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Designing a prototype bionic prosthetic hand

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ABSTRACT

There is an estimated 1.7 million people living with limb loss in the United States today. Approximately 70% have an upper limb amputation, with roughly 10% of them losing their hand below elbow or at the wrist. This project aims to remedy this problem by designing a prototype bionic hand. This prototype will be made as a proof-of-concept that will be made into a fully function prosthetic device through multiple project iterations in the future. There have been a number of solutions to this problem; however, most of them are expensive to manufacture. This report will discuss three concept designs that challenge the existing solutions in different ways. Choosing to use a synthetic tendon system of actuation for the fingers will allow this project to be capable of performing low-stress everyday tasks like holding different sized objects. The bionic hand was controlled using pushbuttons that activate the servos when pushed and released the servos when the pushbuttons are released. This project also used 3-D printing technology for ease of manufacturing and build cost savings. There were many challenges that arose during the building phase of this project, like designing a base board for mounting the electronics and the hand, as well as programming the servos to function properly. The hand succeeded in holding the different sized objects. However it failed to hold and lift a water bottle in a satisfactory manner thus failing to meet one of the requirements.

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LIST OF SYMBOLS

Symbol	Meaning
T_p	Input torque on proximal pulley (from servo output)
F_p	Tension of string
r_p	Radius of proximal pulley
T	Torque on pulley
r_{m1}	Radius of input pulley
r_{m2}	Radius of output pulley
F_T	Fingertip force
I_d	Length of distal segment
r_d	Radius of distal pulley
$I_{running}$	Running current
I_t	Total running current
I_{board}	Board running current
P_t	Total power
ΣI	Sum of the currents
ΣV	Sum of the voltages
t	Time
V	Volts
A	Amps
mA	Milliamps

1 INTRODUCTION

Prosthetic devices are devices that are designed to replace a missing body part, commonly an appendage, of an amputee. Their function can range widely between a cosmetic piece used for appearance purposes to a fully functioning robotic limb that can achieve tasks like the actual body part itself. This project will focus on designing a bionic prosthetic hand that can act as a functional replacement for an amputee hand.

1.1 OBJECTIVE

The objective of this project is:

Develop a non - wearable prototype bionic hand that is electronically controlled using pushbuttons.

1.2 DELIVERABLES

The deliverables for this project are:

1. A functional non-wearable prototype bionic hand.
2. Code for the hand's function.
3. Solidworks files for the components of the hand.
4. Senior design report, senior design presentation, and informative poster.

1.3 DESIGN IMPACTS AND STANDARDS

1.1.1 Environmental

When considering the environmental impact of this design it is important to consider the type of material that is going to be used in the construction of the device. This design is going to be 3D-printed using plastic filament so it will be necessary to choose a type of plastic that won't present a large negative impact on the environment.

1.1.2 Social

As discussed previously in the objective statement, this design is meant to be a non-wearable prototype that will not be introduced into the market for the public to acquire. However it is important to consider the social impact my design would have on a fully functioning prosthetic device. My design would improve the quality-of-life for the end user and reduce the stigma behind prosthetic devices.

1.1.3 Cultural

The use of a prosthetic hand can challenge cultural norms and attitudes towards physical disabilities, potentially leading to greater acceptance and inclusion of individuals with disabilities. While this project is just a prototype/proof-of-concept and won't be put on the market for the public to purchase. It is still important to consider possible impacts that the final version of the device will have on the world.

1.4 REQUIREMENTS

The prototype bionic hand shall…

1. Use individual servos to actuate the index, middle, ring, pinky, and thumb.
2. Weigh no more than 3 lbs.
3. Use a lithium polymer battery as its main power source.
4. Hold a full 700 mL bottle of water (requires 17.7N of grip force).
5. Be equal to or within the size constraints of an average sized human hand.

2 BACKGROUND

2.1 MOTIVATION

There is an estimated 1.7 million people living with limb loss in the United States today. Approximately 70% have an upper limb amputation, with roughly 10% of them losing their hand below elbow or at the wrist [4]. One of the most common methods for replacing a lost appendage is using a prosthetic device. This project aims to address this problem by designing a non-wearable prototype bionic hand that will be eventually made into a fully functioning prosthetic device through multiple future design iterations. This prototype will be capable of performing low-stress tasks such as grabbing and holding various sized objects.

There are different kinds of prosthetics, the main three types are passive prosthetics, body powered prosthetics, and bionic prosthetics. Passive prosthetic devices are usually designed for looks rather than function, although they can be used for balance or holding something from underneath. Body powered prosthetics are fully mechanical devices that offer a little more functionality by allowing the hand to open and close exclusively. Finally bionic hands can replace most of the lost functionality by using electrical components like servos, microcontrollers, and muscle sensors.

2.2 LITERATURE REVIEW

2.2.1 Literature Review 1

There are a variety of devices that have been produced to address this problem. The first of which is a prosthetic hand that is controlled through the use of myoelectric sensors. Myoelectric sensors (EMG sensors) are able to detect the electrical impulses that travel through the muscles when flexed. (See Figure 1)

Figure 1: The Myoelectric controlled arm [7]

This design has a modular forearm section, this allows the device to compensate for the different kinds of amputations that can occur specifically above the elbow or below the elbow. This device uses servos stored in the lower-forearm section of the device that control each finger using a loop of string. This design also includes a wrist joint that can rotate 180 degrees. However with the servos being mounted in the forearm this prevents the device from being used by an amputee who had lost their hand at the wrist. [7]

2.2.2 Literature Review 2

Another piece of literature discusses a design that is also controlled via Myoelectric sensors.

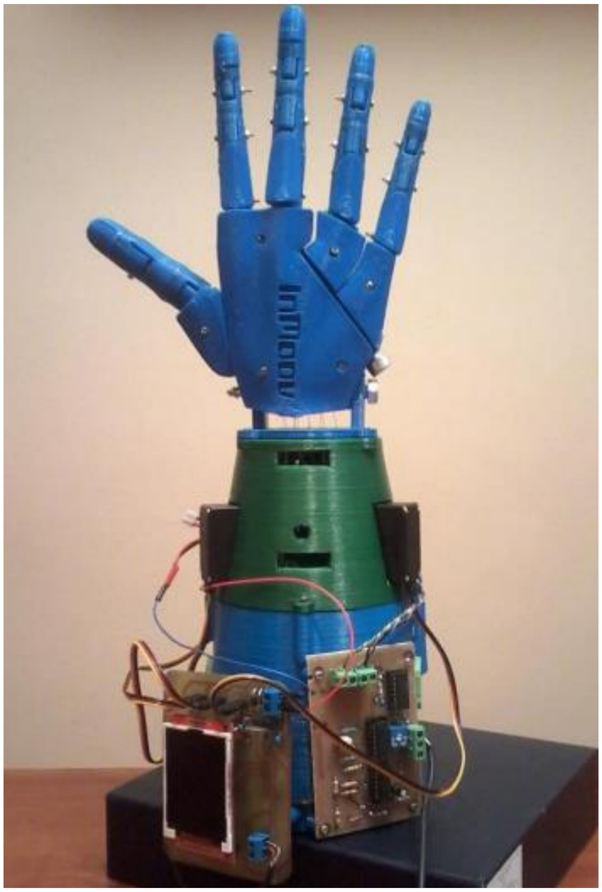


Figure 2: Bionic Prosthetic [6]

This design utilizes strings that act as the device's "tendons" and are pulled by the servo motors located in the forearm section. Using strings as tendons, rather than bars and pins, allows the device to have a highly adaptive grasping. The article does not discuss the total weight of the device, but it can be observed that the prosthetic is bulky and likely weighs more than what a prosthetic should. This is a big drawback, as prolonged use of the device could become tiring and bothersome for the end user. [6]

2.2.3 Literature Review 3

This last piece of literature features a prosthetic device that is mechanically controlled by flexing the wrist. (See Figure 3)

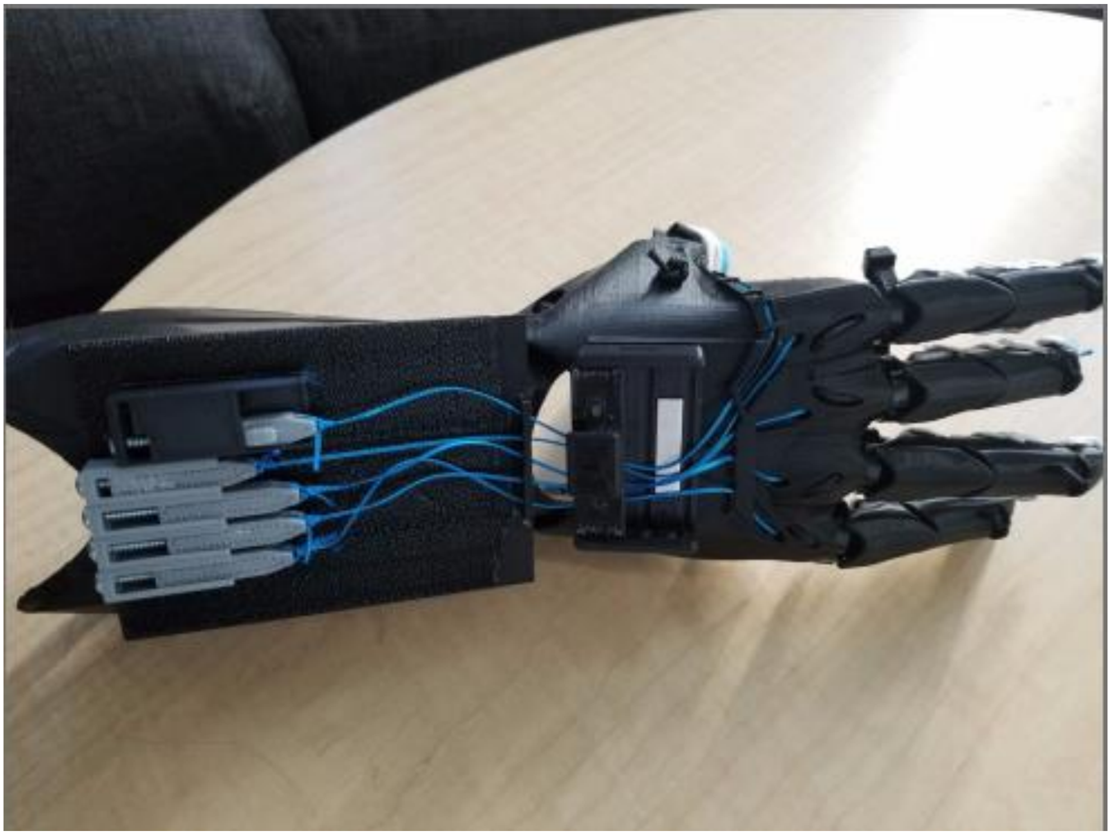


Figure 3: 3D-printed hand [11]

The hand is designed with strings that are connected to pins, which can be adjusted by tightening or loosening the screws that hold each pin in place. This design eliminates the need for electronics such as servos, microcontrollers, and batteries, which significantly reduces the weight of the device. Additionally, the fact that the device is fully 3D-printed further contributes to its lightweight and customizable nature. This literature provides valuable insights into the considerations for designing a prosthetic device that utilizes strings to actuate the fingers.

3 WHAT LEARNED

The literature review brought a great insight as to how prosthetic devices work, and how applying different concepts to their designs can cause their designs to vary from one another. One aspect of bionic prosthetics that is critical to consider when designing a prosthetic is the myoelectric sensors’ function. Myoelectric sensors are sensors that can sense the electrical impulses in the muscles when they are flexed. They can be used as either variable control for the prosthetic or they can function as on/off switches for a more simplistic control approach.

However implementing the sensors requires external circuitry and is much more difficult to program them to work properly.

Another aspect of prosthetics design learned from the literature was the difference between finger actuation mechanisms. Many mechanisms exist, but the main three that seem to be the most used are a bar and pin system, a pulley and string system, and motorized joints system. These three systems have appeared multiple times in the research portion of this project. The bar and pin system offers a more durable and stronger product but loses overall joint flexibility. The string and pulley system is more flexible and lightweight but loses durability and is harder to manufacture. Motorized joints offer the best of both worlds but are expensive to incorporate into a design.

Manufacturing bionic prosthetics can be challenging and costly, which makes them difficult to produce. The reason for this is due to the fact that prosthetics need to be customized to fit the individual's unique anatomy, and the technology involved in creating prosthetics is often complex. This project aims to overcome these challenges by utilizing innovative manufacturing techniques like 3D-printing that will allow the manufacturing of the device to be cost-effective.

3.1 PURPOSE

The purpose of this project is to incorporate some beneficial aspects of the previously shown designs into one prototype that will be made into a fully functional prosthetic device through future project interactions. Considering the social impact of the final design, it needs to be one that can improve the quality of life of an amputee and reduce the stigma around prosthetic devices so that the amputee feels more accepted in society.

