm, there were a number of parameters to consider. One such aspect is the thermoforming ability of different 3-D materials. This aspect was important to consider because this 3D printed material will make up most of the base and cast of the arm. This cast needed to be able to hold all gears and sensors incorporated on the arm and be malleable enough to bend to the proper dimensions for the client. It was important to understand that the material must not be too hot to touch or too brittle else the casting will fail. Because this parameter is incredibly important, the analysis had to be accurate.

To complete this analysis, hard data and calculations were collected. The lab mainly focused on deflection and how it relates to the temperature of the plastic. The hypothesis was that the more flexible plastics would have a much larger deflection length. It was assumed that a high temperature will cause the deflection length to increase and that the closer the plastic reached its glass temperature, the likelier the plastic would begin to deform. The glass temperatures for each material, PLA, ABS, and PC are found below.

Table 5.2.2: Glass Temperatures of the Different Materials

Material	T_m (°C)	T_g (°C)
PLA	185	60
ABS	230	105
PC	260	147

The test incorporated the stress and strain of thermoforming ability. The following equation was made when considering the thermal activation of the material.

$$\Delta L/L = a * \Delta T \tag{8}$$

Where (L) is length, (a) is the coefficient of thermal expansion, and (T) is the Temperature at Celsius. Heat flux was also considered when testing the material and is displayed in equation (2).

$$q =- Ak\frac{dT}{dx} \tag{9}$$

Where (K) is the thermal conductivity, (A) is the cross-sectional area, (dt) is the change in temperature, and (dx) is the change in distance. Finally, the strain of the material was calculated by relating the force to Hooke's law.

$$\sigma = F/A \tag{10}$$

$$\varepsilon E = \sigma \tag{11}$$

Where (F) is force, (A) is area, (σ) is stress, is strain, and (E) is the Young's Modulus. Once the temperature and deflection graph is created, an equation was derived from the data. The equation was compared to the theoretical deflection of the plastic. This determined if the materials behaved as expected and determined which plastic is more malleable.

Procedure:

This experiment took the various temperatures and deflection of the three different potential materials: ABS, PLA, and PC. The factors of safety were .0073, .0126, and .0026 respectively.

Each material was approximately 150 x 60 x 60 mm. The schematic of the area can be seen below.

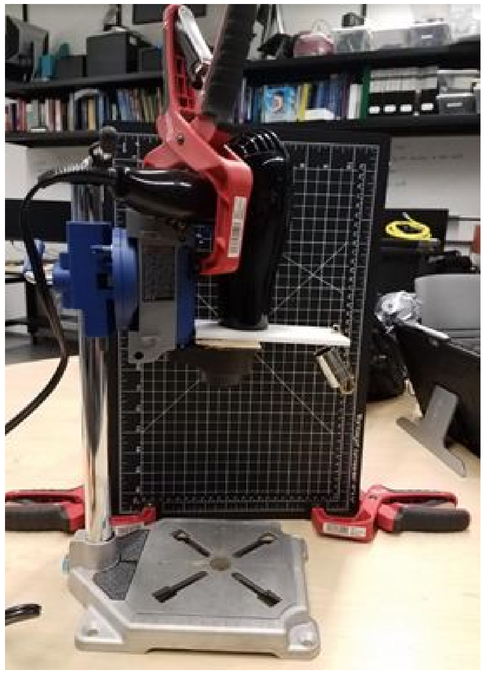


Figure 5.2.2: Schematic of lab

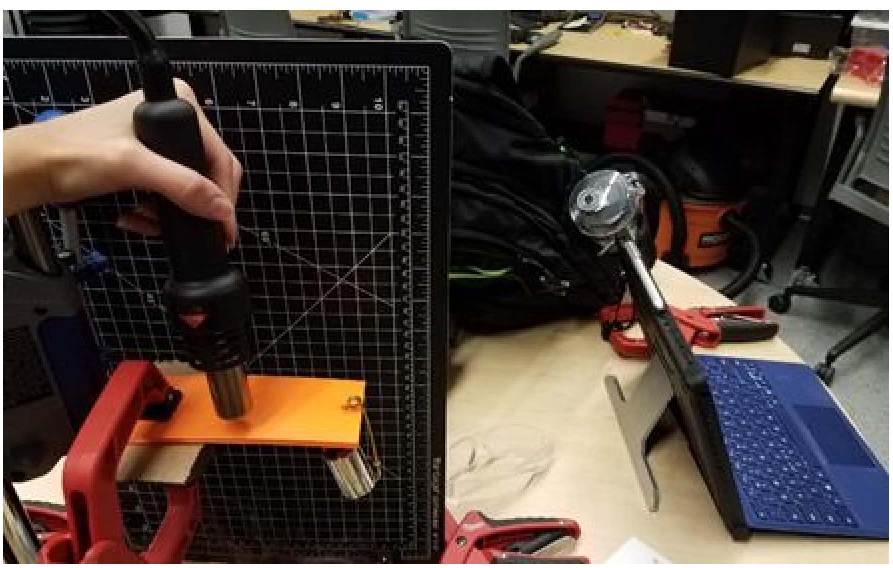


Figure 5.2.3: Visual of How the Heat Was Applied

The materials were to hang of the end of the dremel. A ruler board was placed behind the three plastics to accurately measure the length the plastic deforms in cm. A weight of 70g was hung off the end to ignore the weight of the plastic themselves. this allowed for a controlled force for the stress analysis of the experiment. Because the critical temperatures of the three plastics were so high, a heat gun had to be used to heat the material. Once the plastic was in place, the heat gun was turned to 300C. The nozzle was placed onto the plastic and the temperature was measured using a temperature gun.

The raw data can be found below. One of the main requirements of the experiment was to find a material that would be durable but also able to be made by anyone, instead of requiring special tools. PC immediately fails this test as it did not have any displacement and loss heat fairly quickly. It was therefore not necessary for further analysis. The two other materials were collected for the stress and strain analysis. Below are the data tables that correspond with the following graphs.

Table 5.2.3: Raw Data of PC

Temperature of Hot Gun ©	Temperature of material ©	deflection length cm	Coefficient
	21	23	0
300	130	23	
	151	23	
	116	23	
	119	23	
	120	23	
	125	23	

Table 5.2.4: Raw Data for ABS

Material:	ABS							
Ambient air								
Temperature of hot gun ©	Temperature of Material ©	Delfection Length cm	Coefficient	stress	strain	Modulus	coefficient	Flux (W*m^2)
off	22	23	0.017483	91.4	0.108696	840.88	0.000760109	0.06894375
	27	23						
	86	23						
	127	23						
	132	23						
300	155	22.5						
	156	22						
	157	21						
	165	20.5						

Table 5.2.5: Raw data for PLA

Material	PLA						
Ambient air	23C						
temperature of Hot gun ©	Temperature of Material ©	Deflection Length cm	coefficient	Stress (N)	strain	Modulus	Flux(W*m^2)
	23	23	0.0452	91.4	0.23913	382.2182	0.01630005
300	92	22					
	106	21.5					
	110	21					
	119	20.5					
	125	19.5					
	128	19					
	139	18					
	142	17.5					

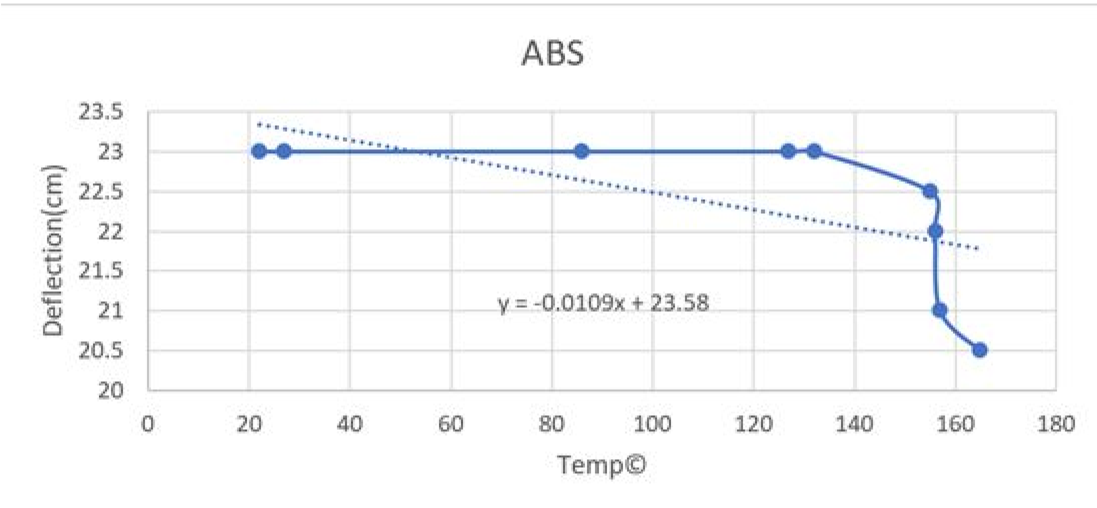


Figure 5.2.4: APS Deflection

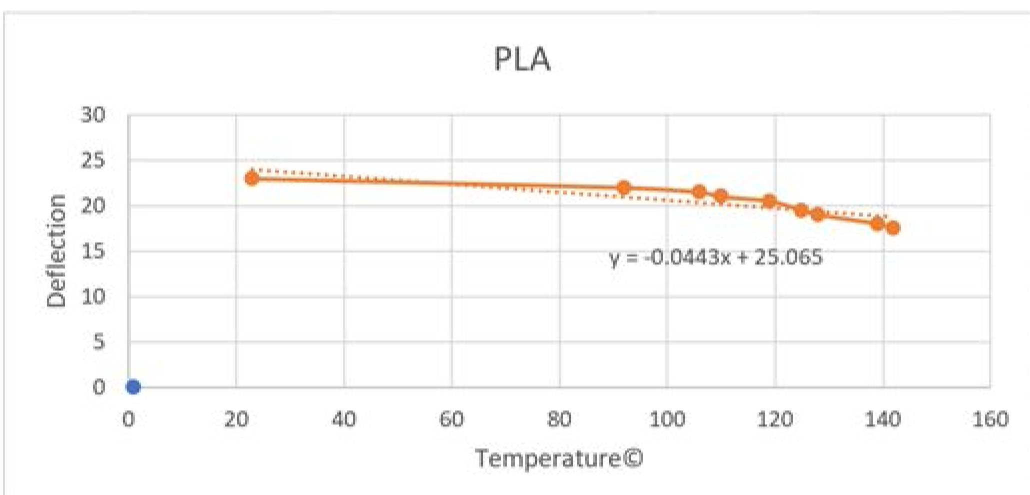


Figure 5.2.5: PLA Deflection

The collected graph essentially gave a force deflection curve and the equation from the slope gave a relationship(coefficient) of deflection vs temperature. Using the experimental values, the equation was then compared to the calculated values in the table.

As shown, both materials appeared to be incredibly flexible once thermally activated. It was also be confirmed by examining the Young's Modulus of the materials. Because PLA had a much smaller modulus, it was concluded that the PLA was mathematically proven as the most flexible material. The team used PLA going forward as it was more likely to mold with little heat. It was probable that it will form after placing the material in boiling water. There were some differences with the graph, however, when comparing the experimental coefficients with that of the calculated value in the table. The displacement from the experiment in ABS was lower than the calculated values while the displacement was higher that the calculated values of the PLA. the difference could have been due a few reasons. It was possible that there was human error or it could have been that the equation was not an effective model to calculate the displacement of ABS material. On the contrary, the calculated and experimental values of the PLA were very close in proximity to each other. A visual understanding of how the plastics were affected can be seen in the picture below.

Figure 5.2.6: Newley Warped Material

This shows just how much each material could bend given the heat and force applied to it. There were some errors when completing this experiment. One of which was how the heat gun did not give an equal amount of heat to the material. This affected the results as the material might not have deformed properly. Another source was human error as the displacement had to be analyzed using a rough estimate. Ultimately, the project was important because it demonstrated how useful PLA was for the project going forward.

5.2.3 Forearm Shape and Mechanical Forces:

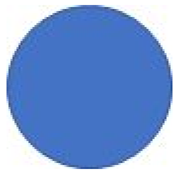
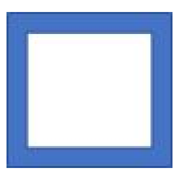
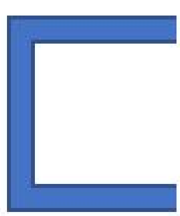
For this analytical analyses, the strength of the forearm was found for many cross sectional shapes. The calculations were based on the assumption that the forearm was treated as a cantilever beam. This is because like the cantilever beam, the forearm is fixed at one location. Specifically, at the elbow. The forearm was treated as a cantilever beam because it was fixed to the patient's limb much like a cantilever is fixed in one location. From this analysis the necessary force to hold the prosthetic securely on the residual limb was found. The change in shape changed the deflection and the bending stress affected. This is important to the prosthetic because the user should know the amount of force the arm can withstand without bending and breaking. Strength was determined by the cross-section's ability to distribute stresses. The stress on a cantilever beam is a function of the force, moment of inertia, length of beam, and the elasticity of the material. To keep the analysis focused on the cross sectional shape, all except the moment of inertia were constant. Each shape had a different moment of inertia which is inversely related to stress. The most successfully strong shape was the hollow semi circle. Based on the calculations, the moment of inertia of this shape was the largest. Therefore, the stresses along the arm were smaller. This was important to the project because the arm needed to support the forces that were applied to it. Thus, the optimal shapes had to be chosen to increase the durability of the prosthetic.

This was important because the attachment to the amputee had to be strong and not fall off the user. The creation of Free Body Diagrams and excel code displayed the effects that different forearm design shapes had on reaction forces, moments, and arm deflection at the joint. This also factored in the location of forces such as distributed loads or point loads. Therefore, this analysis discovered the optimal shape for a forearm that withstood forces and the required reaction forces at the joint will be known. The proper shape and joint was selected for the prosthetic using this analysis.

For this analysis, there were many assumptions made. The first and main assumption was that the forearm could be compared to a cantilever beam. The prosthetic arm would need to be secured to the residual limb. This was be done by fixing one end of the arm to the limb which provided one fixed location to hold the weight of the arm and any other forces applied. Thus, it was comparable to a cantilever beam which is, by definition, fixed in one location. It was also assumed that the weight forces of the straight arm were distributed loads and that the weight of the hand was a point load located at the end of the forearm. All of these assumptions simplified the calculations.

In order to calculate the bending stress and the deflection of the arm, the moment of inertia had to be for each cross-sectional shape. Each of the shapes had unique moments of inertia as seen in the following figures and equations.

Table 5.2.6 Cross-Sectional Shapes and their respective Moment of Inertia Equations

Cross-Sectional Shapes	Image	Moment of Inertia (I) Equation	Variables affecting Moment of Inertia (I)
Circular		$I = \frac{\pi D^4}{64}$	Diameter (D)
Circular and Hollow [2]		$I = \frac{\pi}{64}(D^4 - d^4)$	External diameter (D) Internal diameter (d)
Semicircular and Hollow		$I = \frac{\pi}{8}(R^4 - r^4)$	External radius (R) Internal radius (r)
Square		$I = \frac{b^3 h}{12}$	Base (b) Height (h)
Square and Hollow		$I = \frac{B^3 H}{12} - \frac{b^3 h}{12}$	Internal Base (b) External Base (B) Internal Height (h) External height (H)
"C" shaped and Hollow		$I = \frac{2sb^3hht^3}{3} - A(b-y)^2$	Internal Base (b) External Base (B) Base Thickness (t) Internal Height (h) External Height (H) Height Thickness (s).

The results for the analysis were calculated in Excel. These results varied based on dimensions, load sizes, and the Modulus of elasticity of the forearm. The inputs can be changed in the attached excel sheet to fit the needs of the individual user. The results showed that the shape with the largest moment of inertia resulted in the smallest deflection and the smallest bending stress. This shape was the hollow semicircle. Therefore, the team considered this shape for the design of the forearm.

5.2.4 Hardware and Code

Three distance sensors were compared from three different companies Sparkfun, Amazon, and Polulu [1-3]. All sensors collected to meet a distance range from 0.5 in to 6 in, which is approximately the distance needed to determine if the prosthetic is reaching to grab an object. **Table 5.2.7** compares the important properties of each sensor which includes range, voltage needed, type, pins needed, and cost.

Table 5.2.7- Distance Sensors

Distance Sensor	Range	Voltage	Type	Pins Needed	Cost
ZX Distance and Gesture Sensor	0 - 12 in	3.3V - 5V	Laser	5	24.95
Elegoo HC-SR04	0.78 - 157 in	5 V	Sound	4	9.78
Pololu Carrier with Sharp GP2Y0D815Z0F Digital Distance Sensor 15cm	0.2 - 6 in	5 V	Laser	6	9.75

The three motors listed in **Table 5.2.8** were from the same companies listed in section 2.1. Each motor was evaluated using the properties: input voltage, current required, speed, shaft size, and cost. All properties were important, however, shaft size was not important until further in the design when the attachment is determined.

Table 5.2.8 - Motor

Motor	Input Voltage	Amps	Speed	Shaft	Torque	Cost
URBEST	12V	0.6 A	300 RPM	3 mm /0.118"	7 oz-in	11.99

131:1 Metal Gearmotor 37Dx57L mm	12V / 6V	300 mA	80 RPM	6 mm	250 oz-in	24.95
Stepper Motor	3.2 V	2.0 A	200 SPR	6.35 mm	125 oz-in	30.95

In **Table 5.2.9**, the motor drivers were compared by the number of motors they can operate at the same time, the current that can be ran per channel, whether an additional power supply (other than the microcontroller vin) can be added, the shield compatibility, and the cost. An additional company's board was considered from adafruit.

Table 5.2.9 - Motor Drivers

Motor Driver	Number of Motors	Amps/Channel	Additional Power Supply	Shield Compatible	Cost
SparkFun Ardumoto	2	2 A	no	R3	20.95
SparkFun Wireless Motor Driver Shield	2	1.2 A	yes	R3, Xbee	26.95
Pololu Dual VNH5019 Motor Driver Shield for Arduino	2	12 A	yes	R3	49.95
Adafruit Motor/Stepper/Servo Shield for Arduino v2 Kit - v2.3	4	1.2 A	yes	R3	19.95

Since Arduino is open source and available around the world, these microcontrollers were chosen and compared amongst each other in **Table 5.2.10**. The controllers would need to meet the previous hardware requirements from the components selected above and be able to accommodate possibly multiple sensors.

Table 5.2.10 - Arduino Boards

Microcontroller	Attach-Interrupt Pins	Operating/Input Voltage	CPU Speed	Analog In/Out	Digital IO/PWM	Serial Read Pins	Shield Compatible	Cost
Mega 2560	2, 3, 18, 19, 20, 21	5 V / 7-12 V	16 MHz	16/0	54/15	3	R3	38.5
Micro	0, 1, 2, 3, 7	5 V / 7-12 V	16 MHz	12/0	20/7	1	N/A	19.8
Uno	2, 3	5 V / 7-12 V	16 MHz	6/0	14/6	1	R3	22
Zero	all digital pins, except 4	3.3 V / 7-12 V	48 MHz	6/1	14/10	1	R3	42.9
Due	all digital pins	3.3 V / 7-12 V	84 MHz	12/2	54/12	3	R3	35.5
SparkFun RedBoard	2, 3	3.3 V / 7-15 V	16 MHz	6/0	14/6	1	R3	19.95

The hardware chosen from this analysis was ZX sensor, Polulu motor, adafruit motor shield, and arduino due. All the hardware was compatible with the microcontroller chosen and allowed for wireless connectivity, additional motors, extra sensors, and other future design modifications. The code available in **appendix 6.1** did not run the motor as expected, however, the distance sensor was not tested since it was not available before the deadline for the analysis.

5.2.5 Prototype

Using the results from each analysis, A final design was made. A 3D model was created in order to have a visual understanding of what the arm would look like and where each electrical component would be placed. It is also important to keep in mind that the arm had to be printed flat using different software and thermoformed into its final design. The rubber bands, wires, and electrical components can be added after assembly. A final prototype was constructed using the CAD model and conclusions from the analytical analysis followed by a completed prototype.

Below shows a picture of the CAD model and includes drawings that give more detail as to how the arm was first designed to move. The pictures of some of the parts can be found in the appendix.

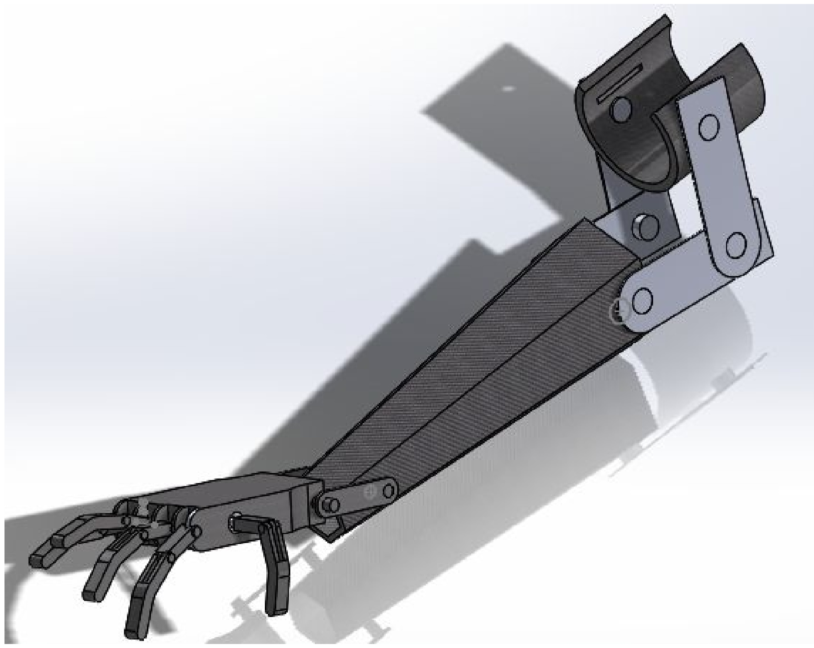


Figure 5.2.14 : Figure of Cad Model

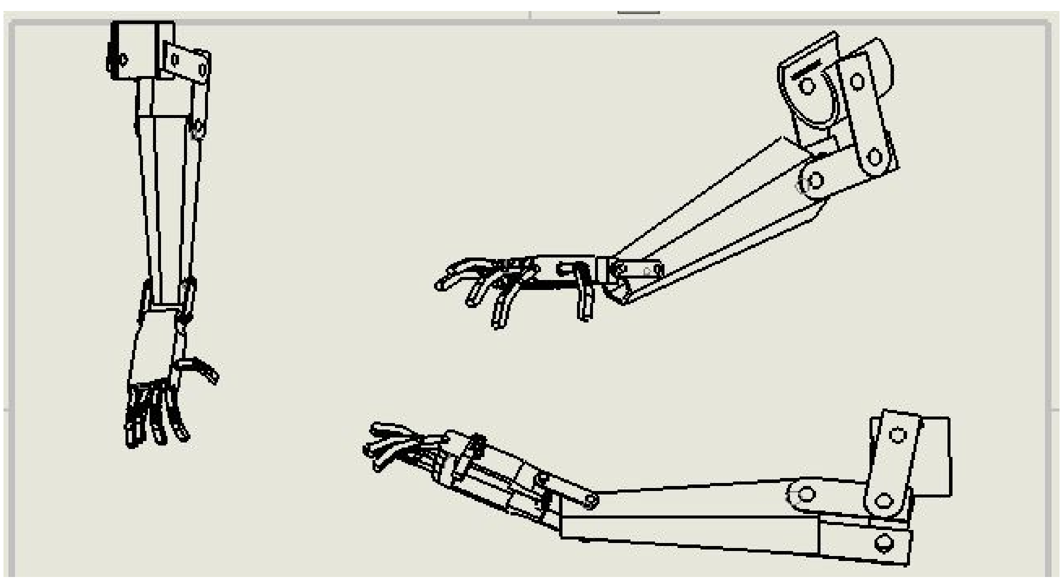


Figure 5.2.15: Drawing of CAD Model

Although not shown, the rotors were at the base of the arm as well as the haptic feedback and bluetooth for the user to avoid a large load at the end of the hand. Our client is a nine year old boy and it is key to avoid too much load in one concentrated area as suggested in the previous analysis. The motors were to be connected to durable strings and rubber bands through the palm of the hand and through the fingers to give as much mobility to the user as possible. All this will be placed in a 3D thermoformed cast made of PLA with possible APA components for the fingers. Sensors will be placed on each fingertip so that the hand will be able to sense when an item is near and close around the object. This movement should activate the haptic sensor and respond(vibrate) to give the user a sense of touch.

This model will include a shoe insole that has not been designed yet. Each toe will correspond to a pressure sensor. This sensor is connected via bluetooth to the arm which is connected to a motor for each finger. This allows for optimal control for each finger and was one of the larger focuses on the design as per the client's request. The team hopes that the sensor in the big toe will allow for the thumb to move horizontally and vertically much like a thumb in real life. Final meetings will help decide what electrical components to incorporated for the best design.

Using the CAD model, the prototype was then be created and gives a better representation of where the sensors and electrical components can be placed. Below shows a figure of the completed design.

Figure 5.2.16 : Picture of prototype

This prototype looks very different from the CAD for a few reasons. It was decided that the stronger attachment could be better made to handle a larger weight distribution and allow for better arm customisation for the user. It was also decided that a partially thermoformed forearm would be better for the design and easier to assemble when placing the wires. The fingers have a third limb attachment to allow for better mobility and more natural look for the fingers. Finally, a top was added to the palm of the hand to better protect the motors and sensors within. It is possible the prototype will be altered during construction because the sensors' weights could mean that the team will need a more durable forearm. Alterations will also take place during the fitting with the client to ensure the fit is accurate and comfortable.

6 PROPOSED DESIGN - First Semester

To begin implementation of the design, the team met with the Electrical Engineering Capstone team to discuss the feasibility of having a foot-controlled prosthetic to discuss the best form of actuation and haptic feedback. The programming of the sensors that would be placed within a shoe insole were still under development, but the mechanical aspect of the design was prototyped. To prototype the final design, the Enable prosthetic design was used as a base and modifications were made to include placement of the sensors and motors. While the Enable design was used for the prototype this semester, edits were made to the design to improve weight, comfortability, and actuation in the Spring. The team planned to coordinate with the EE Team to program a heel-strike to toe-off sensing capability within the insole and bluetooth it to sensors within the finger.

There was also the proposed idea of including a touch screen on the arm with different modes programmed into the arm, and the user can select a mode type and the arm would react accordingly. For example, if the mode selected was "Video Games", the arm will know to only allow motion within certain fingers in certain directions via input from the sensors in the insole. This idea was proposed after a meeting with the client, Nate, who had an interest in the ability to play video games and baseball. This idea will not be programmed for this semester's prototype but the team aimed to include it in the final design.

Multiple arms were prototyped and tested for their durability, wearability, and ease of use. Meetings with the client allowed arm to be properly fitted, sized, and tested for comfortability and likeability according to the client's preference in prosthetic. This allows the team to give Nate an arm he will be happy with come Spring. In terms of the budget used through this design process, Dr. Winfree had supplied $500.00 to each the ME Capstone team and the EE Capstone team. By the EE Team also being a part of the project, some of the prototyping expenses related to the sensors and motors has been taken from their $500.00 budget while the ME Team's budget focused on the physical and mechanical side of prototyping. However, it was safer to assume the prototyping, purchasing of sensors and motors, and other materials were covered by the ME Team. Table 6.1 holds the Bill of Materials for a single prosthetic arm. The plan was to reuse sensors and motors between prototypes in order to save on money, but each prototype will be a new 3D printed arm or part of an arm. Assuming a minimum of five prototypes including the final arm to be given to the client, the only change to the expected cost was saying the quantity of PLA filament is 5 instead of 1. This made the price $323.04, which was still within the

$500.00. However, shipping fees were omitted and sensor and motor types were susceptible to change which also changed in price. Thus, this value was an estimate.

Table 6.1: *Bill of Materials*

Material	Quantity	Quantitiy/Pack	Cost/Part	Cost
PLA Filament	1	1 ct	15.99	15.99
Small rubber bands	1	100 ct	4.75	4.75
Velcro Straps	1	24 ct	8.99	8.99
Foam pad	1	6 ft	12.79	12.79
Arudino: Duo	1	1 ct	35.5	35.5
Large Motor	1	1 ct	24.95	24.95
Small Motor	5	1 ct	8.99	44.95
Motor Driver	1	1 ct	19.95	19.95
Pressure Sensor	10	1 ct	7	70
Battery	2	2 ct	6.59	6.59
Battery connector	1	5 ct	5.39	5.39
Insoles	1	1 pair	9.23	9.23
				259.08

The design can be seen in the exploded view below.