4 CONCEPTUAL DESIGNS

4.1 CONCEPT 1: SYNTHETIC TENDONS

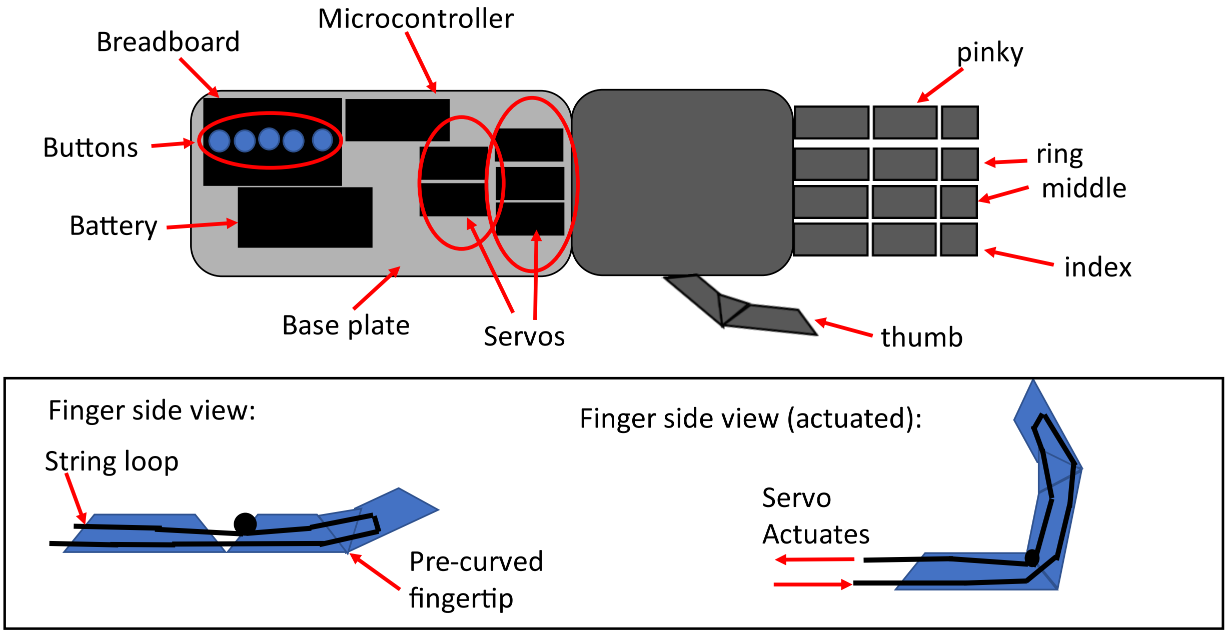


Figure 4: Synthetic tendons concept

This first conceptual design involves the use of strings to function as artificial tendons that, when pulled by a servo motor, will actuate the fingers. Using servo motors rather than DC motors will allow the fingers actuation to be easily programmable because servos don't require the use of motor-drivers or other electronics. This concept is also more lightweight than other concepts due to using the string rather than solid bars and pins. However, a drawback to this design is that strings can stretch and deform over time, causing the hand to not function properly. Another drawback is that when the fingers eventually break, it would be difficult to repair especially for an amputee.

4.2 CONCEPT 2: BAR AND PINS

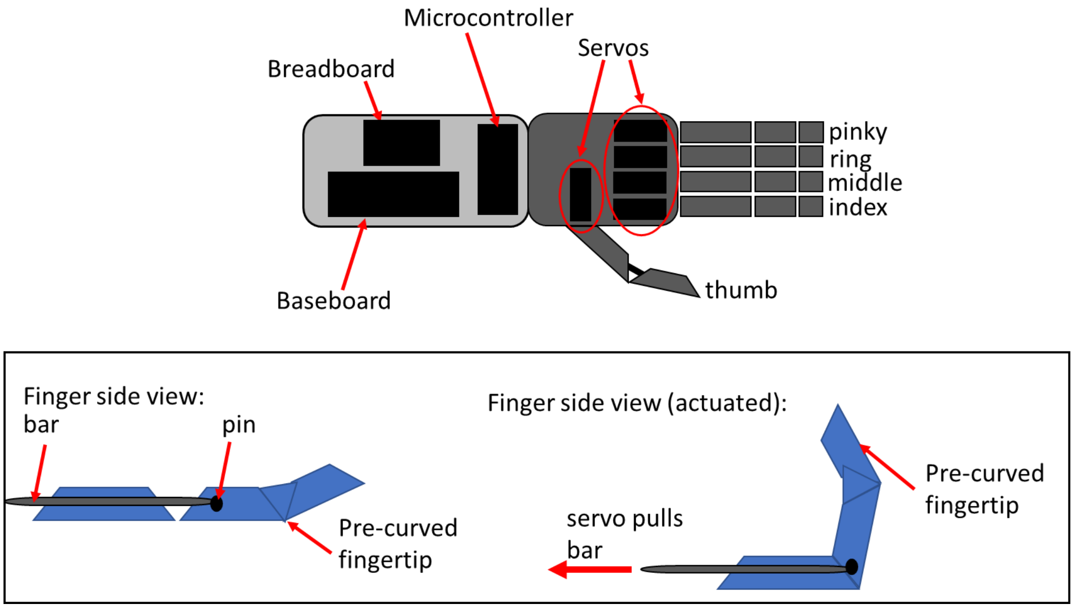


Figure 5: Bar and pin concept

This concept is similar to the previous concept. However, rather than using strings as artificial tendons, this design will instead use a bar and pin system to actuate the fingers. This change will cause this concept to overall be stronger and more durable than the previous concept. This concept would be easier to manufacture using 3D-printing technology. Due to the bar and pins this concept will be heavier and could become tiring to use over long periods of time. This concept could also have problems grasping complex objects due to the rigidity of the fingers' actuation.

4.3 CONCEPT 3: MOTORIZED KNUCKLES

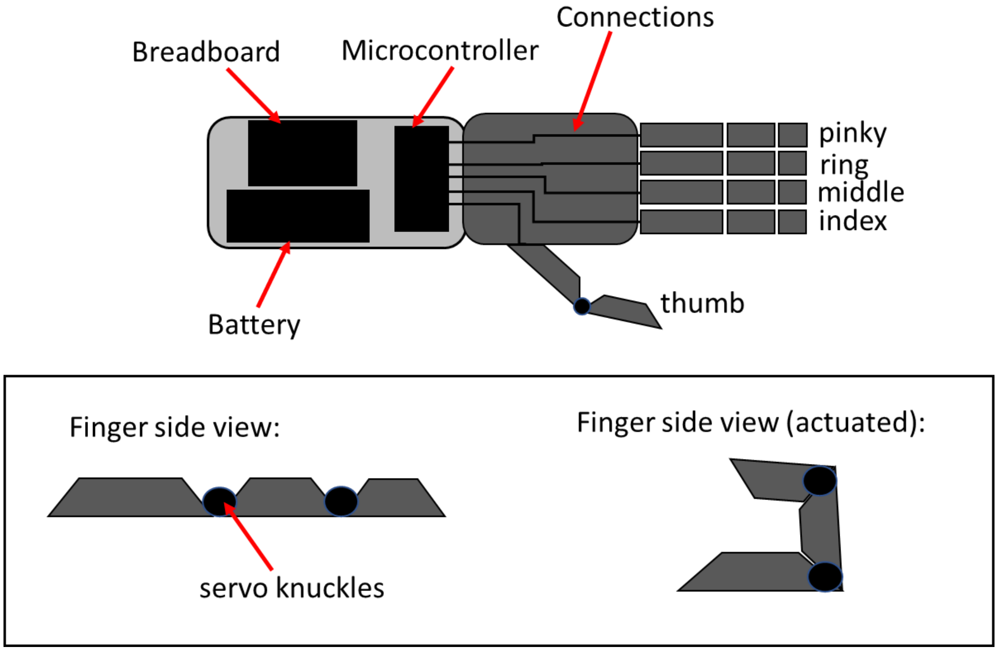


Figure 6: Motorized knuckles concept

This concept utilizes motorized joints to mimic the knuckles of a human hand. The motorized joint would allow the hand to grasp complex objects without sacrificing grip strength. Because each joint would be individually motorized this concept will allow the user to control each finger individually and with great accuracy due to the implanted myoelectric sensors. The complexity of this concept is just too great for any college engineering student. The cost of such a project would be too great not only to manufacture the device but also for the end user to purchase a completed product. This concept is just not feasible for a college level engineering project.

4.4 CONCEPT CHOICE

After reviewing each design and weighing the pros and cons. The concept that was chosen for this project was the synthetic tendon concept. This concept was chosen because it would be the easiest to construct and program.

5 BIG PICTURE

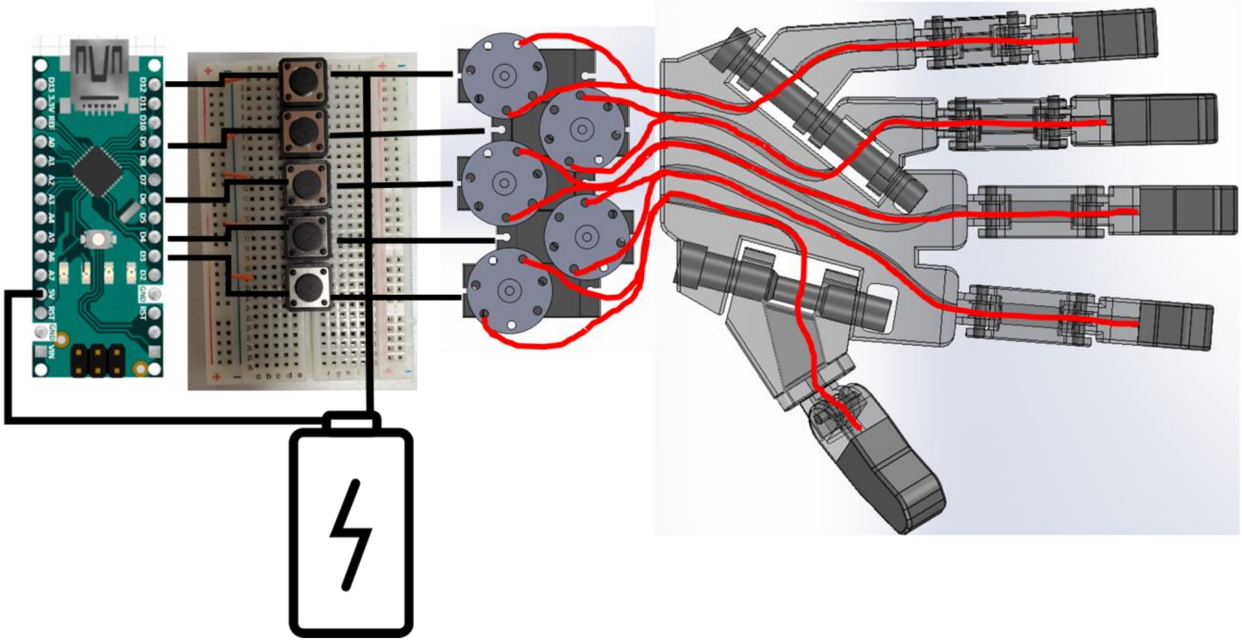


Figure 7: Big picture concept of the prototype bionic hand

Starting on the right of Figure 7, the hand will have the strings (highlighted in red) fed through their channels from the fingertips to the servos where they will be tied off. The servos will be connected to the push buttons, the push buttons will be wired to the microcontroller, which will allow the push buttons to control the servos. Finally All electronic components will be powered by a single battery.

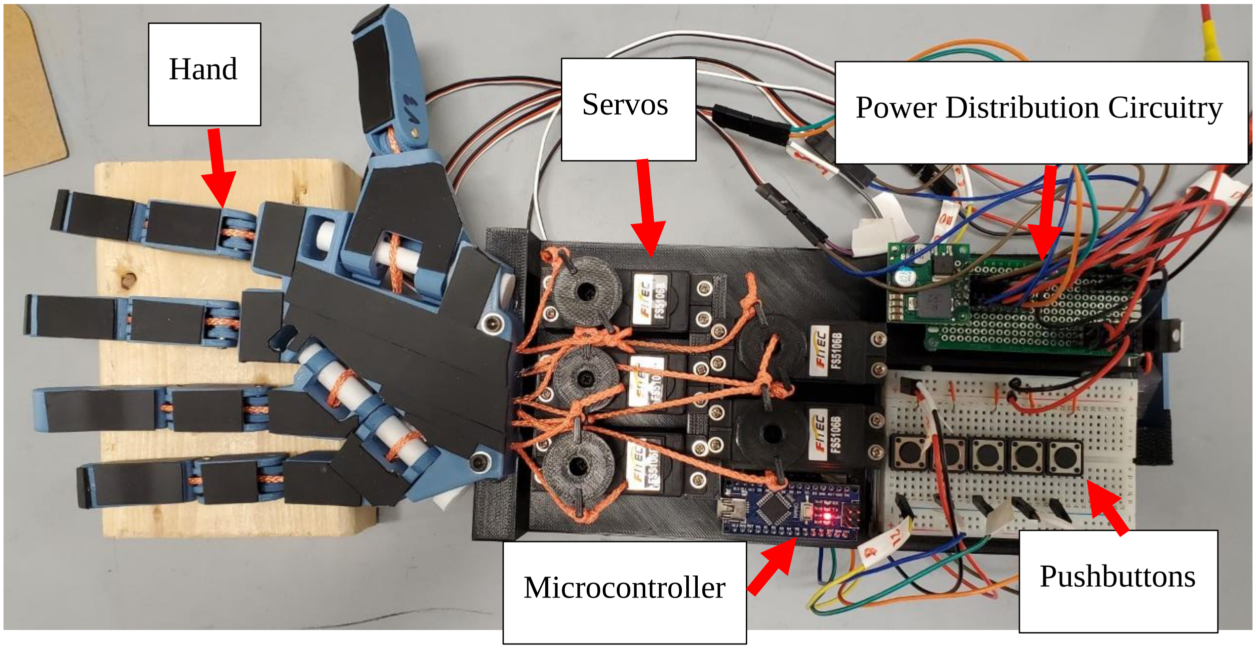


Figure 8: Final iteration of the prototype

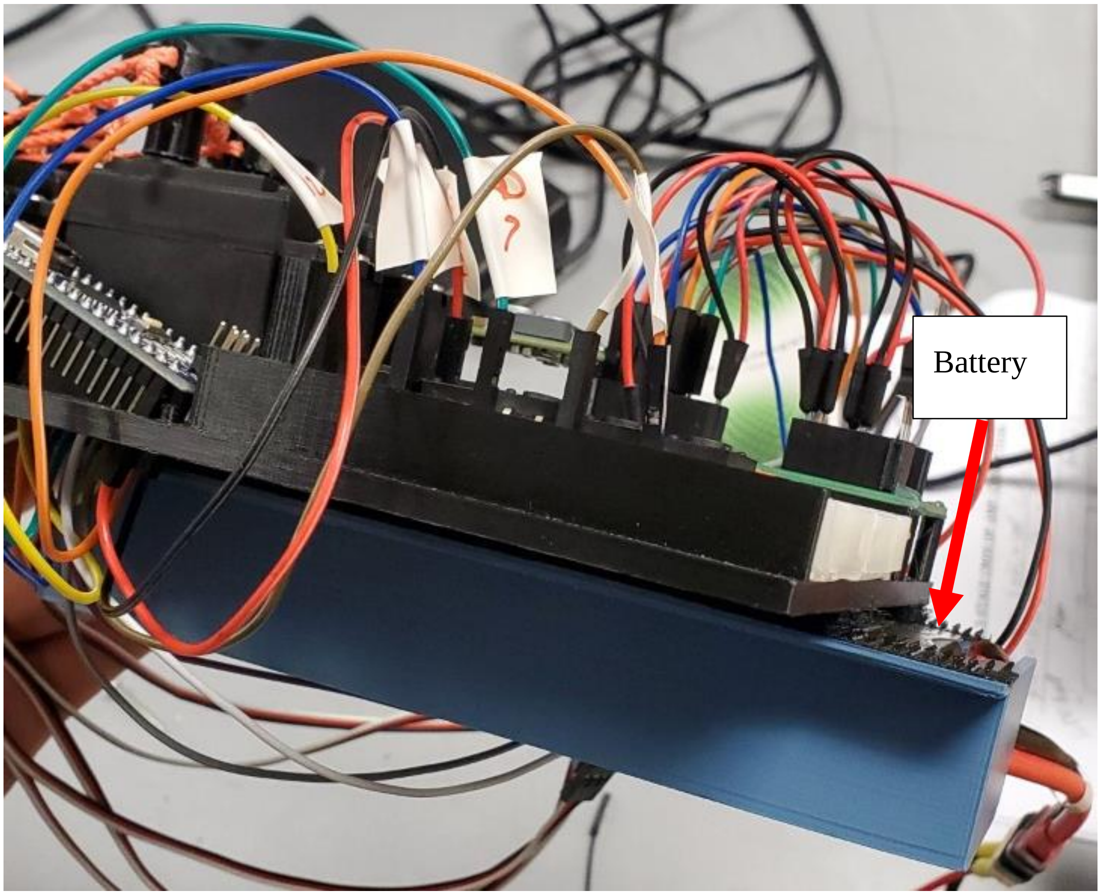


Figure 9: A better image of the battery.