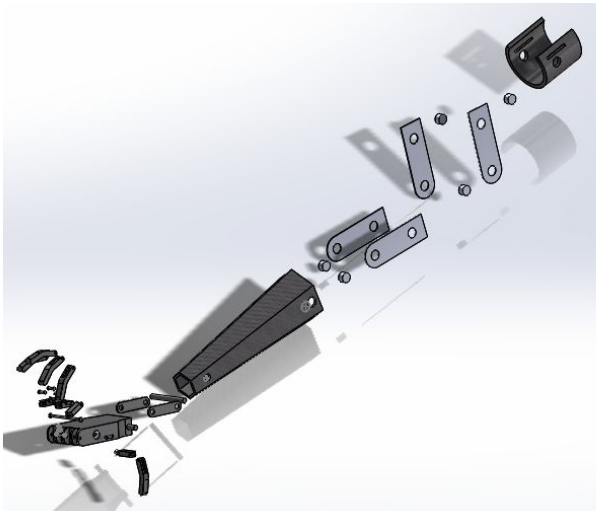


Figure 6.1: Exploded View

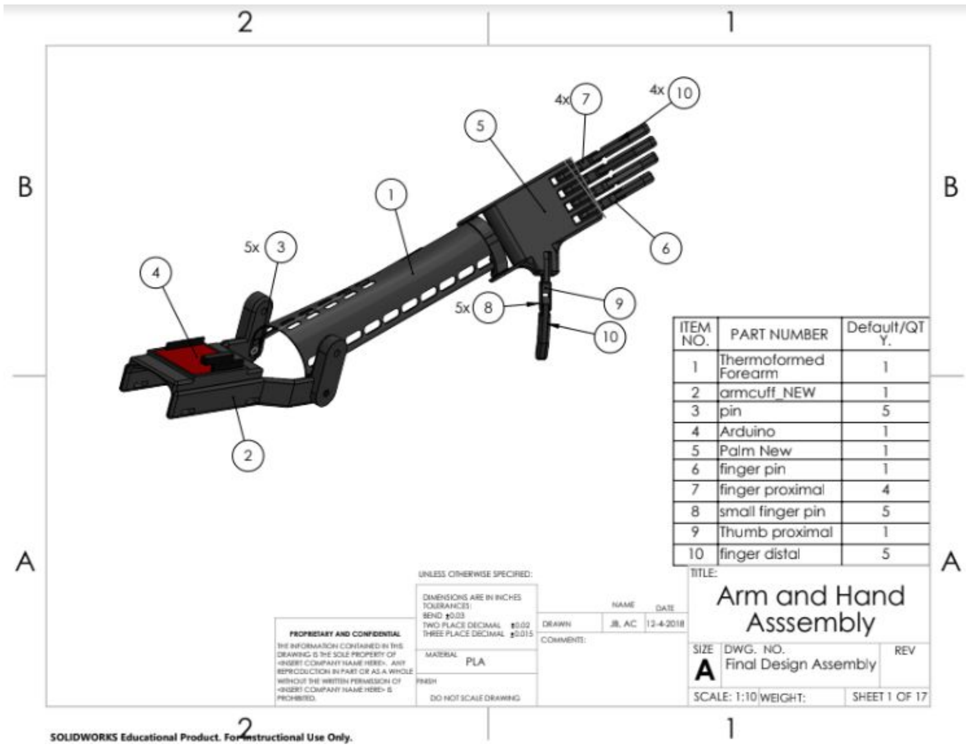


Figure 6.2: Assembly Drawing

The current implementation plan included coordinating a weekly or bi-weekly meeting time with the EE Team to make sure each aspect of the project was up to date and still feasible with each other. In finishing the first semester, both teams had a modified Enable arm and mapped out insole for sensor location, and a brainstorm for the programming behind the bluetooth. Second semester focuses on the programming side within the first few weeks and once the program started to solidify, modifications to support the software were made to the current prototype. While the EE Team worked on the program the first few weeks, the ME Team focused on modifying the CAD to properly include placement holders for sensors and motors. The rest of the semester was cycle of testing, prototyping, and retesting by contacting the client. The Gantt Chart for the Spring semester can be seen in Appendix C.

7 IMPLEMENTATION - Second Semester

When implementing the prototype, manufacturing mainly consisted of 3D printing components of the arm and making alterations when components did not go together. Manufacturing also includes arranging the electrical components within the assembly in order to make a fully functional prototype. Through these methods of manufacturing, multiple design changes had to occur for each component in order to incorporate the electrical components and attachment mechanisms to other mechanical components. Multiple iterations of subsystems occurred throughout the semester in trial and error of prototype assembly. This trial and error was the most efficient method of manufacturing for this project because sometimes visualizing the component in SolidWorks or assembling the prototype only in SolidWorks was inaccurate to what the components would look like or how the components would behave once in a physical form.

7.1 Manufacturing

To manufacture the prosthetic, the mechanical components are 3D printed using PLA filament. The individual components of the arm are designed in SolidWorks CAD and printed. The design in SolidWorks is then modified based upon how the printed prototype functions and assembles with the rest of the components. This process is completed for multiple prototypes until changes no longer need to be made. For the electrical side of the project, all components are ordered and their placement is built into the SolidWorks design. In other words, the 3D printed components incorporate space and attachment mechanisms for the electronic components. Once the electrical components arrive, they will be fitted into the printed designs. Design alterations will be made as necessary to ensure the electrical components work with the prototype.

Once the prototype is assembled, testing will occur. The testing will include measuring forces along the arm in order to determine the force of actuation and the force of grip. The arm will also be weighed and compared to the weight of an average human arm. As the client would ideally like to use the arm in sports, a durability test will be conducted by repeatedly hitting the arm with a mallet for a number of cycles and evaluating any damage. The client will also use the prosthetic arm to lift up to 10 lbs and the connections will be assessed for damage. If the prosthetic passes these tests, it is a functional and durable arm that meets the engineering requirements.

7.1.1 Bill of Materials

To manufacture the arm the resources required are: a 3D printer, 2kg of PLA filament, three microcontrollers, wireless communication modules, batteries and booster chargers, two regulators, 10 pressure sensors, two springs, two shoe insoles, 10” x 8” of foam padding, five servo motors, and three vibrating micromotors. All materials are listed in Table 7.1.1.1 along with their quantity, price, catalog number, and source. The function of each resource listed above is described below. Drawings for many individual parts can be found in the CAD packed, other electronics not included in the mechanical teams CAD package are included in the electrical team’s documentation.

Table 7.1.1.1: BOM

PN	Order	USD	N	USD*N	Vender
1	Amphenol FCI Clincher Connector (2 Position, Female)	9.95	1	9.95	Sparkfun
2	Battery 2Ahr	12.95	1	12.95	Sparkfun
3	Charger and Booster	15.95	3	47.85	Sparkfun
4	Force Sensitive Resistor 0.5"	6.95	5	34.75	Sparkfun
5	Force Sensitive Resistor - Small	6.95	2	13.9	Sparkfun
6	Amphenol FCI Clincher Connector (2 Position, Female)	1.95	7	13.65	Sparkfun
7	SparkFun RedBot Mainboard	52.95	1	52.95	Sparkfun
8	XBee 1mW Trace Antenna - Series 1 (802.15.4)	24.95	3	74.85	Sparkfun
9	270 Degree Carbon Steel Music Wire Torsion Spring with 0.826" Outside Dia.	12.57	1	12.57	Grainger
10	Shoe insoles	8.37	1	8.37	Amazon
11	Foam Pad	14.24	1	14.24	Amazon
12	Digital Servo x4	25.99	1	25.99	Amazon
13	Virbrating motor x10 need 3	9.99	1	9.99	Amazon
14	M3 Screws Assortment Pack	10.99	1	10.99	Amazon
15	Beaded Wire (x24yr)	2.99	1	2.99	Joanns
16	Arduino Pro Mini 328 - 5V/16MHz	9.95	2	19.9	Sparkfun
17	PLA per kg needed	17.99	1	17.99	Amazon
	Total:	393.83	34	383.88	

The half inch Force Sensitive Resistors (sensors), part number (PN) 4, are mounted to two different shoe insoles, PN 10, with one clincher, PN 6, at end of each. These sensors relay pressure information from the toes to two Arduino Pro Minis, PN 16, attached to both ankles.

The Pro Minis are connected to two Xbee wireless modules, PN 8. All components at each foot are powered by one 1Ahr battery, PN 2, which is charged by the booster, PN 3. The XBees at the ankles communicate with a third XBee connected to the SparkFun RedBot Mainboard, PN 7, located on the arm. The Mainboard is wired to four standard servos (PN 12), one micro servo, two vibrating motors (PN 13), and two small pressure sensors (PN 5). The pressure sensors control the standard servos connected to the bending motion of the fingers, while the small pressure sensors are located in the tips of the finger and control the vibrating motors to provide haptic feedback from touch.

The device structure is printed using a 3D printer and an estimated 2 kg of PLA filament, PN 17. At all locations the device might touch the user, foam padding (PN 14) is lined inside the device to prevent irritation.

Links for each part are attached to the part name in Table 7.1.1.1. The Seller is listed in the seventh column with the catalog number for each part listed in the sixth column. This can help to find the part if the link is broken. The price of each part is multiplied by the quantity, or number of units need to purchase to get the final price. The total comes to $384 USD before taxes and shipping. Since this is for both electronic and mechanical components, the total cost of the devices is less than the $1000 budget that was split for both teams but is above the estimated $500 cost of the device.

7.1.2 Schedule

For the Spring semester, the students' focus is prototyping and testing. A Gantt chart of the semester is in Appendix C. Originally, the ME team wanted to meet with the EE team weekly., however this proved not possible once the semester started. As a result, the ME team has focused more on the electrical side of the prototype to make up for missed meetings.

Each team member is responsible for a component of the arm. Responsibilities include designing, printing, redesigning, and coordinating with appropriate team members to make sure the components go together. Each team member completed their responsibility before the hardware reviews. However, the team is slightly behind in assembling, as coordinating the components has been limited. The implementation task of assembling the prototype is in the works over Spring Break, with each team member finalizing their CAD and printing their parts for the hardware review.

The electrical components of the prototype have been ordered. Once these components arrive, the team will implement design changes as necessary to make sure the components are successfully incorporated in the prototype. The team will also check in with the EE team to see how coding of wireless communication is going, and from there the team will gauge the timeline and determine if the ME team needs to do some of the coding.

7.2 Design Changes

As discussed beforehand, there were multiple changes to each component and subsystem of the arm. These changes were either due to motor implementation, user comfort, ease of manufacturing, or adjusted joint and connection work. Specifics on each each design change are discussed below with some components needing more dramatic modifications than others. The most current designs have been 3D printed in CAD and further adjusted. As each part becomes finalised, the team gathers a better understanding of how to best fit the components together. The final design will be the most optimised design for the client.

7.2.1 Cuff

The first design for the cuff, Cuff V1.0, was modeled from the UnLimbited Arm V2.1 of e-Nable [1]. On the new cuff, no thermoforming is needed and a flat placeholder is used to hold electronic components that would be added to the design. Figure 7.2.1 shows the e-Nable design next to the first iteration of the cuff.

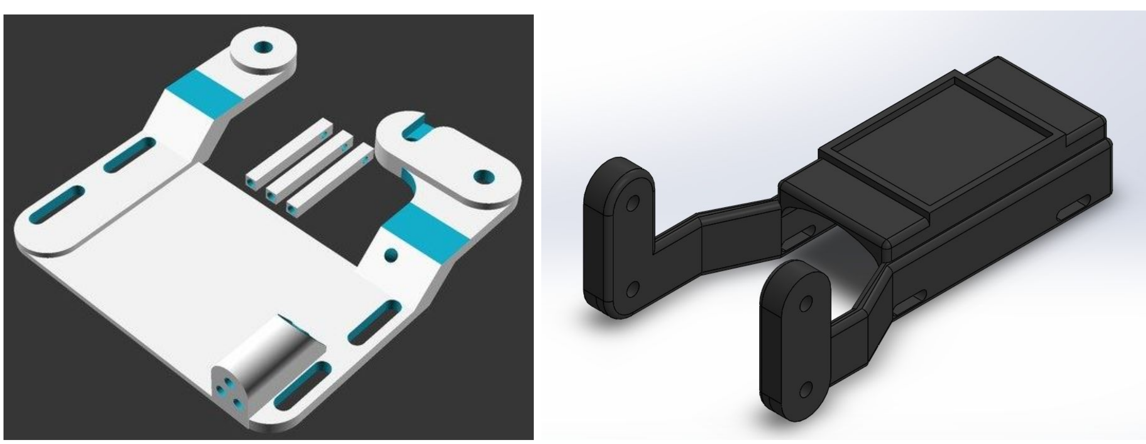


Figure 7.2.1.1: UnLimbited Arm V2.1 cuff left, Active Prosthetic Cuff V1.0 right

Since 3D printed parts have the lowest shear strength along the layer lines, the Cuff V2.0 was redesigned to be thermoformed to reduce the number of layers and keep the layers from being along the line of applied force. The design was also changed to cover the entire arm to reduce stress points caused by the use of straps and allow more room for electronic components. To cover the arm but allow adjustability, the cuff was designed using two pieces connected by a hing. Two casings were added to enclose the electronics and elbow assistant motor. Figure

7.2.1.2 shows the Cuff V2.0 assembled with the electronics holders in green, the two attachable pieces cuff plates in blue, and pins in yellow.

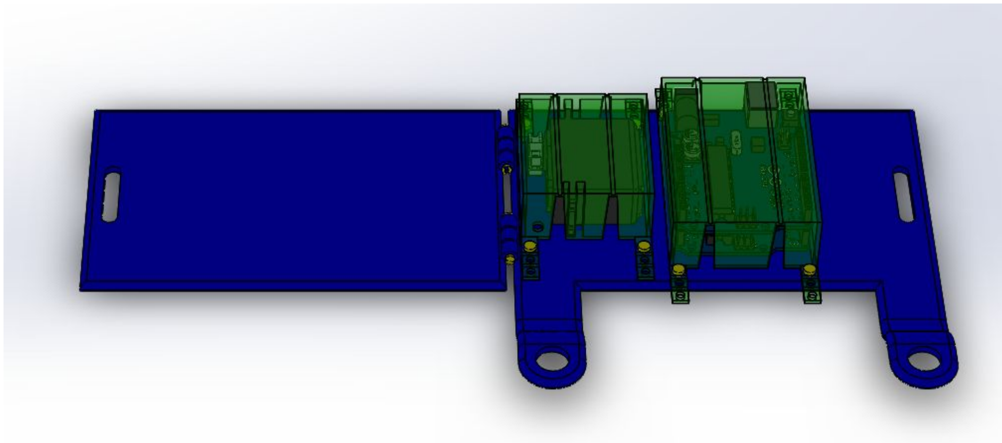


Figure 7.2.1.2: Cuff V2.0

When the design was printed, it was found that the electronics holder could not accommodate for the thermoforming process and did not attach easily or hold the required load. Moreover, the hinge system did not close properly and would not produce adequate support to hold the arm in place. The updated V3.0 cuff increased the thickness and percent infill of the design, allowing it to forgo thermoforming. This design also introduces a new way to attach the electronics casing using small snaps on the side of flat extrusions protruding from the circular wall of the cuff. The design uses the same forearm attachment as previous versions. Figure 7.2.1.3 shows the cuff V3.0 with many of the same components as V2.0 but in the new design without any yellow pins needed.

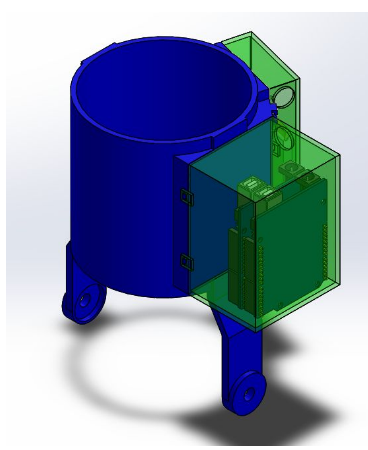


Figure 7.2.1.3: Cuff V3.0

The cuff was revised when a new microcontroller was found that would better suit the needs of the prosthetic. This new microcontroller, the Sparkfun RedBot Mainboard, does not require any shields to run motors or the XBee module. This reduced the depth of the electronics casing allowing the battery, booster, and new controller to fit in a single 1 inch shell. The design also replaced the assistant motor with a high torque assistant spring that would be placed inside the joint of the cuff to forearm attachment. A cut out in the arm was created to reduce interference of the cuff to forearm. Figure 7.2.1.4 shows Cuff V3.1 with the new board in red, and the spring attachment to the forearm in yellow.