In this report will cover several key aspects of this design like the 3D-printed components of the hand, what materials were chosen, and the electronics that were chosen and why they were chosen, as well as some of the challenges that had to be overcome during the construction of the device to ensure that it operated properly.

6 PROSTHETIC DESIGN

6.1 3D – PRINTING

3D – printing is a process that can create a 3D object from a 3D CAD model. Unlike the standard methods of manufacturing objects, which usually involve removing excess material until a desired shape is formed, 3D – printing builds the object up layer by layer. This allows for accurate and rapid prototyping of parts with little to no waste material or monetary cost.

USI has access to several 3D printers for students to use. However due to the quantity of senior design projects using 3D – printing technology this semester I've opted to exclusively use my personal 3D – printer for this project. This decision allows me to print objects at my own pace and without conflict with the other teams. While 3D – Printing is very beneficial for prototyping it is not without faults. 3D – printing can be very fickle and even difficult to use for those who are uneducated about the process. Issues with the device itself can arise very easily and seemingly out of nowhere leading to problems in the process which will produce faulty parts.

3D – printing also has the capability to manufacture complex objects where traditional manufacturing methods wouldn't work (like the palm design for this prototype). There are a variety of materials that can be used for 3D – printing but to take full advantage of its rapid prototyping capabilities plastic will be used.

6.2 MATERIAL SELECTION

There are multiple types of plastics that can be used for this prototype, the two main plastics that are being considered for this project are PLA and ABS. These are the most common filament materials used for Fused Deposition Modeling (FDM) 3-D printing, this will help drive down the cost of production on this project.

Table 1: Material Comparison.[5][9]

Material Comparison	PLA	ABS
Tensile Strength (Mpa)	21 - 60	29.8 - 43
Melting Temperature (^{O}C)	150 - 162	210 - 240
Material Density (g/cm^3)	1.21 - 1.25	1.0 - 1.05
Chosen Material?	Chosen	Not Chosen

As can be observed from Table 1 there are advantages to using either material. PLA has a greater tensile strength than ABS, however it has a lower melting temperature and higher material density than ABS. While material properties are important to consider, it is also necessary to consider how safe each material is to use for 3D printing. PLA is safer to print with because it emits less microplastics and hazardous fumes during the printing process. PLA is also a biodegradable thermoplastic which makes it a viable option for keeping the environmental impact low. Overall, PLA fits the needs of this project the best. It’s readily available, cheaper, and easier to 3-D print making it the best choice of material for this project.[5][9]

6.3 HAND DESIGN

6.3.1 Finger design

The finger design of this device will utilize a string and pulley system which will act as artificial tendons. Each component of the fingers will be 3D – printed using PLA Filament. Each component will be interlinked using connection pins. Each string will have a designated channel that will guide it from the servo through the palm and to each fingertip where it will be tied off. There will be two strings per finger one string will curl the finger once pulled by the servo and the other string will return the finger to its neutral (open) position when pulled by the servo. Each finger requires two strings: one on top so the fingers can be pulled closed, and one on the bottom to ensure that the finger returns to its open position. Without the top string, the fingers wouldn’t be able to close, and without the bottom string, there would be no way to return the finger to its original position. (See Figures 10 and 11)

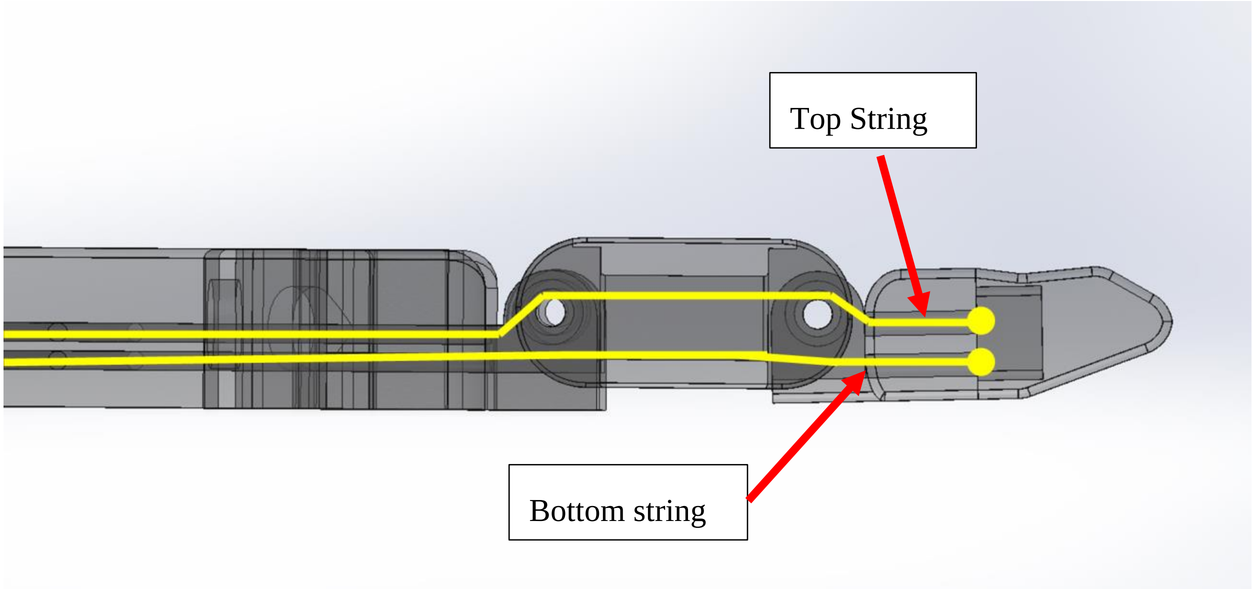


Figure 10: Side view of a finger in the open posistion

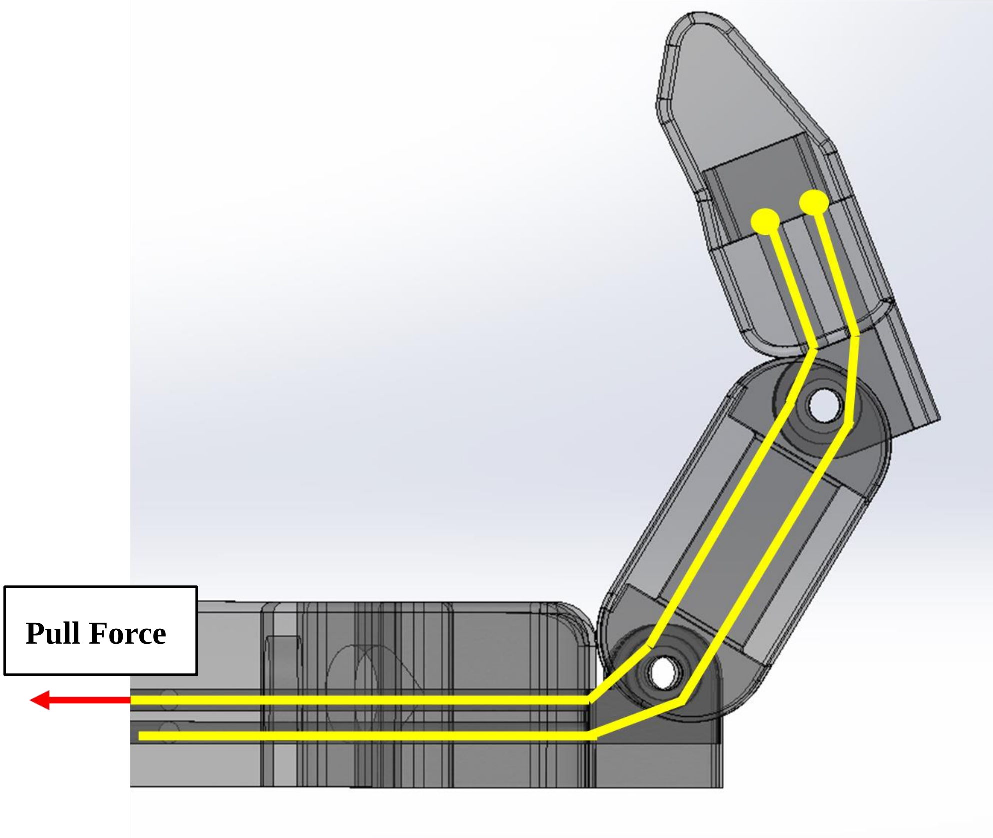


Figure 11: Side view of a finger being actuated

The reason two strings will be used for each finger instead of one continuous string is to negate the possibility of slipping when the strings are pulled by the servo. Slipping would result in either erratic movement or no movement in the fingers. When slipping occurs, the friction between the string and the finger components can cause the string to fray and weaken.

6.3.2 Connection pins

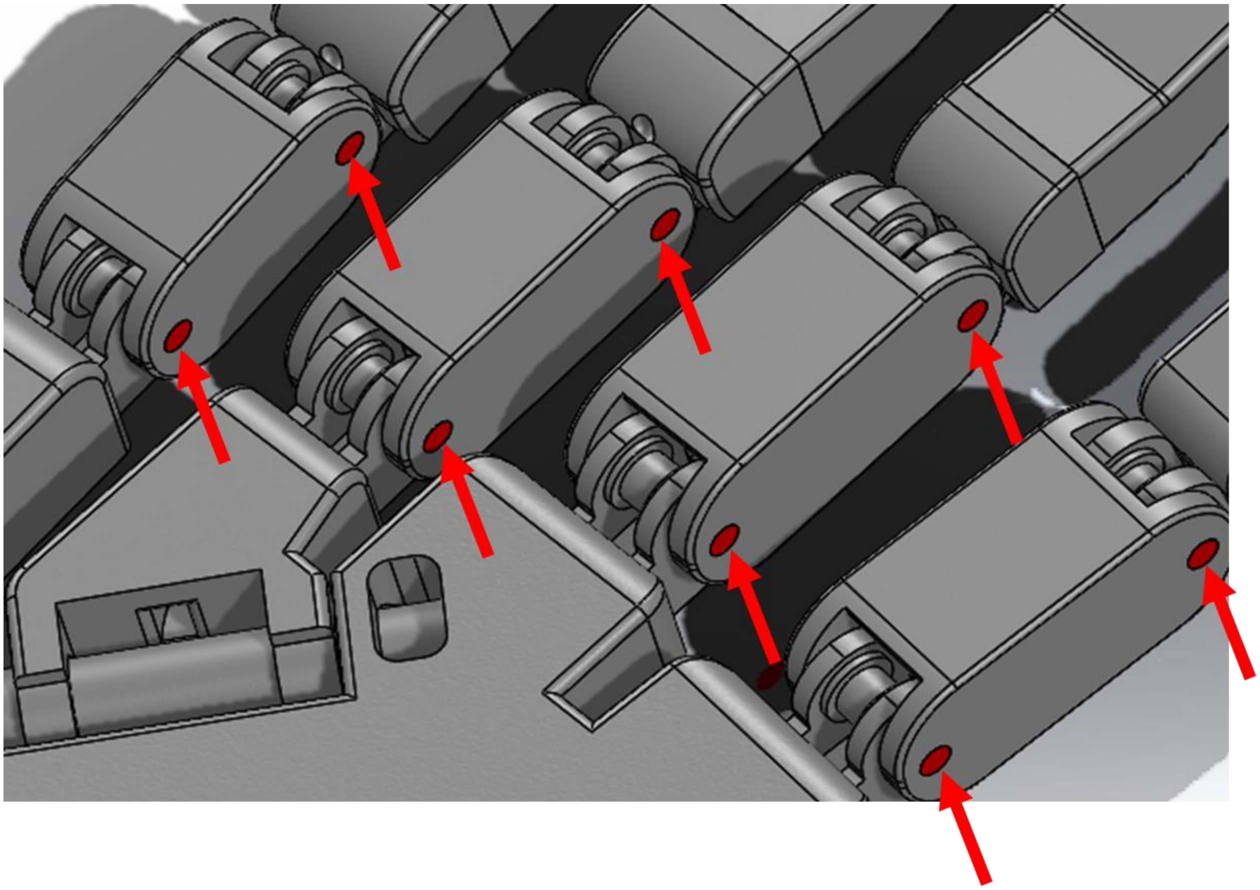


Figure 12: Connection pins

Each component of the fingers will be interlinked using 1/8th inch connection pins. These connection pins will be fitted into the fingers using a friction fit at their connection points. Initially the pins were going to be 3D-printed, however due to the nature of FDM 3D – Printing manufacturing components that require a high amount of precision is very difficult to do. After printing out the connection pins the layers were very uneven and some layers were off centered resulting in a connection pin that did not have a uniform 1/8th inch thickness. This led to the connection pins not being able to properly fit into their holes causing faulty functionality.