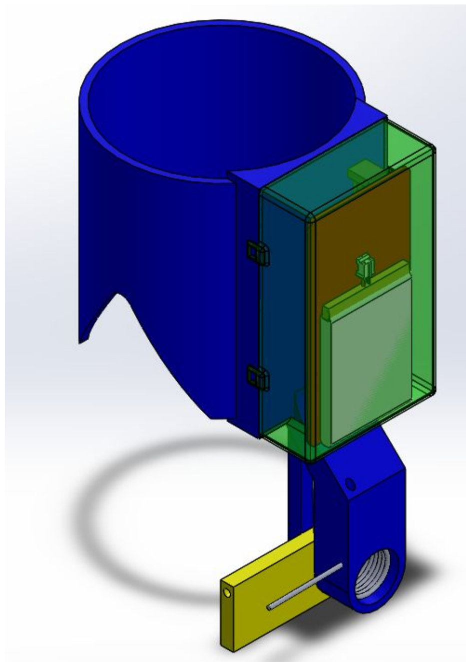


Figure 7.2.1.4: Cuff V3.1

A few revisions to the cuff were made for aesthetics, functionality, and strength. For better stability the second forearm attachment was re-added and both attachments were refitted to hold a lower torque spring. The forearm attachment was design separately at first for testing the two spring torques. Figure 7.2.1.5 shows the forearm attachments in purple with the right attachment made transparent to show the springs inside. The attachments were reinforced with thicker plastic along the connection area. The increased area will decrease the stresses exerted on the connecting pieces. The cuff also had the front cut removed as the new design will not allow for interference with the forearm. All edges of the cuff were curved to reduce the risk that the user might be scratched or irritated by sharp edges. Curving of the joints also reduced localized stress.

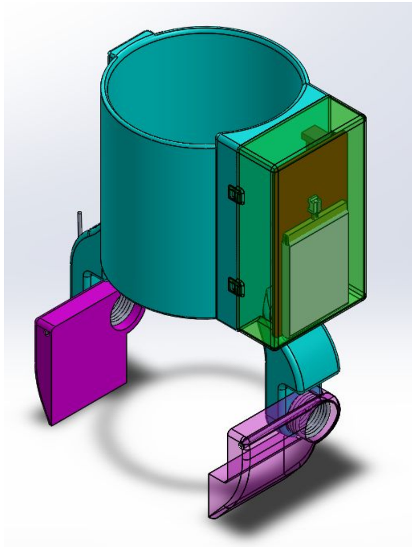


Figure 7.2.1.5: Cuff V3.2

Version 3.2 is where the form is finalized with edits made to the electronics case (ecase) to include more features.

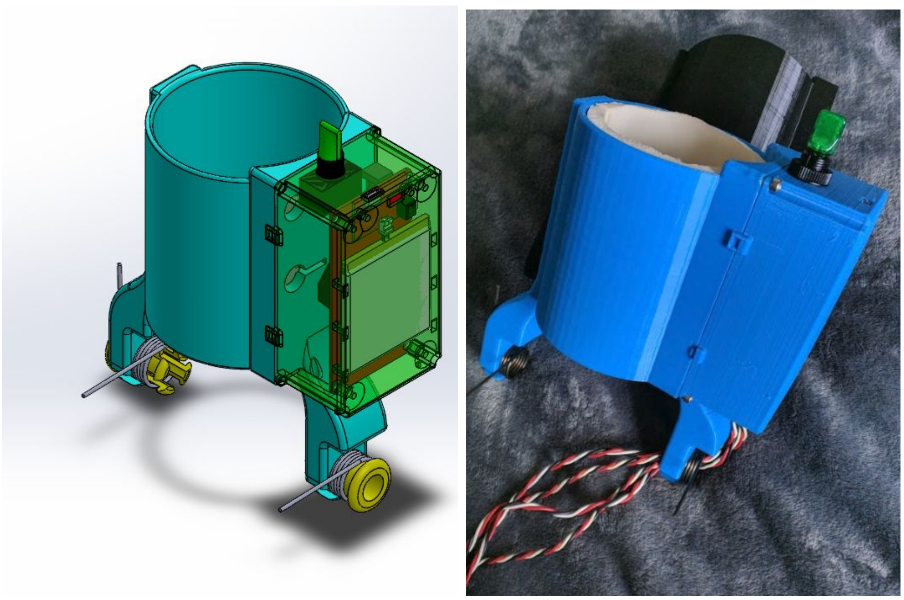


Figure 7.2.1.6: Cuff V3.3

Cuff V3.3 includes all final changes. Pins were created to cover the spring attachments, placement for the mode switch was included on the ecase and cutouts were made in the ecase for access to battery switches and charging ports. This final version is fully functional and assembles to the rest of the arm easily.

7.2.2 Forearm

The forearm went through three iterations after the Fall prototype before a design was agreed to be the most beneficial to the project. The Fall prototype was a single flat piece that was thermoformed to make the arm shape. This design was not efficient due to the forearm needing to house four servo motors for finger actuation. The first iteration of the Spring semester was two flat pieces thermoformed using a mold, so that the forearm would be able to house motors. The printed and thermoformed pieces are shown in figure 7.2.2.1 and the mold is in figure 7.2.2.2

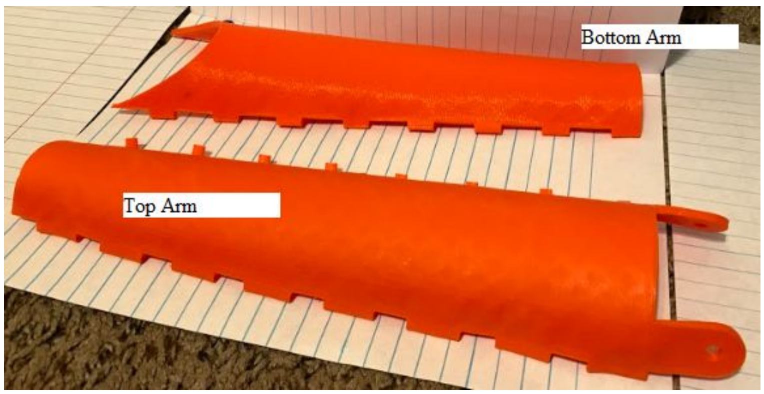


Figure 7.2.2.1: Thermoformed halves

Figure 7.2.2.2: Thermoforming Mold

The team discovered that if the wall thickness of the material is 0.125" and any cylindrical shapes are printed from the circular base upwards, shearing is not a concern and the durability is still as required. In order to incorporate this finding, as well as to simplify the manufacturing process, the second iteration of the forearm was made. This iteration consists of a front half of the arm that will hold the motors on a flat surface that slides in and out, and a back half of the arm that is hollow. Separating the arm in this way allows for protection from the heat of the motors. The two halves are connected by a slip-in knotch inside. The front half of the forearm is in figure 7.2.2.3, the back half in figure 7.2.2.4, and the two halves assembled is in figure 7.2.2.5.

Figure 7.2.2.3: Front half

Figure 7.2.2.4: Back Half

Figure 7.2.2.5: Assembly

After printing the second iteration, the size of the forearm was too fat and needed to be reduced. In order to reduce it and make it look more like the shape of an arm, the third iteration will be a full circle with a flat extrusion inside the front half for the motors. The height of the front entrance to the arm was also to short for motors to fit in the second iteration, so it was increased for the third iteration. The attachment mechanism for the front and back halves was also slightly altered, so that the extruded cut reached the surface of the print for ease of sliding the pieces together, and the slip-in knotch is mirrored on both sides of the cross-section to increase stability of the assembly. The CAD for the assembly is in figure 7.2.2.6.

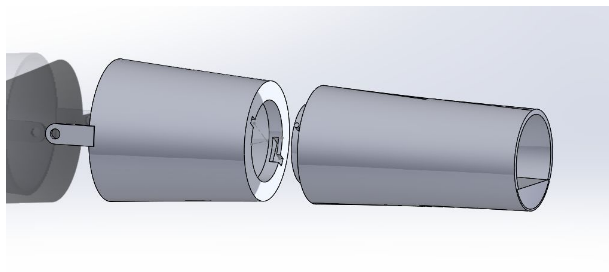


***Figure 7.2.2.6**:* CAD Assembly by Midpoint

This concept was the final shape of the forearm, with changes from here on out only altering dimensions and adding minor adjustments for ease of use, durability improvements, and assembly improvements. These adjustments include adding a lid to cover the motors, adding holes for the wires and threading, adding tubing for the wires, improving the cuff attachment to be built for the spring, adding a palm attachment, adding a key to secure the back and front halves together, and ensuring that there is enough space for the residual limb of the client to be placed within the back of the forearm. The final design of the forearm is in figure 7.2.2.7.

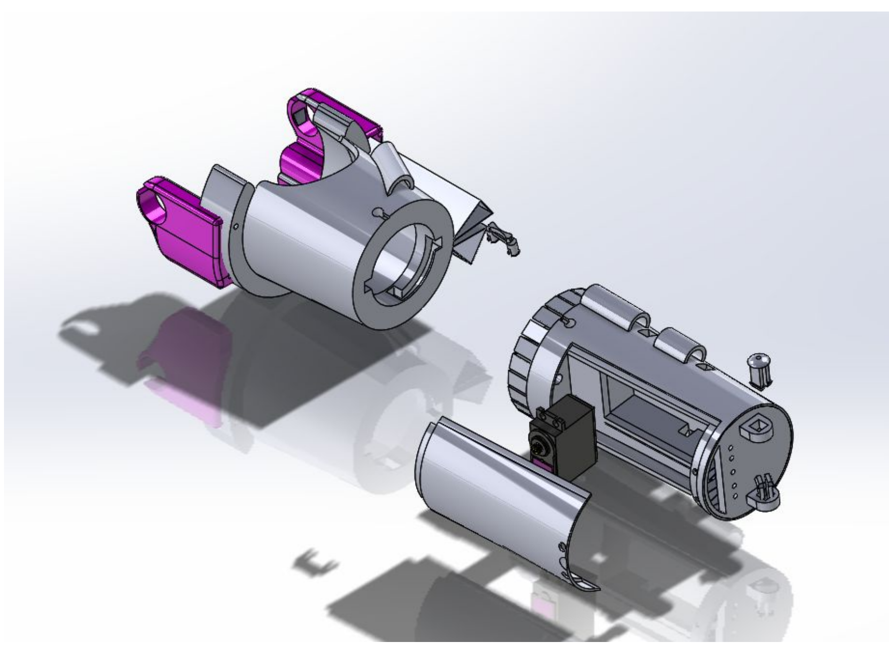


***Figure 7.2.2.7**: Final Design*

7.2.3 Palm

The first design of the palm was a very rudimentary design meant mainly to understand how other parts would be connected together. Below shows the basic CAD of this palm in Figure 7.2.3.1.

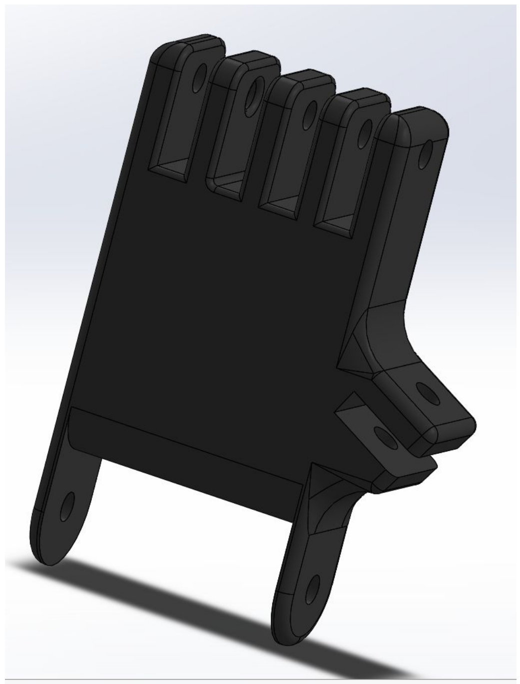


Figure 7.2.3.1: First palm iteration

It was understood that the inside of the palm needed to be hollow to allow the wires and possibly sensors to run through the entirety of the arm. However, it was still unclear as to how that would be assembles and how to guide the user to assemble this themselves. The wrist connection was thought to be a very basic hole and large pin connection which allows the hand to move up and down. It was still undecided as to how the palm cover would connect to the rest of the palm.

The new version during early Spring, shown in Figure 7.2.3.2, had a better understanding of how the fingers connected together. Created in early January, this design would give the thumb full mobility. It was decided that in order for the thumb to have full mobility, the palm would need to have a motor included that could directly pull the wires responding to the pressure sensors. The palm incorporates a ball and socket placement for the thumb. This allows the thumb could move both left to right and back and forth is a s follows: the two pressure sensors corresponding to the two big toes could be able to move this one thumb. One pressure sensor would move it left to right while the other would move it back and forth. This set up allows the client to participate in activities much easier than before. Activities such as playing video games or even grabbing certain objects will now be possible with this design. The four other fingers are still connected as usual with minor changes. The team decided this semester to also connect the fingers using wires instead of rubber bands as previously planned. It will make it much easier to move the fingers to a full grip position and bounce back. Because of this, the rest of the palm was made hollow still below the compartment for the motor for the wires to connect through.

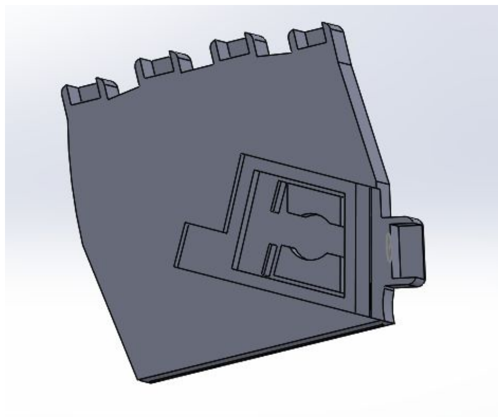


Figure 7.2.3.2: *January Design*

The way the top of the palm connects is through a slide in system, similar to how the bottom of a mouse top connects to the battery component. It can be opened using pressure and requires no special tools. This design will make it easy to open and close and only includes one necessary part unlike another pin connection which would mean more parts and more difficulty assembling and disassembling. It also makes the palm more aesthetically pleasing than before.

The next palm design includes the redesigned top component as well as a better thumb connection. This design can be found Figure 7.2.3.3 and Figure 7.2.3.4 below. With the idea of a ball and socket no longer needed, the palm had to be readjusted. Here, there is room for the motor as well as guides for the wires to go through. Instead of a small portion of the palm being open, the entire palm has an open compartment which should make things much easier to assemble or fix any parts if necessary.