Due to this fact, the connection pins were made out of 1/8th inch brass round stock. Metal round stock has a uniform thickness that will allow for easy installation and allow the connections in the finger components to function properly. The reason that brass was chosen specifically was due to its availability at the local hardware store. This change in material would increase the total weight of the prosthetic because brass is heavier than PLA. However given the small size of the connection pins this change in material can be afforded.

6.3.3 Palm design

The palm is one of the most important components of this prototype. The palm provides the most surface contact when grasping objects. In the prosthetic industry, the most used design for the palm is to have the palm be a solid piece. (See Figure 13)

Figure 13: Example of a solid palm design on a prosthetic hand

This design is beneficial in many ways. It is easier to manufacture because it is just one piece which also makes it easier to disassemble to make repairs. Finally This design can be made to look more like a natural human hand and less robotic. However, due to the palm being one solid piece it lacks the capability to conform to the object that it’s holding; this can make it difficult for the device to grasp objects which is why a segmented palm was designed for this prototype (See Figure 14).

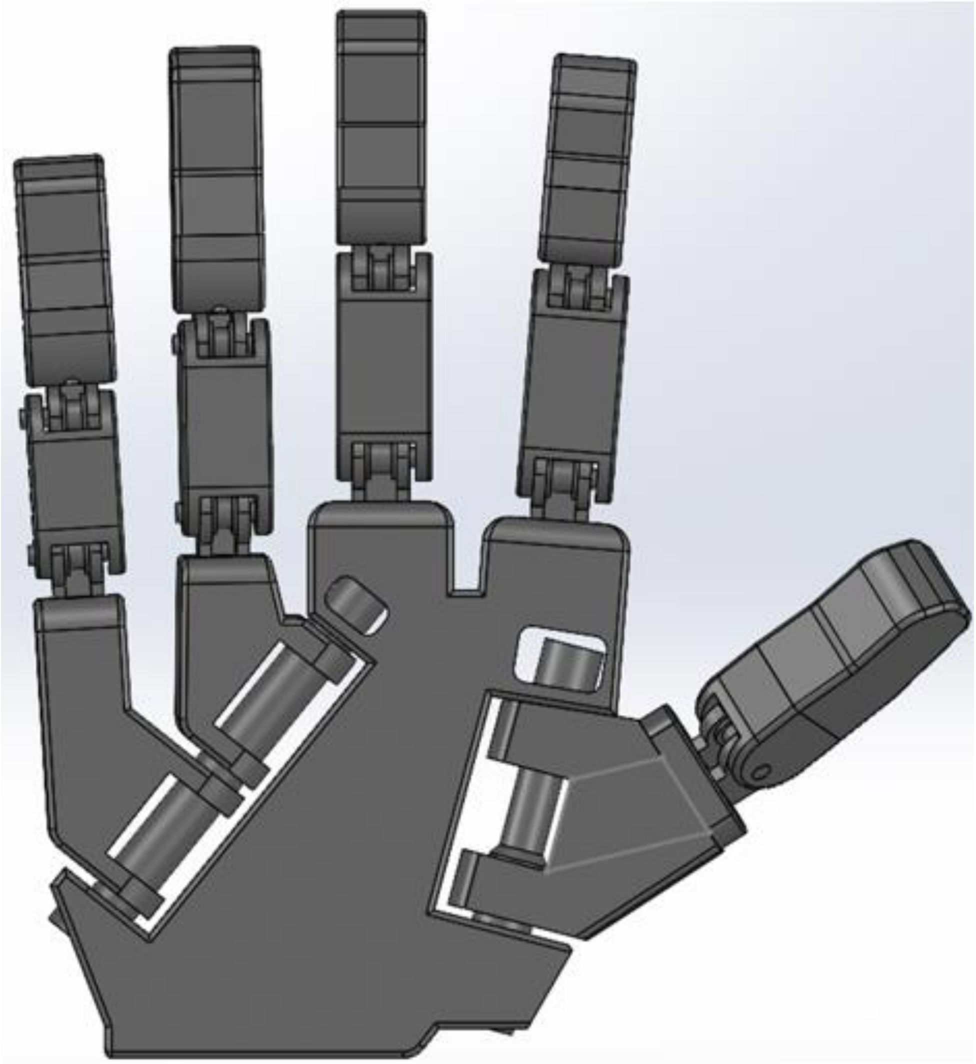


Figure 14: Segmented palm design

This palm design would allow the device to conform better to the object that it is attempting to grasp. While it is more mechanically complex, this design, combined with 3D – printing, will allow for the device to maintain a low weight. The hand is the part of the device that will undergo the most stress during operation, so this segmented palm is designed to allow the servos to be placed elsewhere on the device. This means that they would be out of harm’s way making it less likely for them to need replacing after the hand is inevitably damaged during operation.

6.3.4 Palm segment connection rods

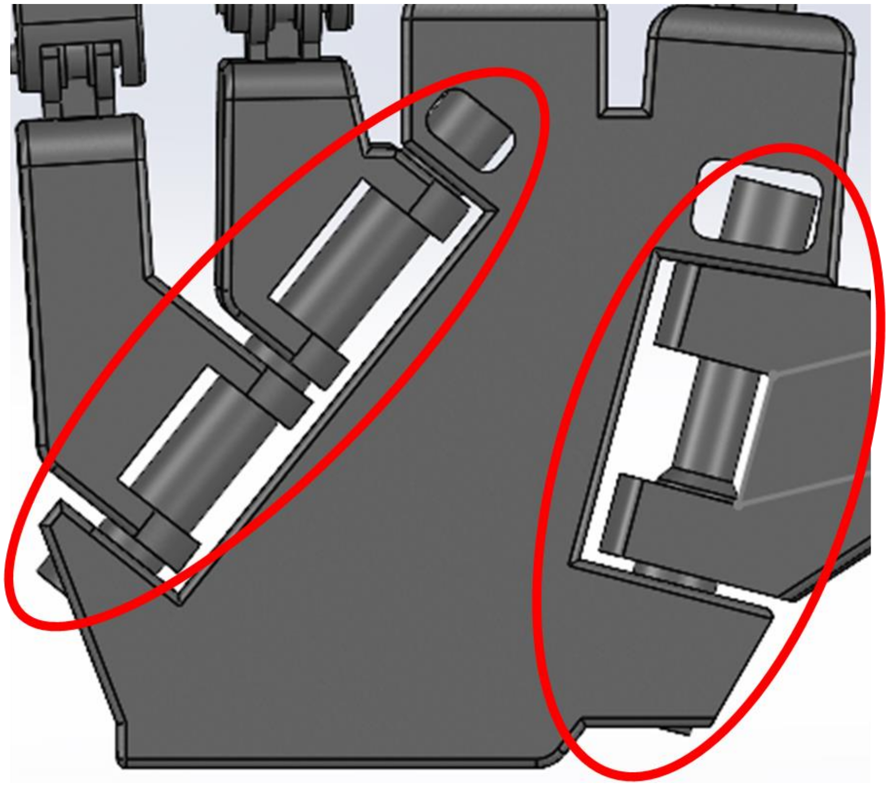


Figure 15: Connection rods

The palm will be divided into segments to increase the degree of freedom and allow the hand to conform better to the object being held. However, connecting the palm segments is crucial to achieve optimal functionality. While bolts could be used as connection rods, they are heavy and made of metal, which may cause damage to the PLA palm segments during operation. To address this, the connection rods will be 3D-printed using PLA, a lightweight and durable material that is less likely to damage the PLA palm segments. This approach will not only keep the device lightweight but also increase its longevity, making the connection rods less likely to damage the device.

6.3.5 String channels

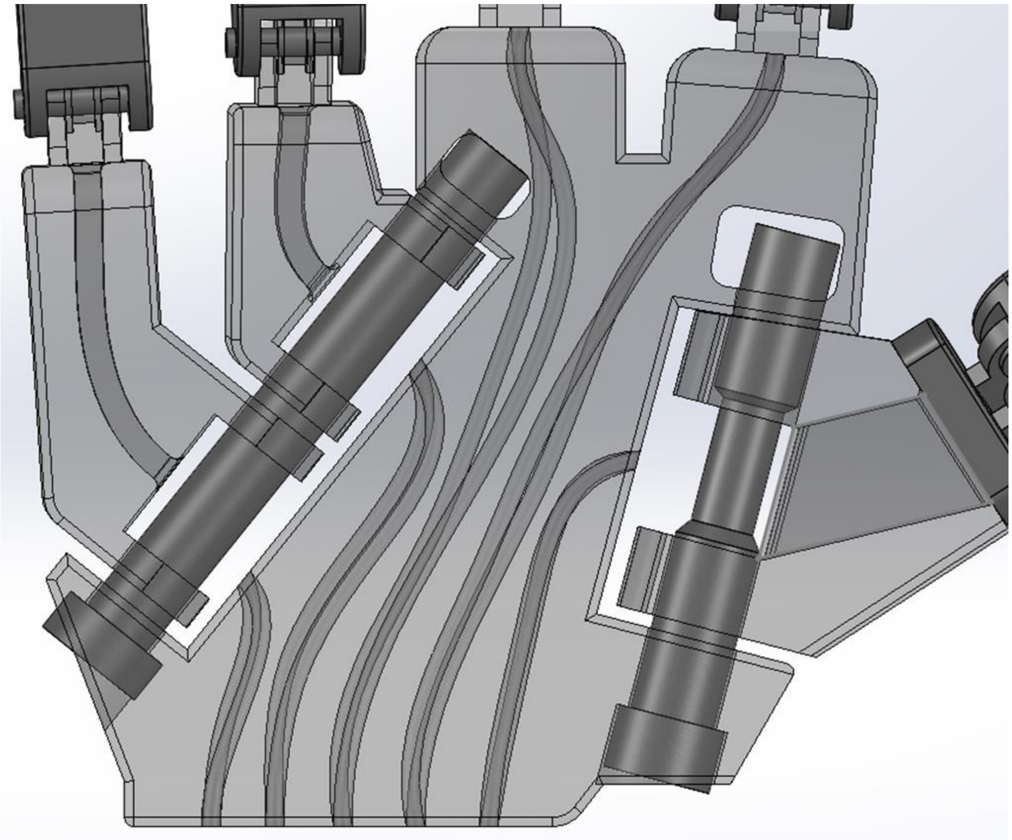


Figure 16: String channels in the palm of the hand

Each finger will have two strings, to attach the strings to the servos from the fingertips and each one will be fed through its own channel from the fingertips to the corresponding servo. This would allow the hand to operate without the risk of the strings getting tangled during operation, which would cause a failure. However, a tradeoff that comes with this design is that high friction areas and pinch points could cause the string to fray and become damaged more easily. Which would negatively impact the device’s functionality.

6.4 BATTERY

6.4.1 Battery Capacity Calculation

Calculating the battery capacity is simple math but there are a lot of variables to account for. Most of the variables are provided in the datasheets for the components that are easily found. When calculating for battery capacity it is best to assume that all of the electrical components are running at full power and drawing the maximum amount of current they can. This is to ensure that the battery capacity won’t be too low for the application.

The only electrical components in this project are the Arduino nano microcontroller and five FITEC FN5106B servos, therefore the needed capacity can be found.

Starting with the Arduino nano microcontroller [8]:

Operating voltage = 5 V

Digital I/O Pins = 22 pins

Current per I/O Pin = 40 mA per pin

Current consumption while running = 19 mA

$$I_t = \left(Quantity * \ I_{running}\right) + I_{board}$$

$$I_t = \left((22\, pins) * (40\, mA)\right) \ + (19\, mA) = 900\, mA\ or\ .9\ A$$

Then the FITEC FN5106B Servos:

Quantity = 5

Operating voltage: 4.8 V – 6 V

Stall current: 980 mA – 1100 mA

$$I_t = Quantity * I_{stall}$$

$$I_t = 5 * 1100mA = \ 5500\, mA\ or\ 5.5\ A$$

Now the total current draw of the whole system can be calculated.

$$I_{Total} = \Sigma I_t$$

$$I_{Total} = (900\, mA) + (5500\, mA) = 6400\, mA\ or\ 6.4\ A$$

Due to time constraints, this prototype bionic prosthetic hand will not be a wearable device. So for the purposes of this project a high-capacity battery that could run the device for hours at a time is unnecessary. With that in mind the battery should only need to support the prototype for no more than an hour for test purposes. So the maximum capacity of the battery can be found below.

$$Capacity = I_{Total} * t$$

$$Capacity = (6400\, mA) * (1\ hour) = 6400\, mAh$$

So the necessary capacity a battery needs to have in order to run this project for an hour is 6400 mAh. However this was calculated assuming the components would be drawing the maximum amount of current, which is not going to be the case, so a 6400 mAh battery will last at least an hour.

The required battery voltage is much easier to find than the capacity. The Arduino nano can only run on 5 V DC and the servos can operate on a range of 4.8 V to 6 V. This means that the battery will have to be able to supply at least 6 V for the system to run. So the battery that is required for this project is a 6 V 6400 mAh battery.

6.4.2 Battery selection

Now that the required capacity and voltage of the battery are known the next step is to choose what type of battery to use. When it comes to projects like this the two most common types of batteries to use are lithium polymer or lithium ion. Each has its own benefits and drawbacks.

Lithium-ion batteries are commonly cheaper and have a higher energy density than lithium polymer batteries. However lithium polymer batteries are generally lighter in weight, smaller in size, and much more reliable than lithium-ion batteries. Lithium polymer batteries are much safer because they are less likely to spontaneously combust during operation or charging. Lithium polymer also has a slower discharge rate which means that it can hold a charge for much longer than a lithium-ion battery. Therefore, a lithium polymer battery will be used to power this device.