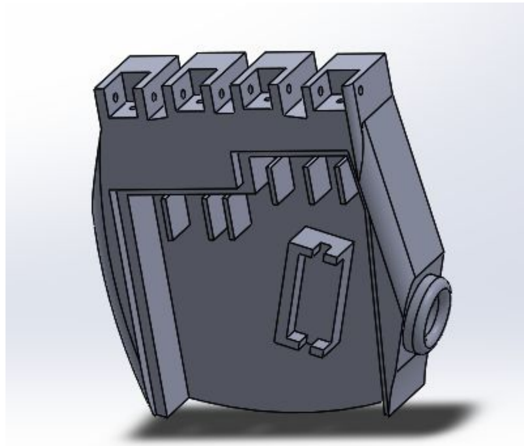


Figure 7.2.3.3: February Design

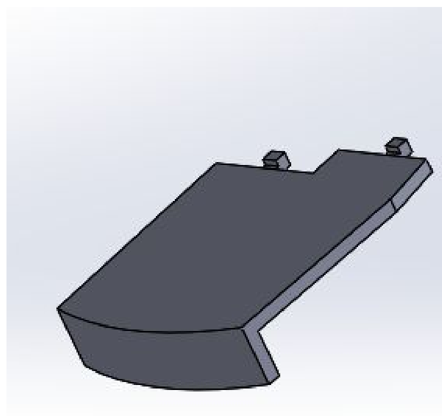


Figure 7.2.3.4: February Palm Top

The overall design was slimed down and to resemble a palm and the top four finger attachments were made thicker for better stability. The thumb connection changed as well to allow for better mobility for the finger.

The final palm design is the most sophisticated version that does not allow for wrist mobility. This design has a better thumb connection that allows the wires to move without getting tangled. It also has improved finger mobility function for a fetter hand holding motion. Figure 7.2.3.5 shows the final palm and palmtop with improvements.

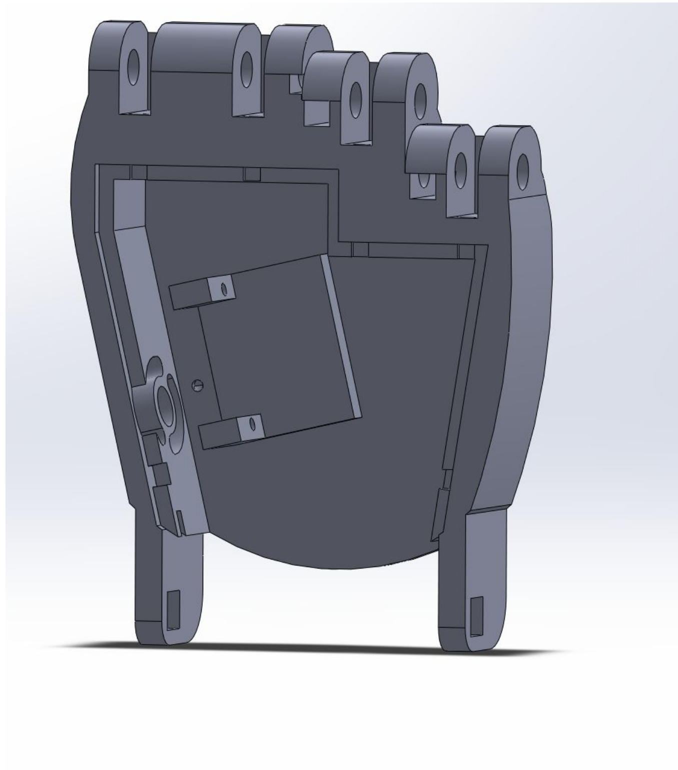


Figure 7.2.3.5: Final Design Palm

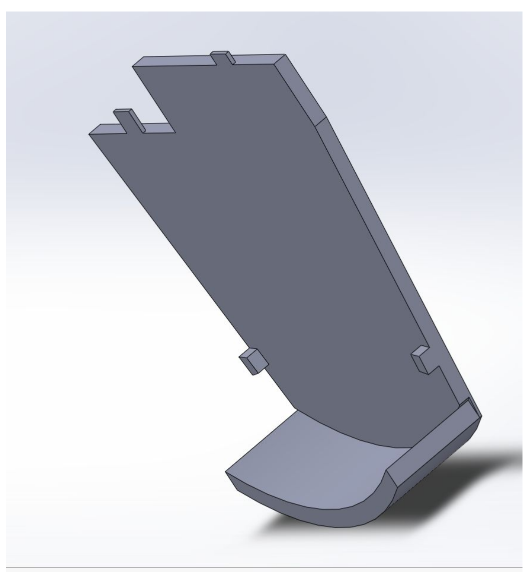


Figure 7.2.3.6: Final Palm Top

This design does not include the guides because they were no longer necessary. This is because the final design has holes created in the back of the palm that the wires can easily slip through. As described in the user manual, the user will slip the wires through the back of the palm, up the fingers, and finally through the bottom hole of the hole to connect to the holes on the forearm. The wires did not tangle and the arm was fully functional when testing it. The pin and thumb holes were enlarged as well to allow for better rotation. For the motor, the final design was edited to just have two small posts that two screws can go through to secure it down. This made it much easier to assemble as well.

As shown, the palm top was adjusted for better security and to allow for the wires to go through the bottom of it. They will now simply slide in from the front and should secure in place from the front inserts shown in Figure 7.2.3.6. The connection to the forearm now has square hole connections so the wrist will not move.Finally, the whole palm design was edited to make a more aesthetically pleasing and less boxy design.

7.2.4 Fingers

There have been many changes to design of the fingers sense fall of 2018. Among these changes is utilizing fishing line for tendons that loops around the fingertips, a tendon channel that crosses to allow the looping, and a channel that will hold pressure sensors that will sense the user grabbing an item. The hinge pins holding the finger segments has also changed to be more functional. The the dimensions of the fingers have been changed since fall to accommodate the other design changes and durability. There is a significant evolution from the fall 2018 design and the current design. The fall, mid spring, and current designs can be viewed in figures 7.2.4.1, 7.2.4.2, and 7.2.4.3 respectively.

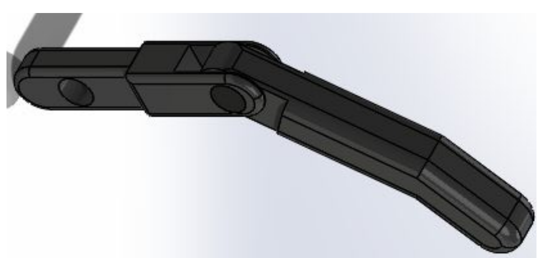


Figure 7.2.4.1 Fall 2018 Prosthetic Fingers Design

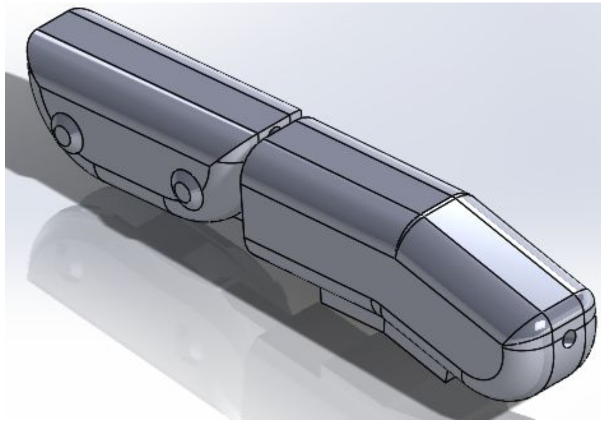


Figure 7.2.4.2 Mid Spring 2019 Prosthetic Fingers Design

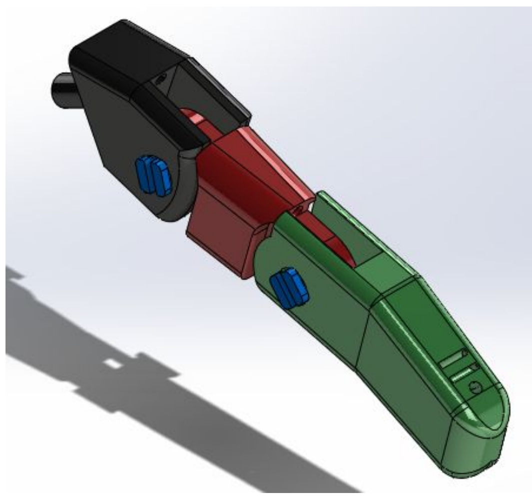


Figure 7.2.4.3 Final Spring 2019 Prosthetic Fingers Design

The fingers of system from fall consisted of a proximal segment, a distal segment, and hinge pins that hold them in together and allow motion. The newer design is very similar and still has these components. However, it has evolved to better suit customer and engineering requirements.

The pins from the original design were not held into place with anything and slide out of the joint. The finger pins are now evolved to have pinheads and horizontal slits. The pinheads are frustum shaped and have a larger diameter than the pin. This allows pin to be held on each end and not fall out of the joint. The new pin design also has a slit cut through it horizontally. The slit allows the end to be pinched or squeezed smaller to fit through the joint hole and then expand back into place once it reaches the other side. The dimensions still need to be perfected to for the pin to fit through the hole and not break as it enters. The mid spring pin design with pinheads and horizontal slit can be seen in Figure 7.2.4.4.

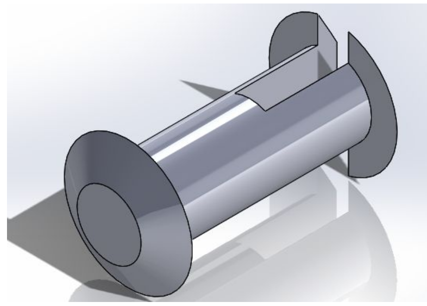


Figure 7.2.4.4 Mid Spring 2019 Hinge Pin Design

The final hinge pin design is similar with minor changes to the dimensions. This was done to account for part tolerancing. The pin head was changed to a rounded square. This change allows it to slip into the finger segments. The final design can be seen in Figure 7.2.4.5.

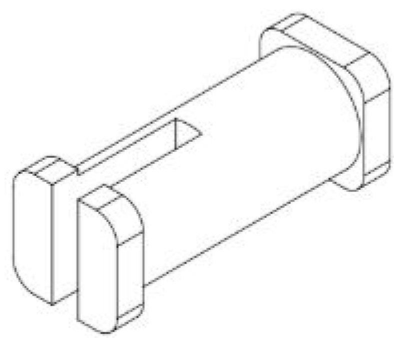


Figure 7.2.4.5 Final Spring 2019 Hinge Pin Design

The proximal and distal segments of the fingers designed in fall did not have controlled motion. This is because there were no tendons running through from the motors to the fingertips. The motion of the fingers is created by pulling on the tendons. This moves the fingers to flex and relax. The solution to this was to add tendon channels that will allow the artificial tendons through the fingers. The early designs in spring of 2019 have done this through tendon channels that went straight through the fingers. These early spring designs could only move the fingers to flex. So, it had rubber bands that would pull the fingers back after the motor tension is released. The rubber bands were hooked onto the backside of the proximal and middle digits. This design can be seen below in Figure 7.2.4.6.

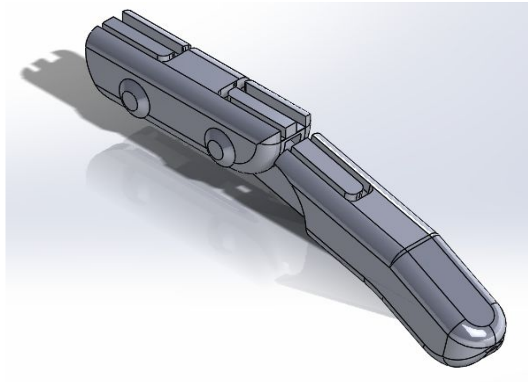


Figure 7.2.4.6 Early Spring 2019 Proximal and Distal Digits

The early spring design was changed to the new design. The reason for the change was to remove the rubber bands. The new design utilizes a crossing channel tendon channel. This allows the tendon to loop around the end of the finger and be pulled in both directions. The new design can flex and extend the fingers using just the motor. Due to this the old design used rubber bands to counteract the polling of the tendons the mid spring and current design is no longer needed. The most recent design also has pressure sensors. The design from fall 2018 and early spring 2019 did not utilize sensors and these are needed to notify the user that they are grasping an object. The new design utilizes sensors. So, a channel was added to hold the pressure sensor wires that channel. The mid spring design of the crossing tendon channels and sensor channels are shown below in Figure 7.2.4.7.

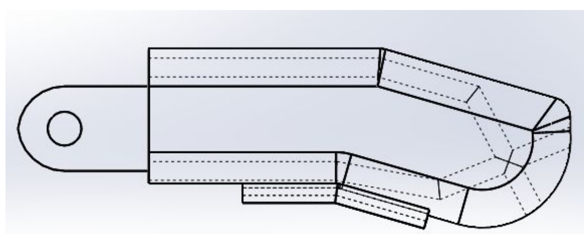


Figure 7.2.4.7 Mid Spring 2019 Distal Digit with Crossing and Sensor Channels

In addition to the sensors the fingers will be given grip so that the patient can hold items without them slipping. The grips are rubber sleeves that slip on over the fingertips.

After many configurations the fingers finally settled on the final design. The tendon channels no longer cross but the tendons loop around the finger creating a knot that keeps the wires from slipping. The sensor channel is also moved inside the finger. This change made the fingers less bulky and more practical. The final Distal digit can be seen in figure 7.2.4.8.

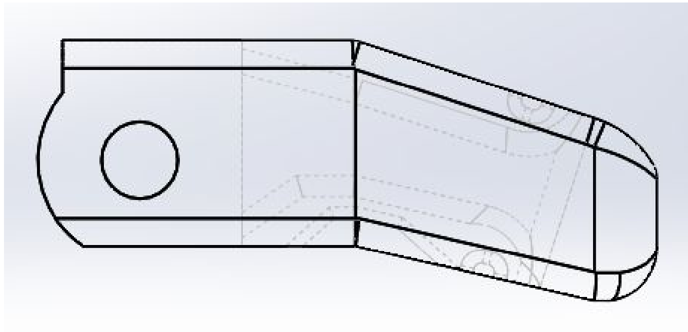


Figure 7.2.4.8 Final Spring 2019 Distal Digit with Tendon and Sensor Channels

The Proximal digit connects the distal digit to the palm and thumb base. These are also equipped with tendon channels. The design for the proximal segment remained generally the same. The design was only changed to smooth the edges and make it more aesthetically pleasing. The proximal digit can be seen in figure 7.2.4.9.