The battery selected for this project is the Gens Ace 2S lithium polymer battery. (See Figure 17)

Figure 17: Gens Ace 2S lithium polymer battery

This battery has a voltage rating of 7.4 V and a capacity of 5000 mAh. This capacity is lower than 6400 mAh capacity previously calculated, however it is stated in the previous section that this device doesn’t need to run for more than one hour. Using the following calculation it can be found how long the battery will last.

$$Capacity = I_{Total} * t$$

$$(5000\ mAh) = (6400\ mA) * t = .781\ hrs\ or\ 46.9\ min$$

According to the above calculation this battery would last approximately 46.9 minutes of continuous operation. However this value was calculated under the assumption that all of the components will be demanding full power at all times. This simply would not happen in the real world so the total run time of the device using this battery will actually be longer than the calculated time.

6.5 MICROCONTROLLER

The microcontroller for this project is the most crucial part of this project. It is what controls the servo motors and is used to program different grip patterns for the hand. For the scope of this project it will be used to simply operate the servos via pushbuttons where pushing a button will activate the corresponding servo and not pushing the button will cause the corresponding servo to return to its original position.

6.5.1 Arduino nano

There are many different microcontrollers on the market today and each has their specific functions allowing them to be implemented in a variety of projects. The microcontroller chosen for this project is the Arduino Nano. (See Figure 18)

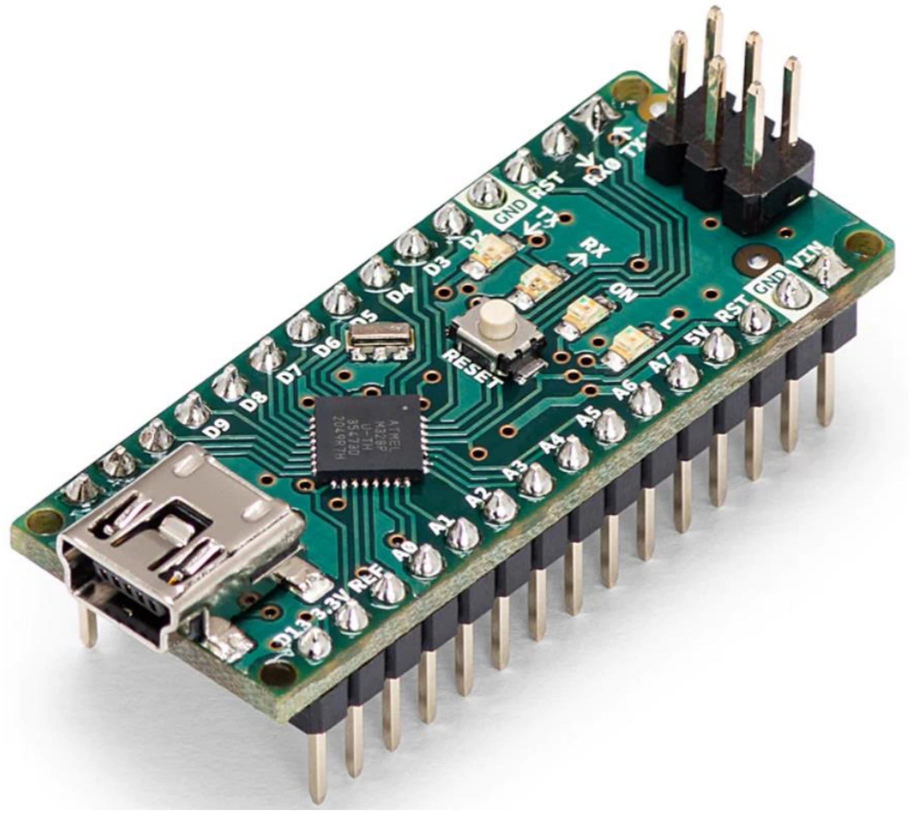


Figure 18: Arduino Nano [2]

This microcontroller was chosen because of its functionality in spite of its small footprint. This is one of the smaller microcontrollers on the market however it is still capable of driving multiple peripherals simultaneously. The Nano has 14 digital input pins which is plenty for controlling each of the 5 servos and 5 pushbuttons in this project. It is also worth noting that the Nano only needs a 5 V 19 mA power source for operation which will save on battery life. [2]

6.6 SERVOS

Servo motors utilize DC motors that are connected to a control circuit and a set of gears that allow the servo to only rotate from 0 degrees -180 degrees. Servos are beneficial for this project because they can be programmed to hold their positions and resist external forces. This would allow the hand to close its finger and keep it closed if needed. Servos also don’t require any extra external circuitry to control them because the circuitry is already integrated into the device. Servo motors can also come in many sizes ranging from 9 grams to 152 grams for various applications.

6.6.1 DIYMORE 9g servos

The servos that were initially chosen for this design were the DIYMORE 9g servos. (See Figure 19)

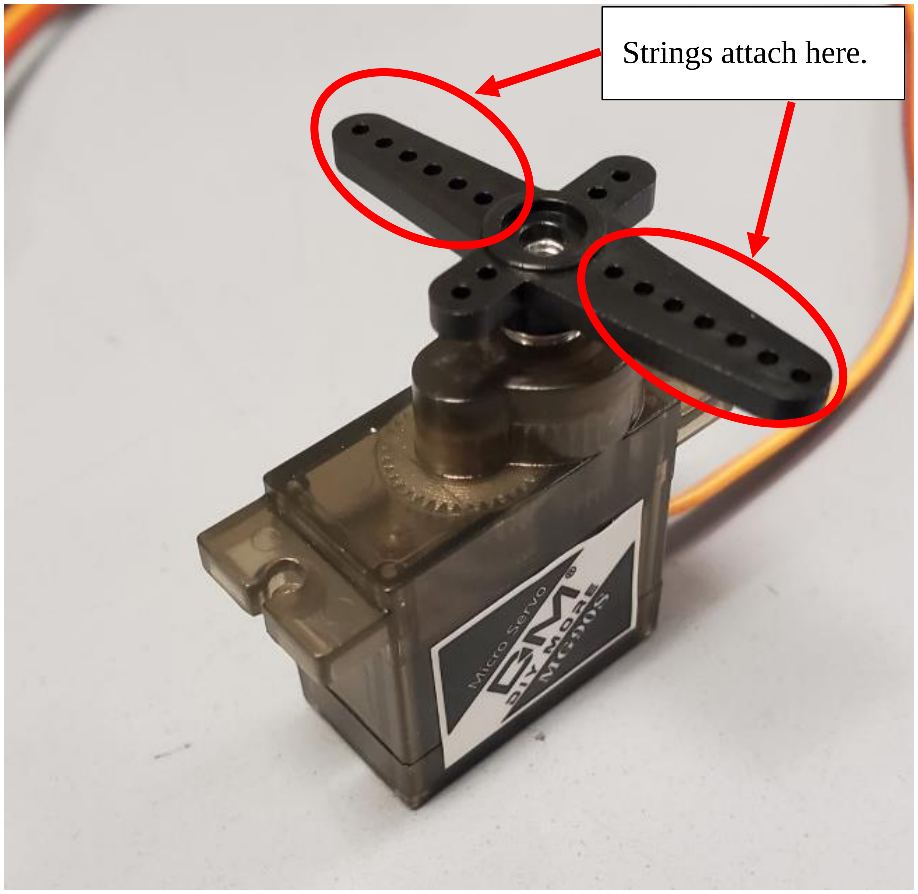


Figure 19: DIYMORE 9 g servo

These servos were chosen for their small form factor. These servos are approximately 22.8 x 12.2 x 28.5 mm (LxWxH) and offer .196 N-m (2 kg-cm) of torque with all metal gears. These servos also don't have a high-power consumption with an operating voltage of 4.8 V and a stall current of 1300 ± 40 mA which will allow for a smaller battery when this prototype is eventually made into a fully functioning prosthetic device. A calculation was performed to find out if these servos can provide the necessary force to lift and hold the 700 mL water bottle.

Required Grip Force: 17.7 N (Calculation located in Appendix I)

Force servo applies to the string: 19.69 N (Calculation located in Appendix I)

Theoretical force generated by each finger:

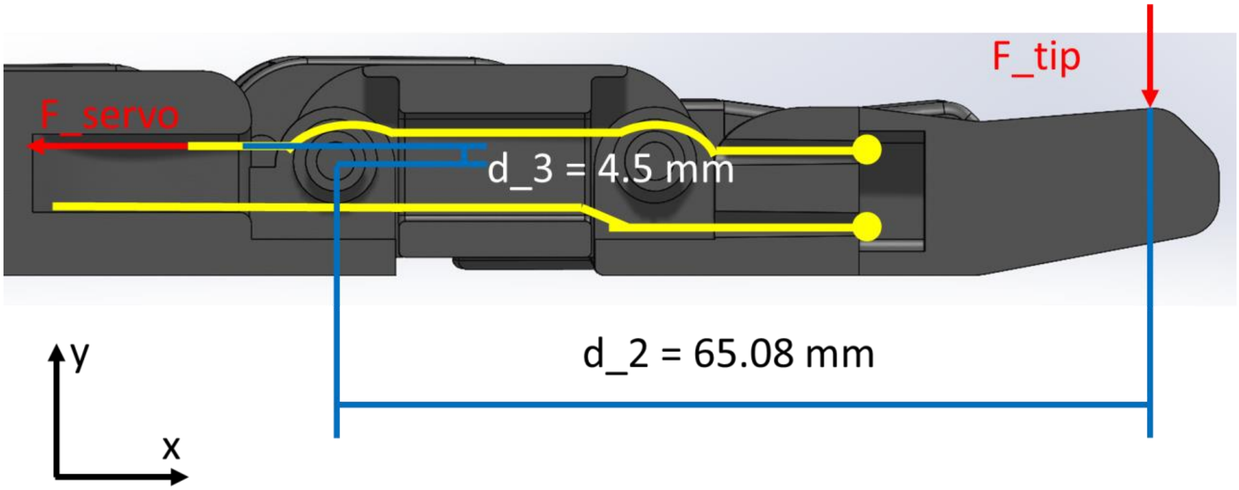


Figure 20: Diagram of finger for calculation

$$F_{servo} * d_3 = F_{tip} * d_2$$

$$(19.69\ N)(.0045\ m) = F_{tip} * (.06508\ m)$$

$$F_{tip} = \left(\frac{(19.69\ N)(.0045\ m)}{(.06508\ m)}\right) = 1.36\ N$$

According to the calculation, each finger generates about 1.36 N of force. Adding all of the fingers together yields about a 6.8 N grip force in total. Based on this calculation, these servos lack the torque necessary to provide the proper grip force to lift and hold the full 700 mL. Consequently, the fourth requirement cannot be met. (Detailed calculations can be found in Appendix I)

There are some different solutions to this problem. The first solution would be to acquire bigger servo motors, this would increase the input torque pulling the string which would yield a greater grip strength that would be capable of meeting that water bottle requirement. The other option would be to install rubber pads on the contact surfaces of the hand to increase the coefficient of friction between the hand and the bottle. This would increase the frictional force between the hand and the bottle making it easier for the bottle to resist the gravitational force pulling it down.

6.6.2 FITECH FS5106B servo

The new servos that were chosen were the FITECH FS5106B servos. (See Figure 21)

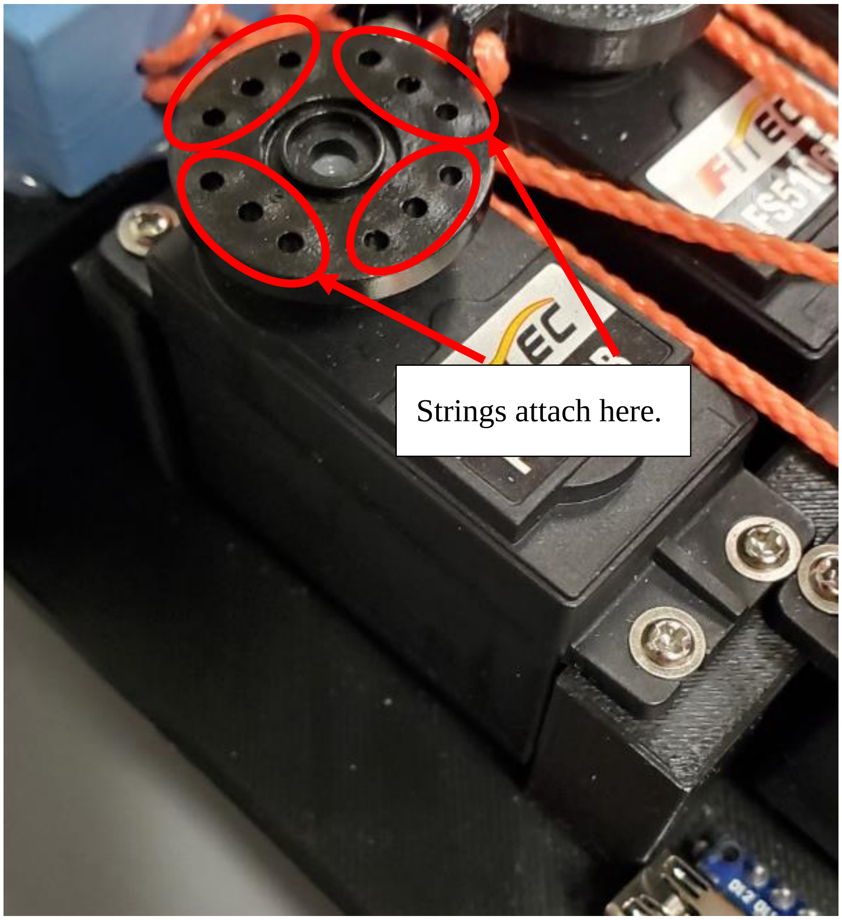


Figure 21: FITECH FS5106B servo

These servos can produce approximately .582 N-m (6 kg-cm). Accounting for this new higher torque in the calculations reveals that these servos will produce a total grip force of approximately 20.32 N which is sufficient to hold a full 700 mL bottle of water which only requires 17.7 N of grip force. However a big downside to using these servos is that they are larger than the DIYMORE servos. Although these servos have nylon gears which do assist in conserving weight, extra precautions may need to be taken to account for the extra weight in other aspects of the design. [10]

6.7 *FINGERTIP CAP CONNECTION*

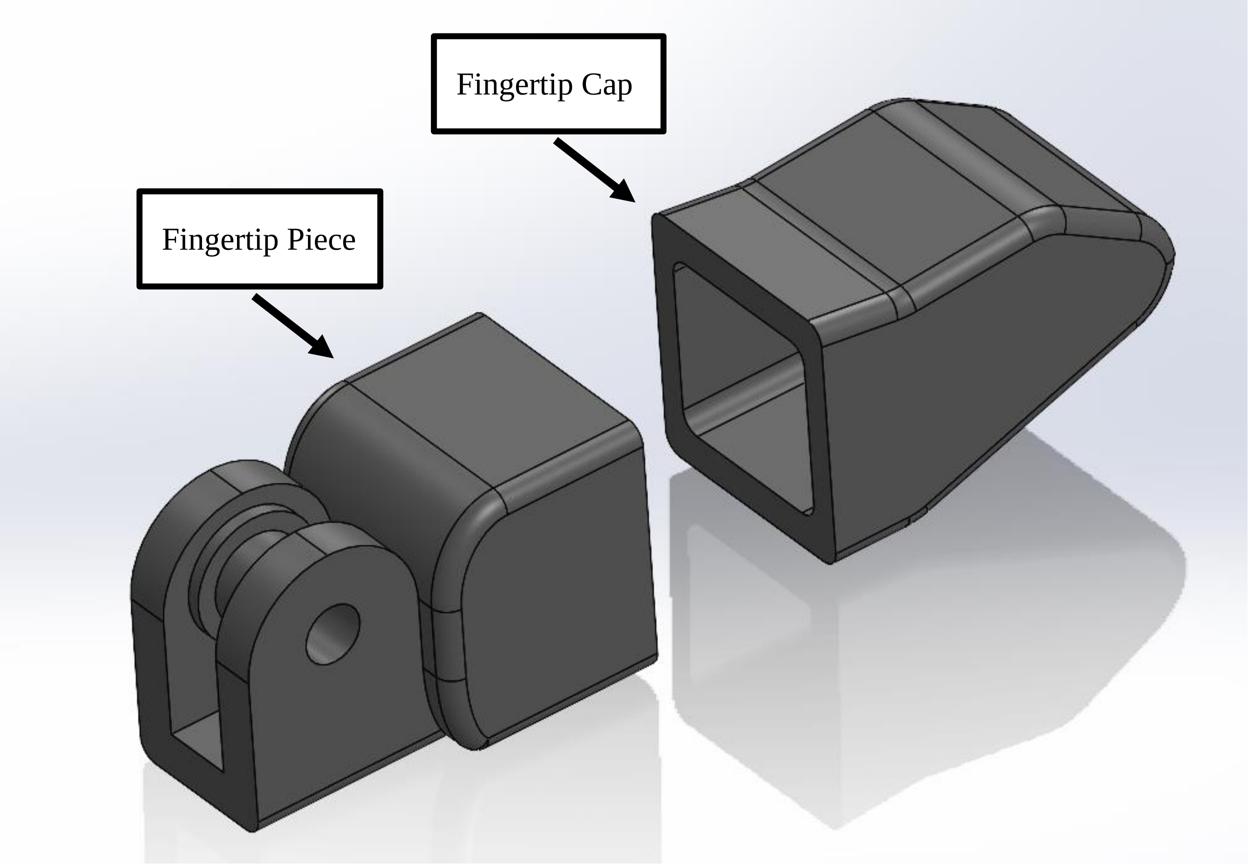


Figure 22: Fingertip cap connection highlight

Considering the nature of 3D-printing discussed in section 5.3.2 of this report, it can be difficult to manufacture smaller geometries with precision. This is why the fingertip cap wasn’t designed to have any interlocking components or mechanisms. Due to this fact, the fingertip cap has to be adhered to the fingertip piece. There are multiple methods of adhering the caps to their respective fingers. The two methods that were considered were super glue and a technique called PLA welding.

6.7.1 Super Glue

Super gluing is the most common method of adhering 3D-printed components together. It makes for an easy way to make a reliable connection. However, if not properly applied, super glue connections can break easily. This could be problematic due to the nature of this project. If the fingertip caps are glued improperly then the connection would fail making it harder for the device to grasp objects.

6.7.2 PLA welding

PLA welding is a bonding technique that involves using a soldering iron to melt the 3D printed components together, creating a strong seamless bond. The connection will be able to withstand a lot more stress and strain because it is made out of the same material as the parts themselves. However this technique also introduces safety concerns. When plastic is melted it releases harmful chemicals into the atmosphere, so if this technique is to be used then it should be done in a well-ventilated area or with a respirator of some sort, otherwise it can be hazardous to the person doing PLA welding. Considering the hazardous nature of PLA welding, superglue will be used to connect the fingertip caps to the fingertip pieces.

Regardless of adhesion technique, the connection will need to be tested to make sure it will withstand the stresses of operation. The methodology and results for this test can be found in section 7.1.1 of the report.

6.8 PROGRAMMING

Before writing the code for the prototype a simple flow chart was made to line out the code’s functions. Flow charts are a great tool that can be used in the preliminary stage of coding to help outline the proper logic.

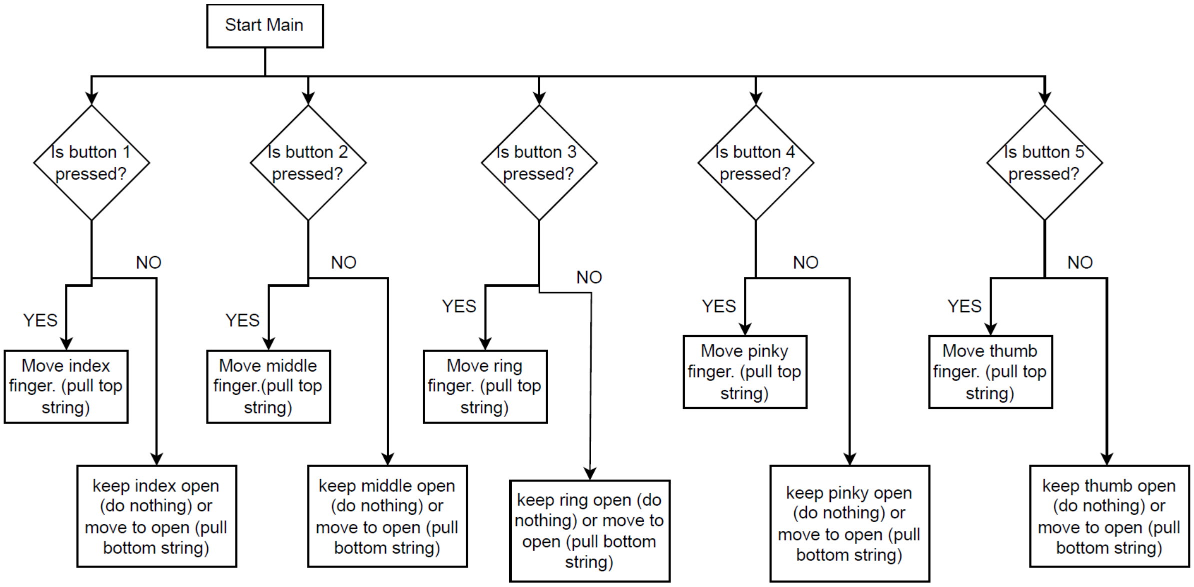


Figure 23: Snippet of the flowchart that covers the main function of the program (the full flow chart can be found in Appendix J)

The code for this prototype will follow a fairly simple structure. If a button is pressed then the corresponding servo will pull the top string moving the finger to its closed position. When the button is released the servo will pull the bottom string and the finger will move back to its open position or stay open if the button was never pressed to begin with.

7 DISCUSSION

7.1 TEST PLANS

7.1.1 Fingertip cap connection

The methodology for testing this connection involves clamping the fingertip to a table so that the connection is hanging over the edge. A weight will be attached to the end of the fingertip and gradually increased until failure or until a reasonable weight has been surpassed.

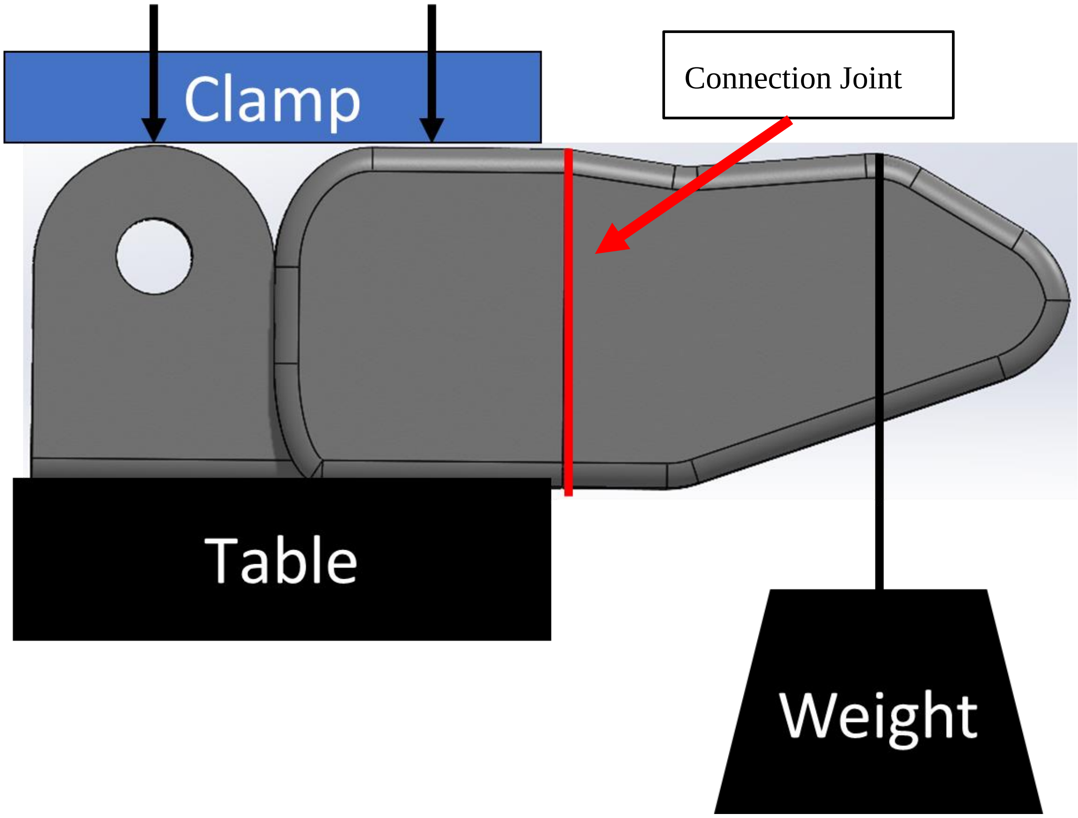


Figure 24: Fingertip Connection test methodology

The weight that was hung off of the fingertip first started at 1lb and gradually increased until the weight measured 20 lbs.

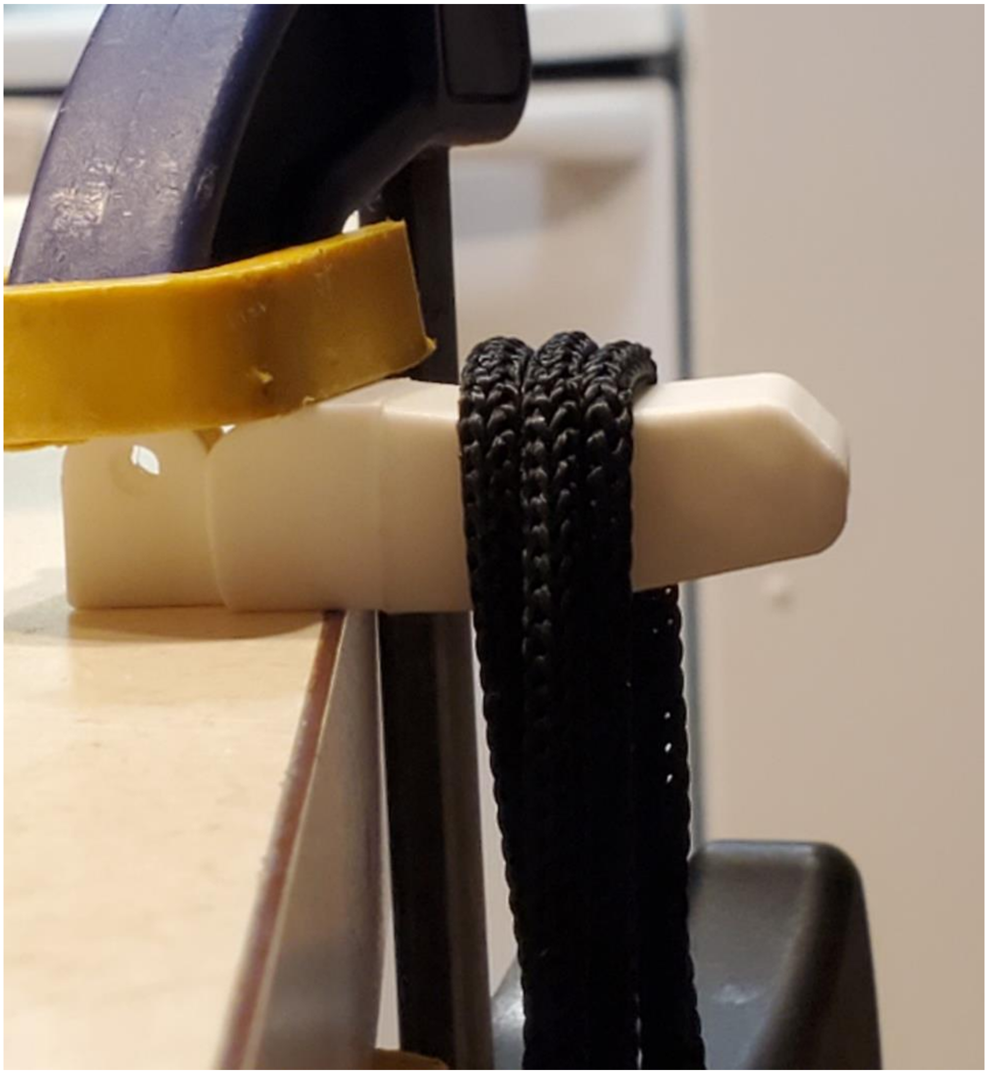


Figure 25: Real image of fingertip cap test.