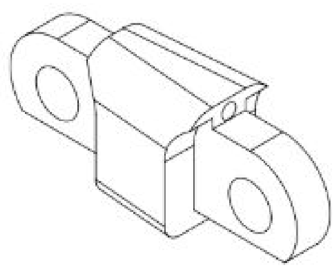


Figure 7.2.4.9 Final Spring 2019 Proximal Digit with Tendon Channels

The finger that was be changed the most was the thumb. The thumb is a little different from the other fingers because it needs to have a larger range of motion. This was accomplished by attaching the proximal segment of the thumb to a rotating base. This rotating base has its own motor specialized in rotating the thumb along many different planes. This rotation creates more issues because the thumb will still have tendons traveling through its proximal and distal segments.The rotation could cause the tendon thread to get tangled. To adjust for this, the rotating base has specialized tendon channels so that the string from the proximal and distal finger do not get tangled when the thumb rotates. In addition, the palm was designed to have circular slits that allow the tendons to travel through the plam without getting tangled. The rotating base can been viewed below in Figure 7.2.4.10.

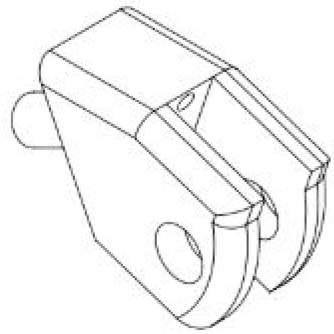


Figure 7.2.4.10 Final Spring 2019 Rotating Base with specialized Tendon Channels

There have been many changes and adaptations to the original finger design. These include hinge pin edits, tendon channel alterations, sensor implementation, and rotating thumb base. Each change has made an improvement on the design and fulfill customer needs.

8 Testings

To test the prosthetic arm, there were seven engineering requirements established by Dr. Winfree. These engineering requirements were:

1. Scalable Size
2. Weight
3. Budget
4. Durability
5. Force to Actuate
6. Force of Grip
7. Number of Parts

Each engineering requirement had a limit to reach in order to be considered a successful design. The arm needed to be scalable between 6-18 inches in length, weigh less than 3 pounds, and have less than 100 parts in the assembly. When considering its force, it must withstand up to 10 pounds of weight, have an actuation force less than 5 lbf, and have a grip force less than 2 lbs. The entire arm, when fully assembled, must be within a budget of $500. A summary of the testing procedures is in table 8.1.

Table 8.1 *Testing Procedures*

Engineering Requirement	Testing Procedure
Scalable Size (6-18in)	Scale in SolidWorks
Weight (~3 lbs)	Weigh using fishing scale
Cost ($500)	Tally Receipts
Force to Actuate (<5 lbf)	Measure from force sensors (1 lbf)
Force of Grip (2 lbf)	Measure from motors (9.5 in*lbs)
Number of Parts (<100)	Tally Parts
Durability (>10 lbf)	Withstands extreme forces

1. The scalability test is done by changing the dimensions of the CAD to ensure that no components fail between size changes. If components fail, or features overlap that should not, then the design needs to be altered.

From this test, the scalability of the design can be found in table 8.2. There are multiple parts to the device and each part must be functional at different sizes. Some parts must keep key dimensions in order for other components to to fit together. The purchased parts are not adjustable. Therefore, the CAD must be able to accommodate the purchased items while still being customizable. Due to this, some items and parts are only adjustable in certain directions or not adjustable at all. The table shows which parts can be changed, its scalable direction, and the range in inches for each.

Table 8.2: Device Parts and Size Ranges in Length, Width, and Height

Part	Scalable? (Yes/No)	Range in Length (in)	Diameter (in)
Cuff	Yes	N-A	2.5-6
Forearm- Back half	Yes	3-6	2.5-6
Palm	Yes	2-4	N-A
Fingers	Yes	1.5-4 (in)	N-A

Each subsystem of the prosthetic could be scaled in the desired directions needed when measuring a new client. The cuff only needs to change in diameter to fit different upper arms, the back half of the forearm needs to increase in length and diameter, the palm needs to increase in length and height, and the fingers need to be scalable in length. This was evident by using SolidWorks to change lengths and diameters of the subsystem. The total length of the arm is scalable between 10.5-18 inches. While the arm could not be scaled to 6 inches, this length range is required in order to incorporate the servo motors used. Therefore, this sizing is acceptable.

2. The weight of the arm was measured by using a bucket and a scale. Due to the current state of the product is in multiple pieces due to the electrical components being separate from the mechanical components, the pieces were put into this bucket and weighed individually, with the total weight being the summation. The empty bucket was weighed first to establish the zero value in the analysis. Figure 8.1 shows the weighing process.

Figure 8.1: Weighing Test

The resulting weight of the prosthetic was 2 lbs, therefore the prosthetic passes the test.

3. The budget is calculated by summing up the materials used to produce a single prosthetic arm. Table 7.1.1.1 is the bill of materials for one full functioning prosthetic, located in section 7. The total budget for one prosthetic is $383.88, which is less than $500. Hence, the prosthetic meets this requirement.

4. The durability test is done by submitting the prosthetic to a large force for a number of times, whether by using a tool or throwing it at the ground. The prosthetic was thrown and hit. In other words, the team treated the arm carelessly and as if the client was banging it into a lot of walls and tables while in use, which is considered an extreme scenario. Figure 8.2 is the arm prior to testing. Figure 8.3 shows the result of the durability test after dropping it on concrete from shoulder height. Figure 8.4 shows the result of throwing the arm down a flight of stairs. Figure 8.5 shows the result after a few more throws down stairs.

Figure 8.2: Before Testing

Figure 8.3: After test 1

Figure 8.4: After test 2

Figure 8.5: Final Aftermath

After test 1, a few of the pins broke on impact, which separated the subassemblies and assembly. However, the individual subassemblies did not have cracks or damage to them. After test 2, the cuff attachments and wrist attachments broke because these were attached to the thinner parts on the arm. However, the individual components were still intact. After test 3, almost all of the pins broke, the palm had a crack in it, and the forearm motor lid was also cracked. Some of the breakage was due to shear on the parts when printing.

As a result of this durability test, the pins need some diameter adjustments and printed flat in order to ensure less shearing fractures or other forms of breakage on impact. This test gave an understanding of the extreme stresses the arm could handle. The arm will survive everyday bumps from tables or walls and can likely survive if the client fell and landed directly on the arm at least once. Any further accidents concerning repeated falls or drops will mean that the components would have to be reprinted.

5. When the engineering requirement of actuation force was given, it was made without consideration of the pressure sensors in the insole. The pressure sensors in the insoles can detect up to 1 lbf. The amount of pressure put on these sensors relates to the amount of actuation the servo motors give to the fingers. Because the sensors can only sense up to 1 lbf, 1 lbf is all that is necessary to actuate. Hence, this requirement is tested by putting pressure on the sensors and ensuring actuation occurs. This requirement is met.

6. The force of grip could not be measured due to the slight dimensional errors for running the wire through the palm and fingers. However, the motors can produce a force of of 9.5 lb*ins. With the wires properly threaded, the force would increase to the user's advantage. Thus, it is safe to assume that the force of grip is within the engineering requirements.

7. To determine if the number of parts is less than 100, every piece was counted as a part. This number included pins, screws, wires, sensors, subassembly components, and electrical components. Table 8.4 and 8.5 display the part, number, and quantity.

Table 8.4: Part List and Quantities Pt 1

Part Number	Part Name	Quanity
1	Digit 1 Rotating Base	1
2	Digit 1 Proximal	1
3	Digit 1 Distal	1
4	Digit 2 Proximal	1
5	Digit 2 Distal	1
6	Digit 3 Proximal	1
7	Digit 3 Distal	1
8	Digit 4 Proximal	1
9	Digit 4 Distal	1
10	Digit 5 Proximal	1
11	Digit 5 Distal	1
12	Rotating Base Hinge Pin	1
13	Finger Hinge Pin	5
14	Mini Pressure Sensors	2
15	Palm Pin Long	1
16	Palm Pin Short	2
17	Finger Grips	5
18	Palm	1
19	Palm Cover	1
20	Micro Motor Screws	2
21	Micro Motor	1
22	Beed Wire	5
23	Servo Motors	4
24	Servo Motor Screws	16
25	Front half	1
26	Back half	1
27	Motor lid	1

Table 8.5: Part List and Quantities Pt 2

Part Number	Part Name	Quanity
28	Motor lid pins	2
29	Forearm key lock	1
30	Palm attachment pins	2
31	Torsion Springs	2
32	Cuff	1
33	Foam roll	1
34	Vibrating motors	3
35	Electronic Cover	1
36	Battery 1Ahr	1
37	Battery 2Ahr	1
38	Charger and Booster	3
39	Amphenol FCI Clincher Connector (2 Position, Female)	7
40	SparkFun RedBot Mainboard	1
41	RedBot Screws	4
42	XBee 1mW Trace Antenna - Series 1 (802.15.4)	3
43	Shoe insoles pack	1
43	Ankle band	2
43	Ankle attachment	2
	Total	98

The total number of parts is 98. Because screws and pins are required to hold the larger components and the electronic components in place while vibration occurs, this number is a necessity to have a fully durable and functional prosthetic. The number of parts can be decreased in some cases. These cases are include items that are redundant.

Throughout the testing of the prosthetic arm, the different technical and customer requirements were met. These requirements were scalability, weight, budget, durability, actuation force, grip force, and part count. Overall, the arm was successful in meeting the requirements. There are, however, a few exceptions. These failures to meet expectations have simple solutions. The arm successfully met the scalability, weight, budget, durability, actuation, and grip. The number of parts did not meet the limit requirement but this will be rectified by removing redundant parts. The durability will also be improved by making the attachments denser and/or larger. With minor changes, the hand meets all the requirement tested.

9 Conclusions

This section discusses the post mortem analysis of the Active Prosthesis. This includes details on the project's success and contributions that led to a successful are analyzed in detail. Why some goals were met and others were not is an important part to this project as it impacts quality of the device given to the client. When goals are not met future improvements must be considered. The second part to this conclusion examines the goals that were not met and suggests future work for the Active Prosthesis.

9.1 Contributors to Project Success

After the research, design, and implementation of the project, it can be concluded that the project was a great success. The team completed the purpose and goals of the device. These were to create an active prosthetic device that could give someone a sense of touch by providing feedback, with the goal of having a lightweight, aesthetically pleasing, and mobile device. The team wanted this device to exceed the users' expectation in both function and design. The final design met all of these requirements by implementing a foot controlled component. This would allow the user to move the individual thumb with full mobility and included pressure components that responded to both the grip and vibrating motor; meaning, the harder a user pressed on the pressure sensors, the bigger the force and vibrations would be produced. The device was lightweight in that it had an additional spring assist that would reduce the overall weight. It was also shown to be fairly comfortable with the additional padding in the cuff. All of these features helped meet both the customer and engineering requirements. The active prosthetic device even included additional features that were not previously required. These include grips on the fingertips to better hold different objects as well as a stylus on the pointer finger that allows the user to use their phone. Even with all the necessary components, the final design is a user friendly and scalable device that can be improved on by the Enable team as well as other people around the world that have ideas on how to improve the device.

The success of the design also benefited from time management. The team aspired to complete each task in a timely manner to have a successful design. Although not all tasks were completed three days ahead of time, the final design was completed in time for UGRADS. Each team member had different backgrounds, skill sets, and personalities. These difference brought more success to the design as each member was already familiar with their share of responsibilities or tasks. There was rarely any issue with the team collaborating with each other as each member found they could use their skill set in some way to help the project move forward. Whether by expressing their confidence in presentations, utilising their research or design skills, or by organising the BOM or papers, each team member found some way they could help contribute to the project.

The ground rules were followed fairly well in that the team was able to successfully meet each week and gave thorough updates on their part of the design. The team members were respectful of each other and did not insult one another during the meetings. Each member selected the part of the arm they wished to design and edit so everyone could contribute to the design. The team utilized the coping strategies well and took breaks if there was any tension during the meetings. No member physically left the room however, and usually chose to listen to music or take a moment for themselves if tensions rose. Because each member had a passion for biomechanics and prosthetics, the team took the project very seriously and tried to help each other if anyone experienced issues.

Most of the potential barriers were avoided during the project. While at some parts of the year some members took on more work, it was found that each member took turns in handling a larger workload. The scheduling aspect was difficult but still successful in that the team could still meet most weekends. If the team member had to be absent, they would still contribute to their assigned task and even participate in a phone conference or google drive if necessary.

As described, the design and project was very successful due to the collaboration of each team member and the hard work dedicated to the design of the project. It was only through successful time management and an equal passion for this project that led to its success. It is hoped that the teams design can be further improved upon in the future.

9.2 Opportunities/areas for improvement

The active prosthetic was a great success. Despite the success of the project there are a few opportunities to improve the device. The team successfully completed the purpose and goals from the team charter. The team also successfully worked together and followed ground rules to be successful and meet all their requirements. The team also faced problems but these were remedied via organizational actions to improve performance. All this and more lead the team to learn technical lessons from the year.

The success of the team can be measured by the by the completion of the project Purpose and Goal stated in the Team Charter. The purpose as stated in the Team Charter is to create a prosthetic arm device that gives a "sense of touch and mobility to children who have lost a limb, allowing them to better interact with the world around them." Although the arm exceeded the requirements, there are still opportunities for improvement. The arm, although meeting the durability standards, can be upgraded by strengthening parts. In particular, the attachment pins and clasps arm small and could benefit from being made from stronger materials than 3D printed plastics. Another enhancement is making the form of the arm look more organic and slimmer. The final design is bulky and looks more robotic than an ordinary human arm. This can be improved by smoothing sharp edges using smaller electronic to reducing the arm size. The active prosthetic arm wonderfully met the goals and requirements of the team. This success is credited to the team members following the their ground rules and coping strategies.

In the team charter, the ground rules and coping strategies were instituted to ensure the project was a success. Some of the rules that the team instated were: meeting at least once a week, provide constructive criticism, keep updated on tasks, be respectful, and take cleansing breaks during tense situations. The coping strategies from the start of the project helped cool tensions in the team. Although when issues did arise, the team communication coping strategy lead to harsh comments. Because the communication did not work as planned, the strategy was changed to taking cleansing breaks apart to cool down. This new strategy kept the team in better harmony. Despite the few team disagreements, the team reconciled and as a result the project was back on track and even more successful. The success aided the project's performance.

The project performance was dependant on how the team worked as a group and on individual assignments. Some of this was positive as discussed above but some were negative. the team struggled with time management near the end of the project. There were many changes to designs near the due date. Thus, the last iteration of the product was finished after extensive and long hours. In addition, the stakeholder satisfaction is currently unknown. The electrical components were not completed by the Electrical Engineering team. So, the client has not used the arm for long and does not have the product as a whole. Thus, the user satisfaction data is inconclusive. However, the product does fulfill the customer requirements required of the Mechanical Engineering team. So, it is expected to satisfy the client. The methodologies helped the team to create positive project performance.

The team did face challenges throughout the project. The main challenge, as discussed above, was time management. This can be fixed by organizing the time management and improve performance. In the future, the team should aspire to complete tasks days prior to the due date. This would allow more time to make changes if needed and result in better results. This project taught the team certain technical lessons. Some technical lessons that were learned include advanced SolidWorks CAD skills, familiarity with arduinos, and understanding the mechanics of the human arm. These not only advanced the team's knowledge but were important in designing their successful active prosthetic arm.

10 REFERENCES

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11 APPENDICES

11.1 Appendix A: Additional Concepts

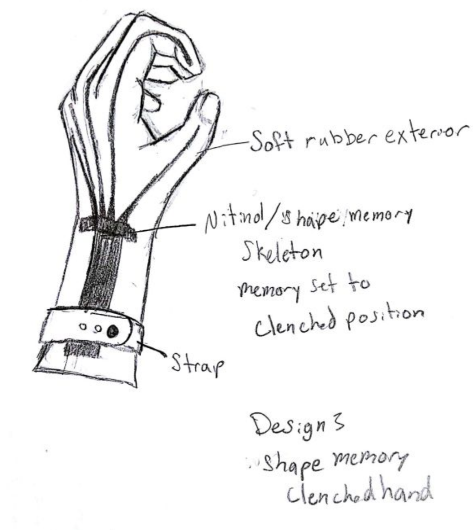

Figure A1: Shape Memory

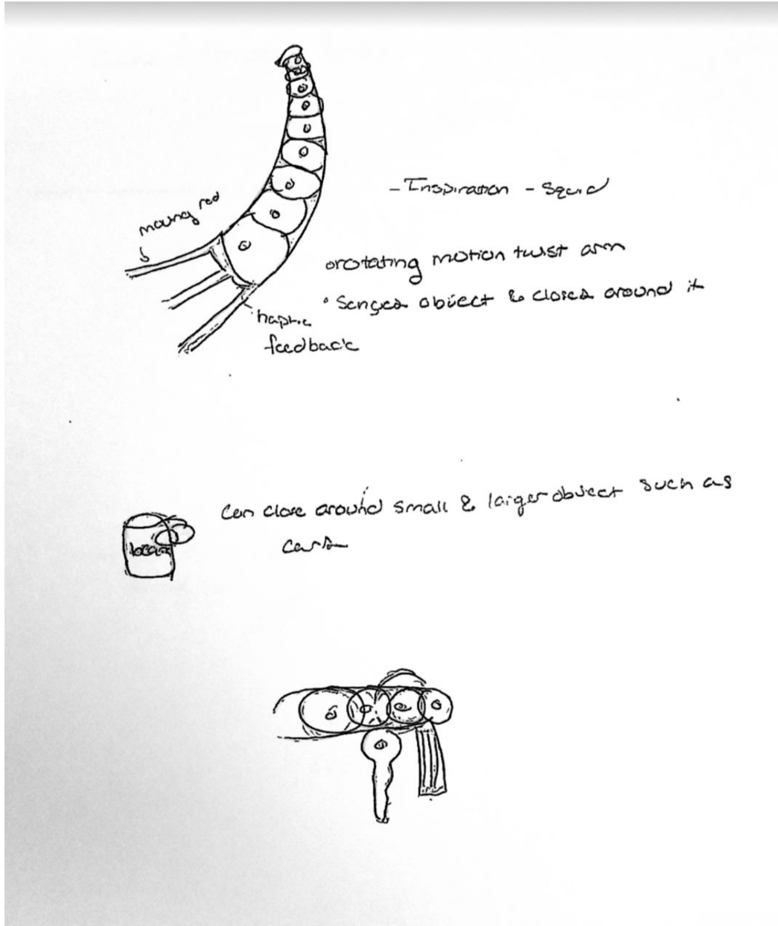

Figure A2: Cool Hand Squid Man

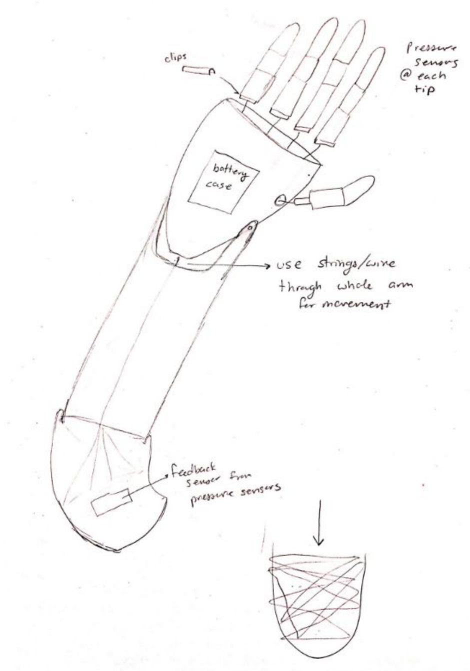

Figure A3: Clip-o-Grip

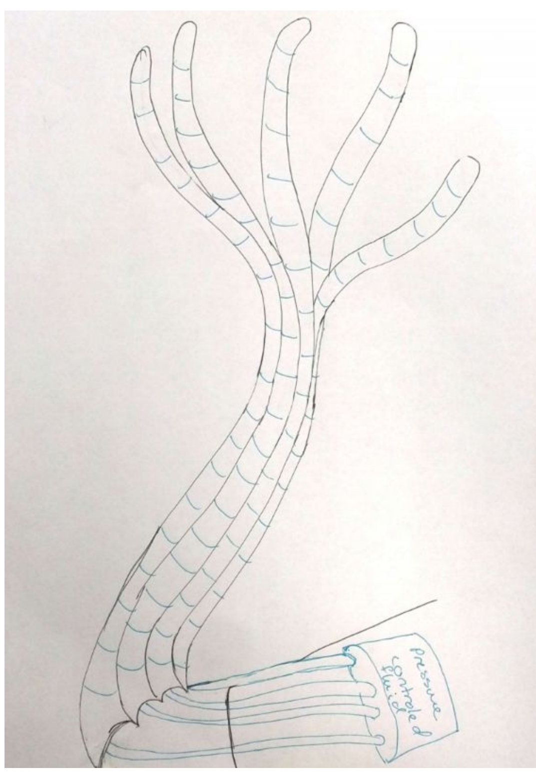

Figure A4: Vine Grab

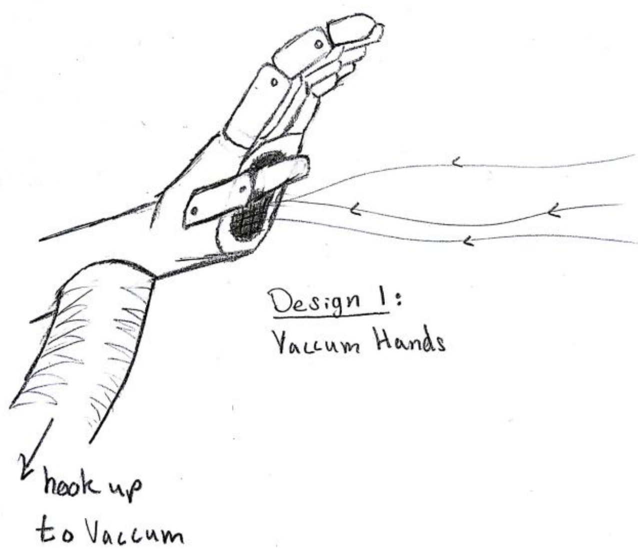

Figure A5: Vacuum Hands

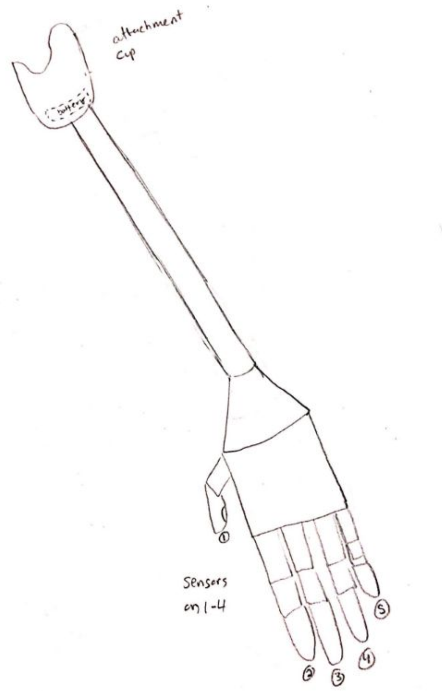

Figure A6: Need-Forearm-Muscles

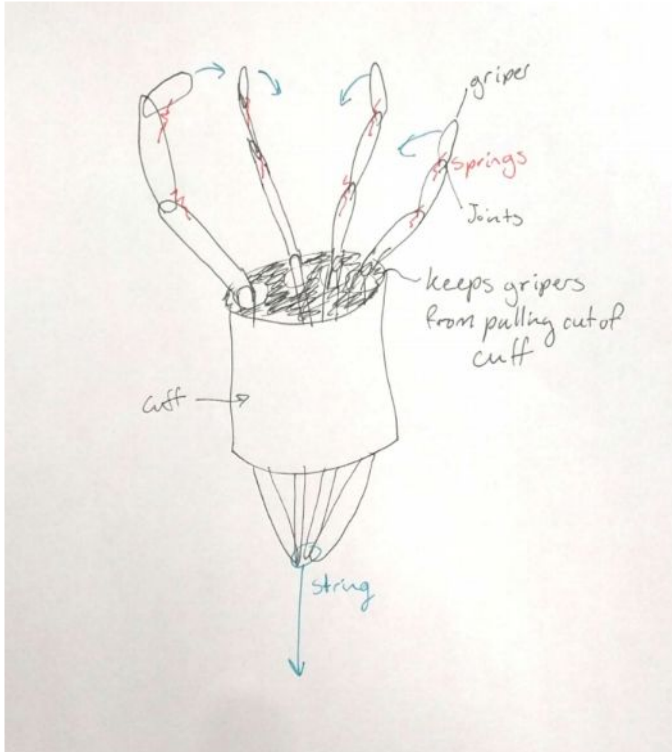

Figure A7: Pincer

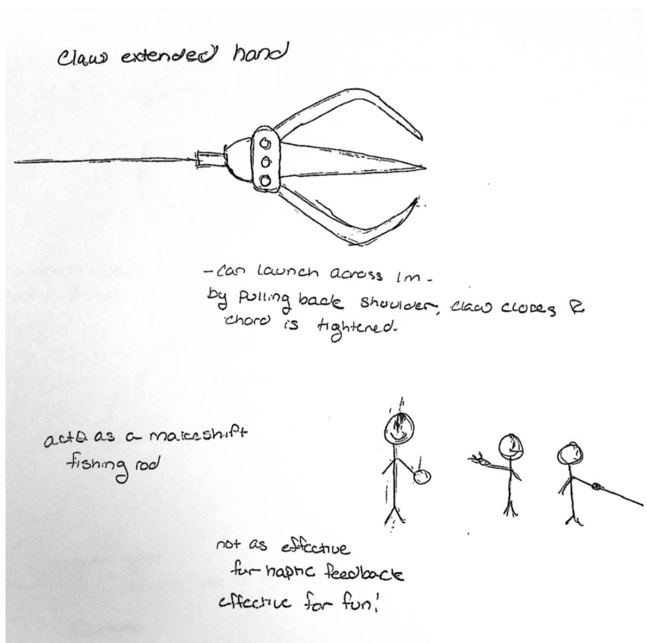

Figure A8: The Claw

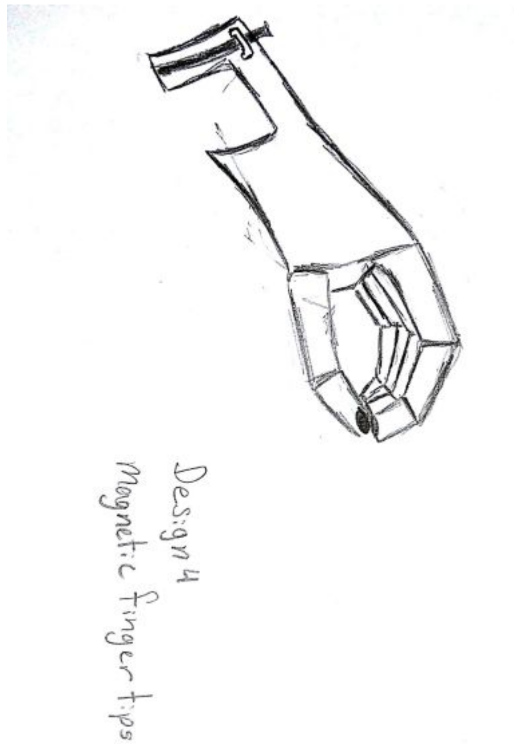

Figure A9: Magnetic Fingertips

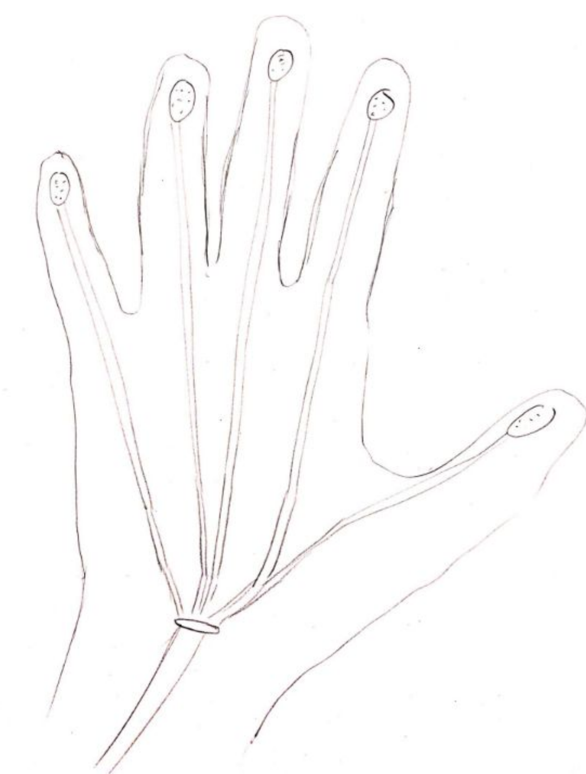

Figure A10: Visible Nerves

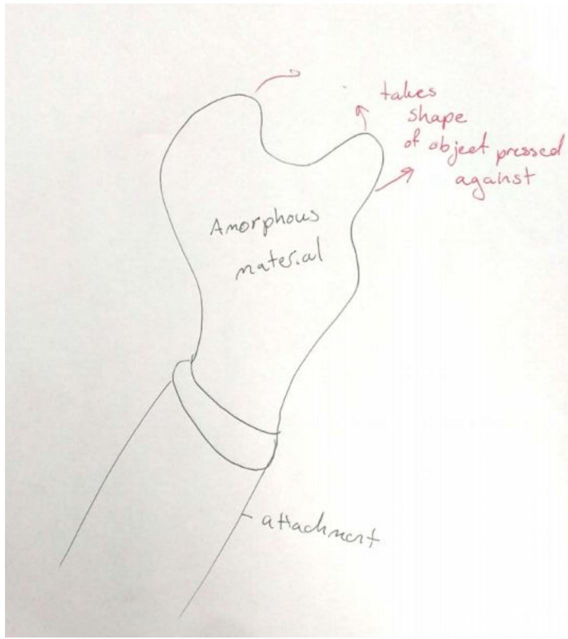

Figure A11: The Blob

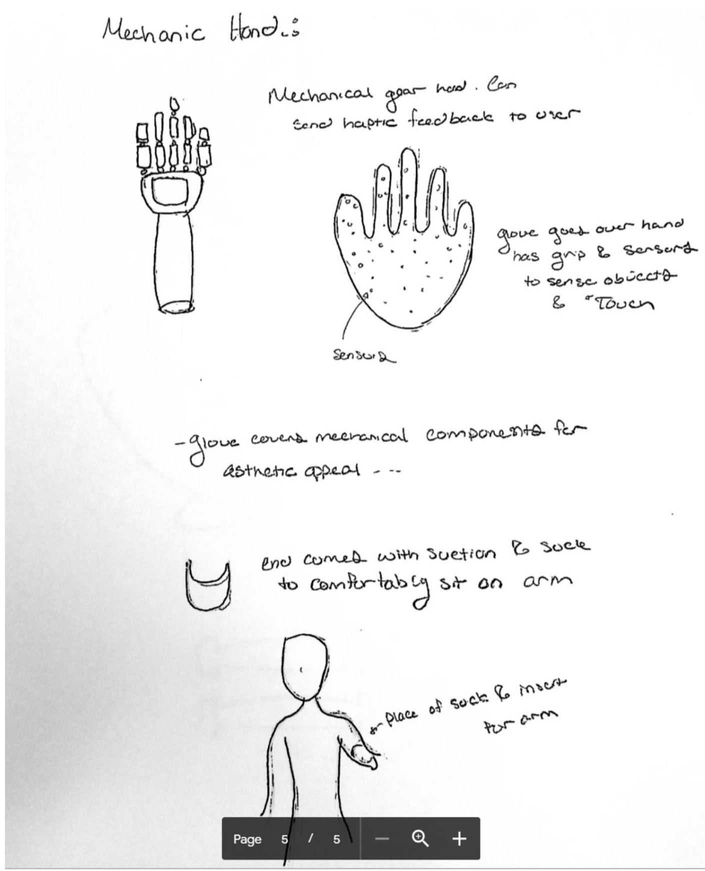

Figure A12: We Got You Covered

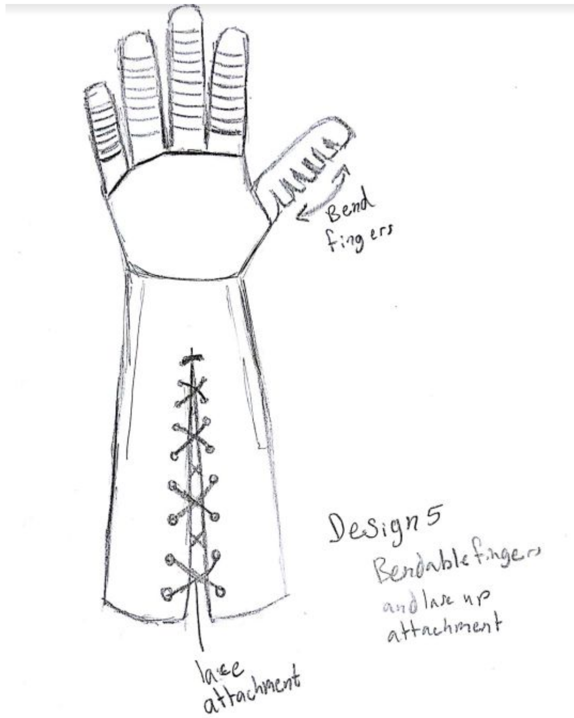

Figure A13: Bendy Fingers and Lace Up

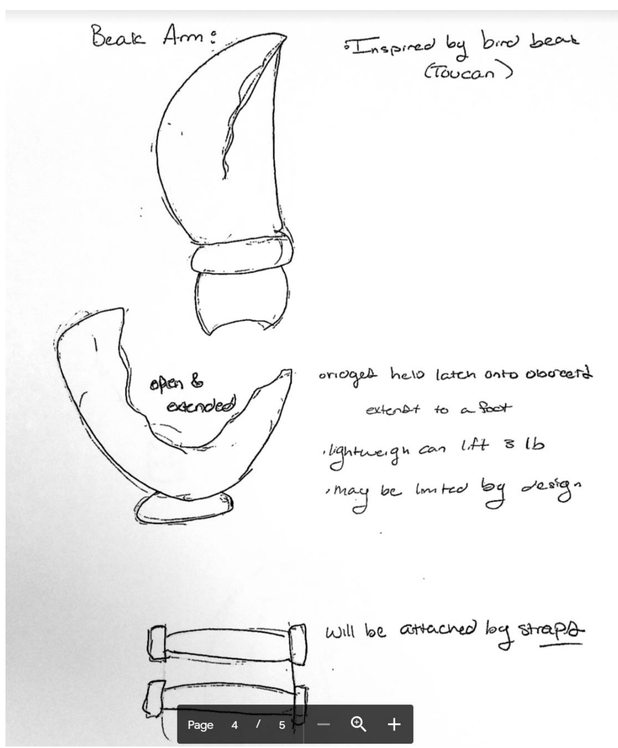

Figure A14: You Can Toucan

11.2 Appendix B: Code Analysis

```
//Library
#include <Wire.h>
#include <ZX_Sensor.h>
#include <Adafruit_MotorShield.h>

// Create motor shield object
Adafruit_MotorShield AFMS = Adafruit_MotorShield();

// Select motor
Adafruit_DCMotor *myMotor = AFMS.getMotor(1);

// Constants
const int ZX_ADDR = 0x10;  // ZX Sensor I2C address

// Global Variables
ZX_Sensor zx_sensor = ZX_Sensor(ZX_ADDR);
uint8_t x_pos;
uint8_t z_pos;
uint8_t z_posnew = 0;
uint8_t z_posold = 0 ;
uint8_t dz_pos = 0;

void setup() {

  uint8_t ver;

  // Initialize Serial port
  Serial.begin(9600);

  // Initialize ZX Sensor (configure I2C and read model ID)
  if ( zx_sensor.init() ) {
    Serial.println("ZX Sensor initialization complete");
  } else {
    Serial.println("ZX Sensor initialization incomplete!");
  }

  // Read the model version number and ensure the library will work
  ver = zx_sensor.getModelVersion();
  if ( ver == ZX_ERROR ) {
    Serial.println("Error reading model version number");
```

```
  } else {
    Serial.print("Model version: ");
    Serial.println(ver);
  }
  if ( ver != ZX_MODEL_VER ) {
    Serial.print("Model version needs to be ");
    Serial.print(ZX_MODEL_VER);
    Serial.print(" to work with this library. Stopping.");
    while (1);
  }

  // Read the register map version and ensure the library will work
  ver = zx_sensor.getRegMapVersion();
  if ( ver == ZX_ERROR ) {
    Serial.println("Error reading register map version number");
  } else {
    Serial.print("Register Map Version: ");
    Serial.println(ver);
  }
  if ( ver != ZX_REG_MAP_VER ) {
    Serial.print("Register map version needs to be ");
    Serial.print(ZX_REG_MAP_VER);
    Serial.print(" to work with this library. Stopping.");
    while (1);
  }
}

void loop() {
  // If there is position data available, read and print it