Table 2: Table of results from fingertip cap test

Test	Weight (lbs)	Fail?
1	1	no
2	5	no
3	10	no
4	15	no
5	20	no

As can be observed from Table 2, the test specimen was clamped to the table so that the connection point was hanging off of the edge. A bag with a negligible weight was hung off the fingertip cap and the weight were increased from 1 lb to 20 lbs by increments of 5 lbs. The superglue connection did not fail under a 20-pound stress; therefore superglue was found to be a viable option for connecting the fingertip piece to the cap.

7.1.2 Servo Test

In order to verify the servos' functionality each servo was tested using Arduino's onboard example programs. The Arduino's example program for servos involved making the servo turn from a starting position to a final position. Each servo was wired to the Arduino and tested to verify functionality.

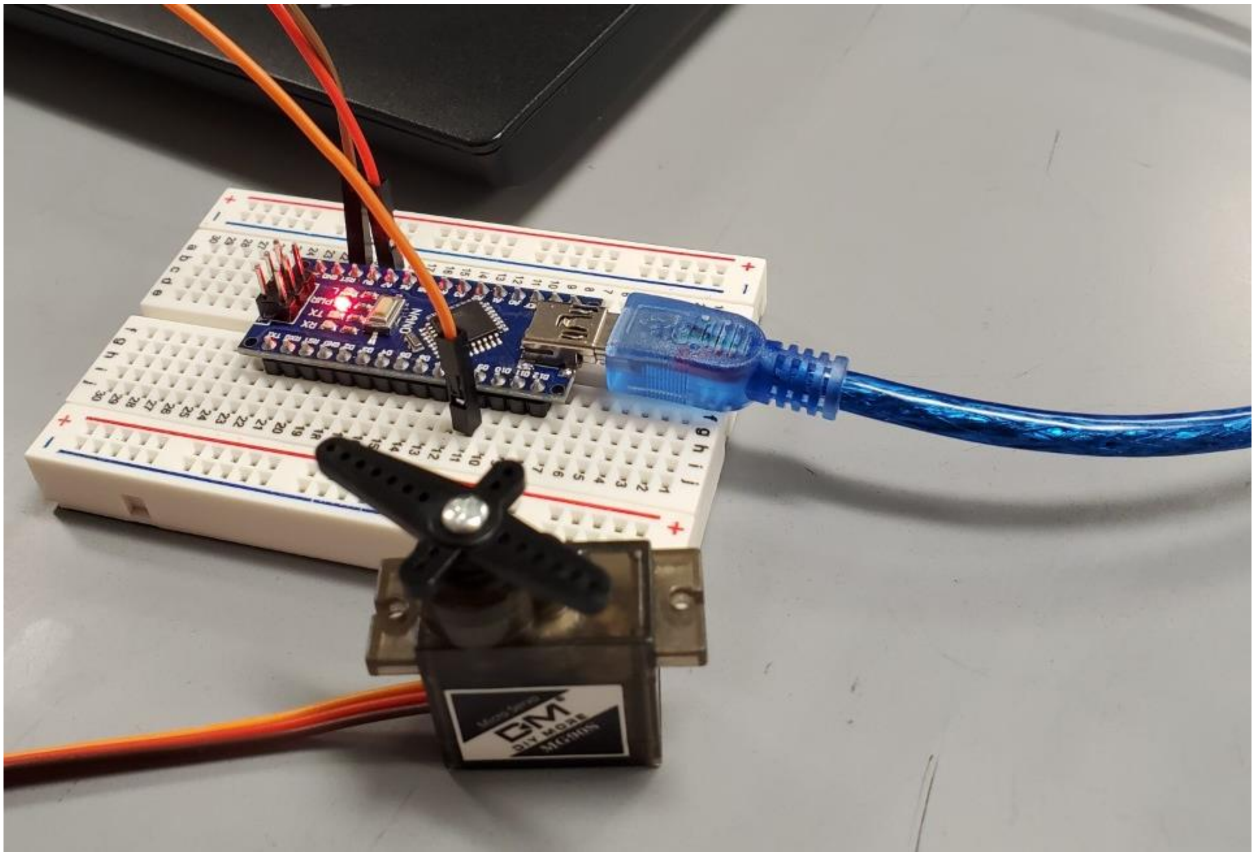


Figure 26: Servo wired to the Arduino for testing.

During testing two servo motors burned up during testing. After further research it was found that for some servos the 180^{O} range of motion is nominal. So if a program tells the servo to perform a sweeping motion from 0^{O} to 180^{O} the servo could be pushed past its limits, causing it to burn up and cease functioning. After adjusting the testing program to make the servo sweep from 15^{O} to 165^{O} this prevented the program from overexerting the servos and allowing them to function properly without burning out.

7.1.3 Device Test Plan

When testing the prototype's functionality each finger was tested by opening and closing each finger multiple times using the pushbuttons. After each finger's functionality was verified the prototype was tested in its capability to pick up several different objects of varying sizes and geometries.

The first set of objects that the prototype was tasked to grasp were a couple of smaller objects like a dry erase marker and a screwdriver. (See Figure 27)

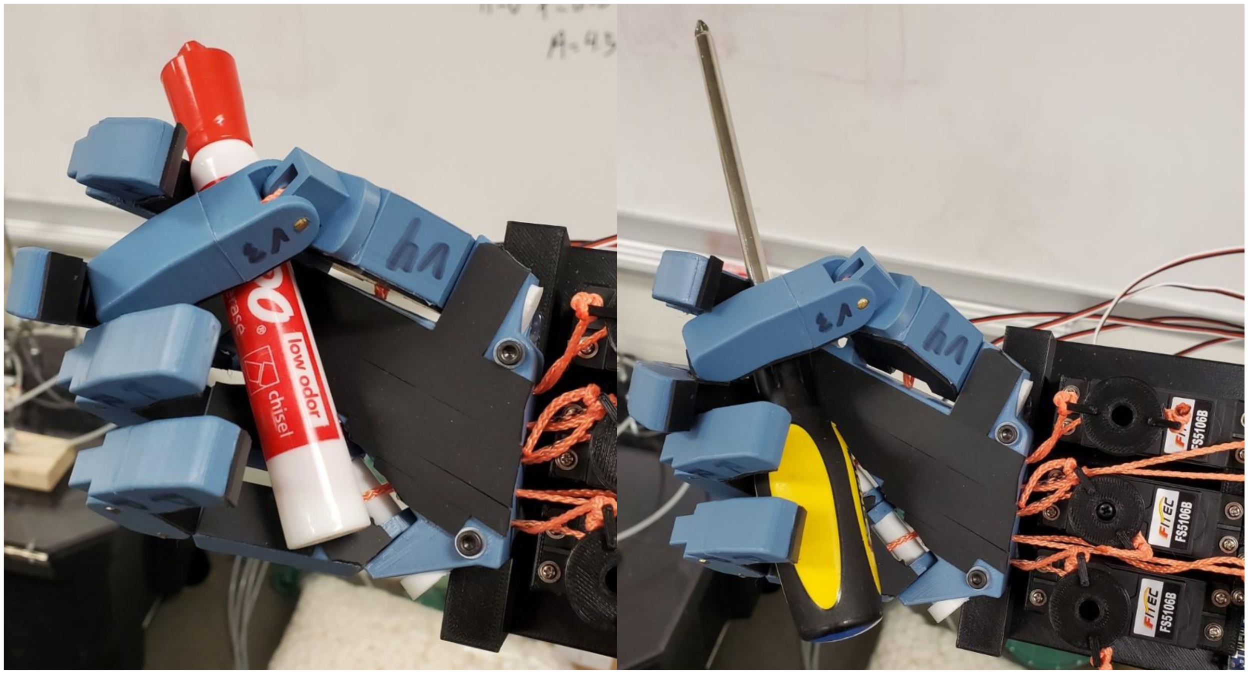


Figure 27: Hand grasping a dry erase marker and a screwdriver.

The second set of objects the prototype was tasked to hold were a couple of medium objects like a stress ball or a roll of masking tape. (See Figure 28)

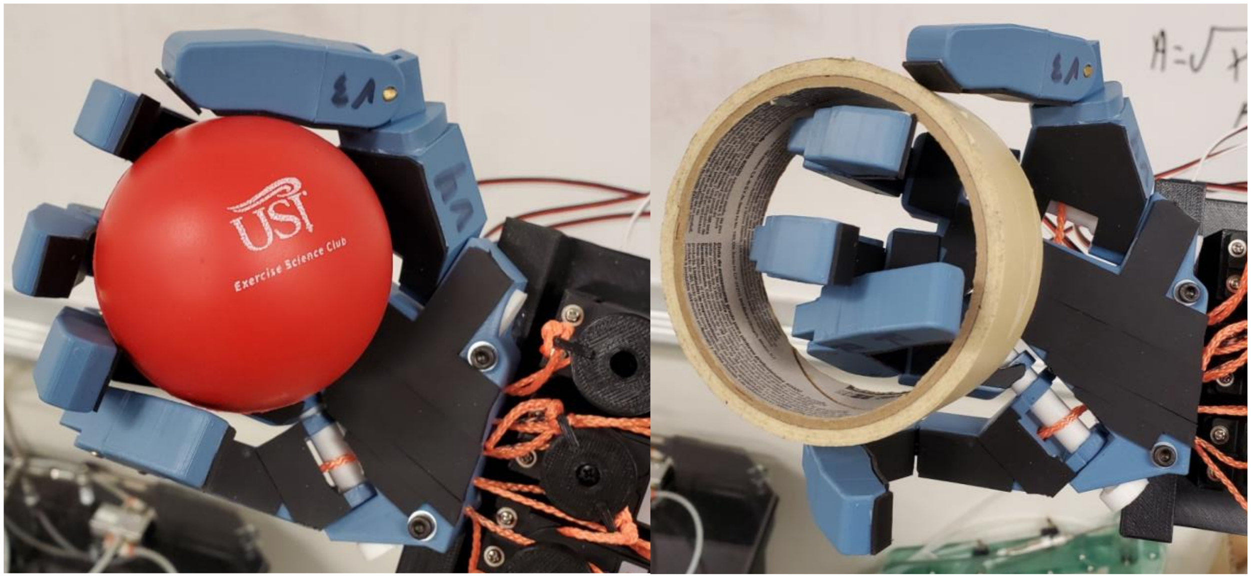


Figure 28: Hand grasping a stress ball and a roll of masking tape.

The last set of objects the prototype was tasked to hold were a couple of large objects like a 700 mL bottle of water or a 1 kg spool of 3D-printing filament. (See Figure 29)

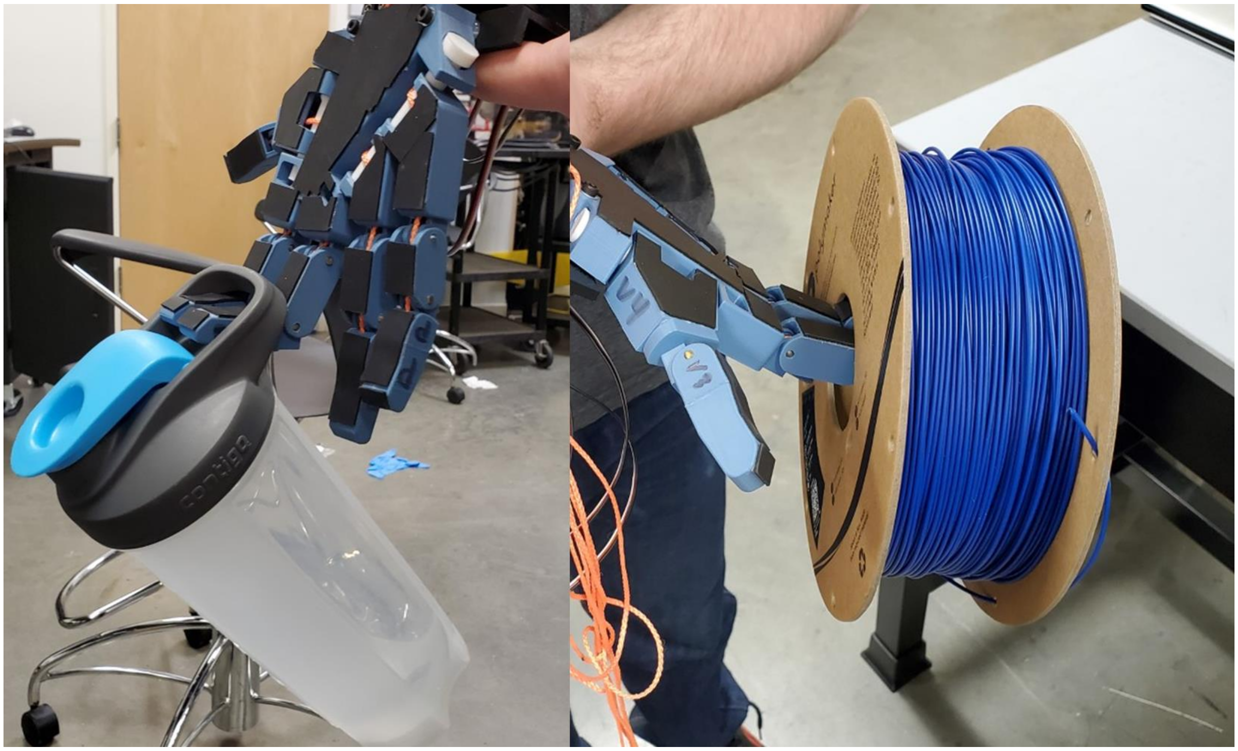


Figure 29: Hand lifting and holding a full 700 mL water bottle and a 1 kg spool of filament.