  if ( zx_sensor.positionAvailable() ) {
    z_posnew = zx_sensor.readZ();
    dz_pos = z_posold - z_posnew;
  }
  uint8_t i;
  Serial.print("tick");
  if (abs(dz_pos) > 0) {
    if (dz_pos > 10) {
      myMotor->run(FORWARD);
      myMotor->setSpeed(150);
      delay(10);
    }
    if (dz_pos < -10) {
      myMotor->run(BACKWARD);
```

```
    myMotor->setSpeed(150);
    delay(10);
   }
  }
  if ( zx_sensor.positionAvailable() ) {
   z_pos = zx_sensor.readZ();
   if ( z_pos != ZX_ERROR ) {
    Serial.print(" Z: ");
    Serial.println(z_pos);
   }
  }
  Serial.print("tock");

  z_posold = z_posnew;
  Serial.print("tech");
  myMotor->run(RELEASE);
  delay(1000);
}
```

11.3 Appendix C: Spring Gantt Chart

Task Name	Duration	Start	Finish	Resource Names
Individual Post Mortem	11 days	Mon 1/7/19	Mon 1/21/19	Allison Cutler, Felicity
Implement Proposal Changes	61 days	Fri 12/14/18	Fri 3/8/19	Whole Team
Weekly EE Team Meetings	64 days	Tue 1/22/19	Fri 4/19/19	At least 2 ME & 2 EE
Website Checks	**85 days**	**Mon 1/14/19**	**Fri 5/10/19**	**Jannell Broderic**
Check 1	20 days	Mon 1/14/19	Fri 2/8/19	Jannell Broderic
Check 2	81 days	Mon 1/14/19	Fri 5/10/19	Jannell Broderic
Presentations	**63 days**	**Mon 1/28/19**	**Wed 4/24/19**	
Midpoint Presentation	33 days	Mon 1/28/19	Wed 3/13/19	Whole Team
Final Presentation	31 days	Wed 3/13/19	Wed 4/24/19	Whole Team
Individual Analysis 2	**30 days**	**Mon 1/21/19**	**Fri 3/1/19**	**Whole Team**
Wireless Communicati	30 days	Mon 1/21/19	Fri 3/1/19	Allison Cutler
PID	30 days	Mon 1/21/19	Fri 3/1/19	Felicity Escarzag
Tolerances	30 days	Mon 1/21/19	Fri 3/1/19	Toni Goss
Sim. in MATLAB	30 days	Mon 1/21/19	Fri 3/1/19	Jannell Broderick
Hardware Reviews	**55 days**	**Mon 1/28/19**	**Fri 4/12/19**	
HR1	**20 days**	**Mon 1/28/19**	**Fri 2/22/19**	**Whole Team**
Prototyping and CAD	**17 days**	**Thu 1/31/19**	**Fri 2/22/19**	**Whole Team**
Forearm	17 days	Thu 1/31/19	Fri 2/22/19	Allison Cutler
Fingers	17 days	Thu 1/31/19	Fri 2/22/19	Jannell Broderic
Cuff	17 days	Thu 1/31/19	Fri 2/22/19	Felicity Escarzag
Palm	17 days	Thu 1/31/19	Fri 2/22/19	Toni Goss
HR2	**23 days**	**Mon 2/25/19**	**Wed 3/27/19**	**Whole Team**
Redesign Forearm	19 days	Sun 3/3/19	Wed 3/27/19	Allison Cutler

Task Name	Duration	Start	Finish
HR2	**23 days**	**Mon 2/25/19**	**Wed 3/27/19**
Redesign Forearm	19 days	Sun 3/3/19	Wed 3/27/19
Order electrical component	5 days	Sun 3/3/19	Thu 3/7/19
Update BOM	4 days	Sun 3/3/19	Wed 3/6/19
Final Product Testing	15 days	Mon 3/25/19	Fri 4/12/19
Midpoint Report	44 days	Mon 1/14/19	Thu 3/14/19
Final Report	30 days	Mon 3/25/19	Fri 5/3/19
CAD	78 days	Mon 1/14/19	Wed 5/1/19
UGRADS	**24 days**	**Mon 3/25/19**	**Fri 4/26/19**
Poster	18 days	Mon 3/25/19	Wed 4/17/19
Presentation	0 days	Fri 4/26/19	Fri 4/26/19
Operations Manual	50 days	Fri 2/1/19	Fri 4/26/19

Figure C1: Written Schedule

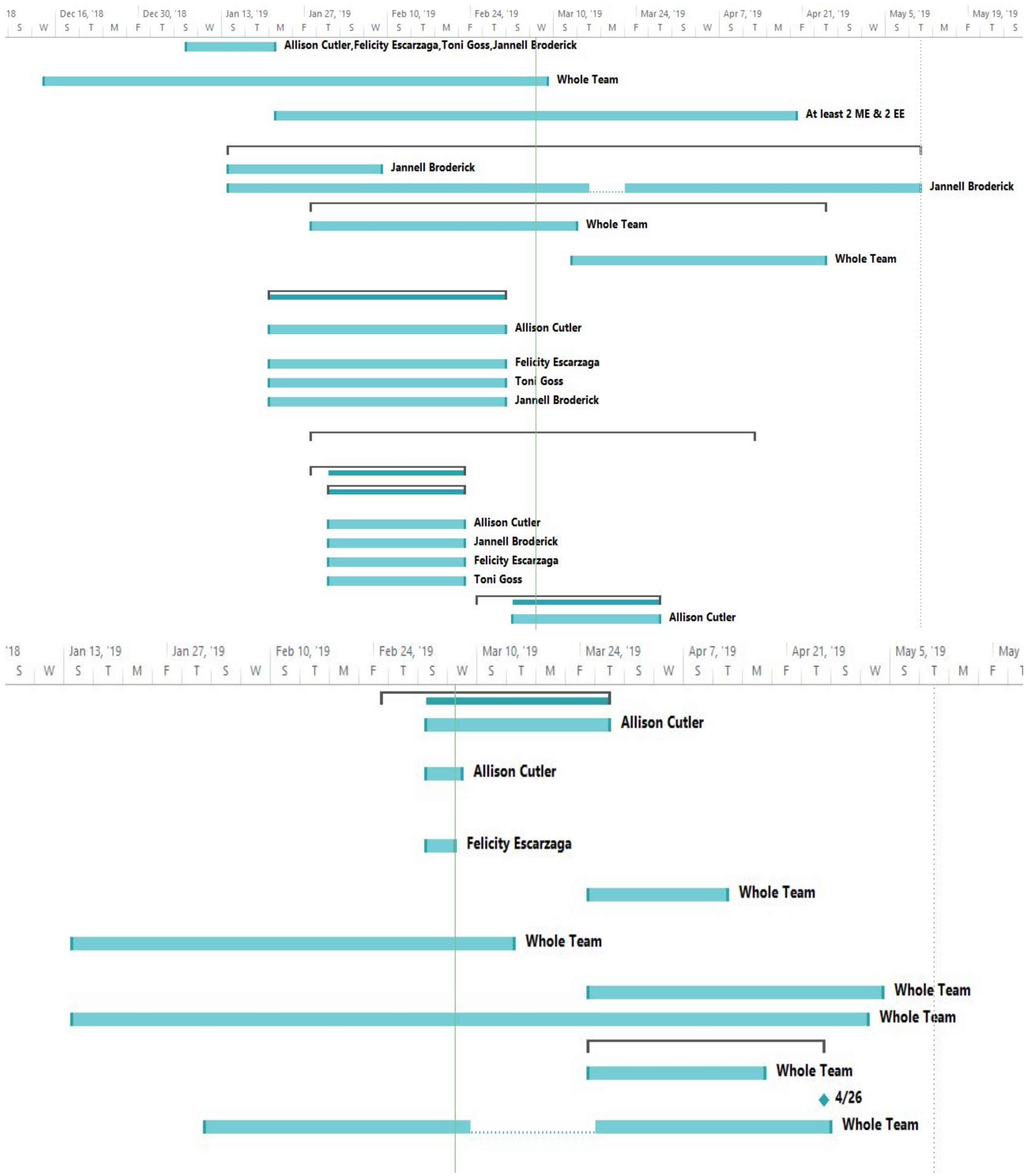

Figure C2: Charted Schedule