As depicted in Figure 29 (on the left), the hand is capable of grasping both large objects. However, during testing it was observed that the hand was unable to hold the water bottle as originally intended. The hand was initially intended to hold the bottle of water in a manner that mimicked a human would hold it before taking a drink from it (See Figure 30).

Figure 30: Human hand holding a bottle of water. [8]

It was observed during testing that the hand couldn’t hold the bottle of water because of how the thumb was designed (See Figure 31).

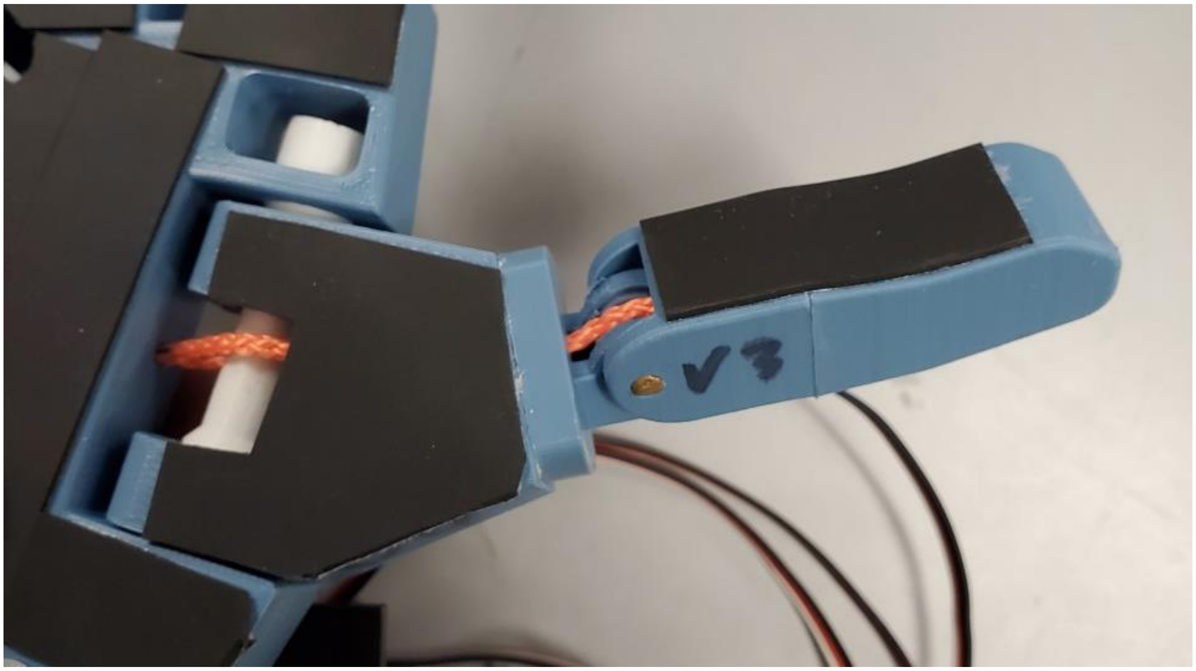


Figure 31: Picture of the thumb

Notice in Figure 30 that the thumb is slightly tilted forward rather than facing straight up. This was done to mimic how the human thumb is naturally tilted forward. However, this positioning causes the thumb to be too close to the palm when closed, and its placement is too high up on the palm, which can interfere with the middle finger's range of motion. Unless the object has a smaller circumference, the thumb is unable to wrap around the object, and instead pushes the object away when attempting to grasp it. (See Figure 32)

Figure 32: Thumb in the closed position.

7.1.4 Weight analysis

The third requirement of this project stated that the bionic hand shall weigh no more than 3 lbs. To meet this requirement, each component was weighed using a scale and their weights were recorded in a table. The sum of all the component weights was then calculated to determine the experimental total weight. This process helped in identifying areas where weight had to be reduced to meet the requirement.

Table 3: Mass table

Complete Mass Table		
Quantity	**Part name**	**Mass (g)**
1	3D components	190.15
5	Servos	45.00
1	Arduino Nano	7.00
1	Wiring	29.75
10	String	10
1	Breadboard	44.80
1	Battery	282.00
5	push buttons	1.15
	Total (g)	609.85
	Uncertainty (g)	± 10
	Weight (lbs)	1.34

After the device was fully constructed it was weighed to measure its actual weight.

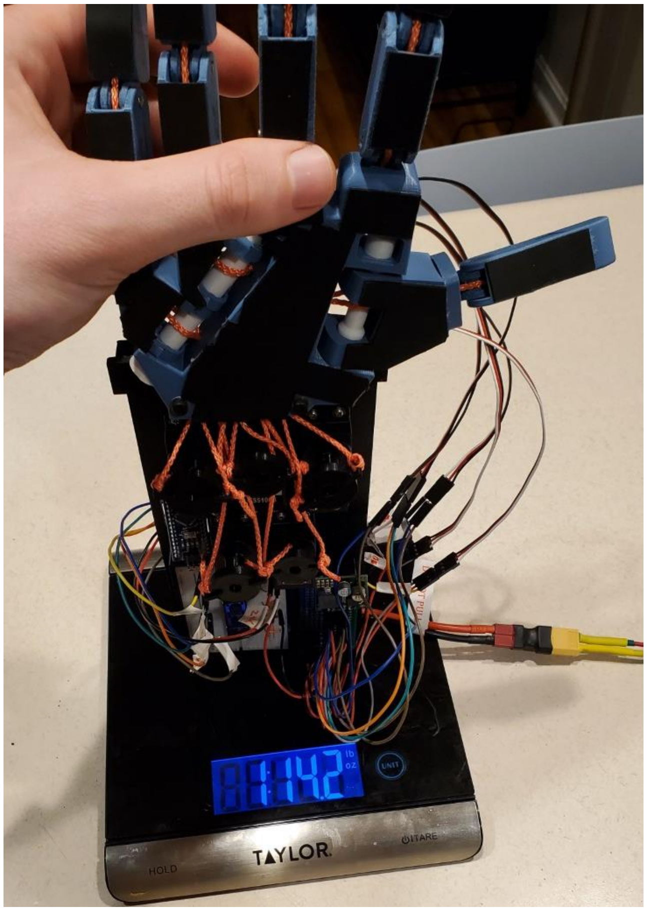


Figure 33: Hand being weighed using a scale.

Figure 34: Weight of the hand

As can be observed in Figure 34, the total weight of the hand is about 1 lb 14.2oz which roughly equals about 1.89 lbs which means that the prototype meets the third requirement.

7.2 CHALLENGES

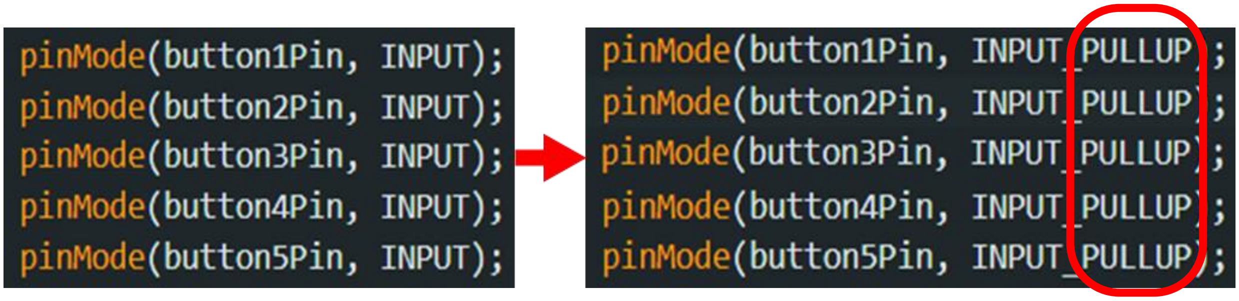
During the construction of the prototype, there were many challenges to overcome in order to ensure proper functionality. The biggest challenges occurred during the programming, servo implementation, power system implementation, and designing the base board where the components were mounted.

7.2.1 Writing the program

The biggest issue that was encountered was when the servos began moving rapidly without any input from the push buttons. When a pushbutton was pushed the corresponding servo would stop rapidly moving. After further review it was observed that the servos were actually rapidly moving from 15^O to 165^O which suggested that the input value (the button state in the code) for the servo was a floating value.

A floating value, in programming, is a value that hovers or “floats” between high and low voltage values; in the context of this project the high and low values are 5 V and 0 V respectively. When an input device such as a pushbutton is wired to a digital input pin with a floating voltage value it creates an unreliable signal causing the output device (servo motor) to rapidly flip between its on and off states. The solution to this problem is to implement a pullup or a pulldown resistor into the pushbutton circuitry.

The Arduino nano already has pullup resistors for each digital input pin that can be implemented by simply modifying the code.



```
pinMode(button1Pin, INPUT);
pinMode(button2Pin, INPUT);
pinMode(button3Pin, INPUT);
pinMode(button4Pin, INPUT);
pinMode(button5Pin, INPUT);
```

```
pinMode(button1Pin, INPUT_PULLUP);
pinMode(button2Pin, INPUT_PULLUP);
pinMode(button3Pin, INPUT_PULLUP);
pinMode(button4Pin, INPUT_PULLUP);
pinMode(button5Pin, INPUT_PULLUP);
```

Figure 35: Image of the code that was modified.

After making this change the servos acted as intended by only turning when a button was pressed.

7.2.2 Servo Implementation

Servo horns are mechanical components that are used to connect a servo motor to other components, such as a control surface on a robotic arm. They are typically attached to the servo motor's shaft using screws. (See Figure 36)

Figure 36: Servo horn implemented on to the servo.

The challenge with implementing the stock servo horns was that they did not have the correct size holes for the string to be tied to. (See Figure 37)

Figure 37: Image of the stock servo horn. The string mounting holes are circled in red.

Custom servo horns were designed to solve this problem. (See Figure 38)

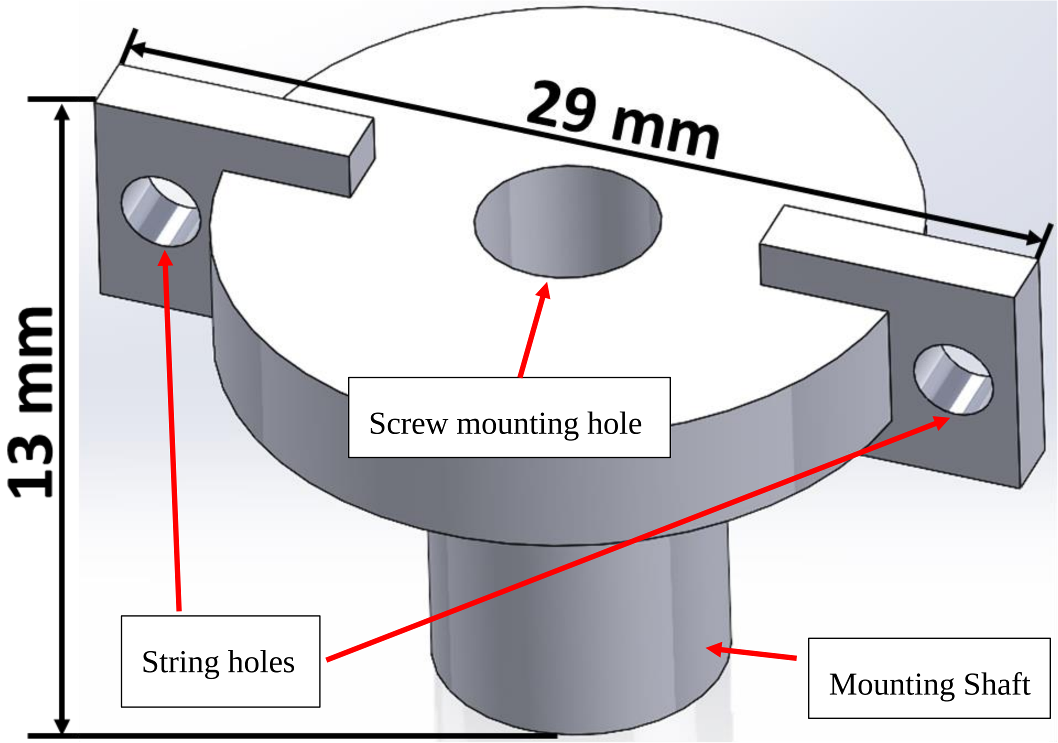


Figure 38: Solidworks rendering of custom servo horn.

This final design of the servo horns features two holes for string to be attached to. Given that the servo has nylon gears the mounting shaft size needed to be precise in order to avoid slippage during operation. These new servo horns are wider than the originals, so much so that they could interfere with each other during operation so three of them were made to be 10 mm taller to avoid this issue. (See Figure 35)

Figure 39: Custom servo horns implemented into the device.

7.2.3 Power system

With the change in servos there needed to be a change in the power system of the device. Each of the new servos has a stall current of about 1.1 A. The 5 V output pin on the microcontroller can only output .5 A, this means that they would not be able to be powered by the 5 V pin on the Arduino. This means that the servos will need to be powered directly from the battery. In order to accommodate this change in power consumption a new power distribution circuit would need to be designed to properly power the system. (See Appendix H to see the functional block diagram)

The new servos have an operating voltage of 4 V – 6 V, however, the battery has a voltage of 7.4 V, this means a voltage regulator will need to be used to drive down the voltage from the battery so that it is suitable to power the 5 servos. A traditional linear voltage regulator could regulate the voltage from the battery down to the proper 6 V level. However, linear amplifiers are not particularly good at supplying current. So a buck converter will be used instead. Using a buck converter, the voltage can be driven down without negatively impacting the current. Each servo requires 1.1 A for operation, 5 servos need to be powered meaning that the regulator needs to have an output of about 5.5 A. This means that a 6 V buck converter with a 5.5 A output current is needed to power the servos. A Pololu 6 V, 5.5 A D36V50F6 step-down regulator was chosen to solve this issue. (See Figure 40)

Figure 40: Pololu 6 V, 5.5 A D36V50F6 step-down regulator

The microcontroller will also require a voltage regulator for safety and stability purposes. The onboard voltage regulator on the microcontroller is notorious for its terrible heat dissipation, which can cause other components on the board to be damaged, as well as its inability to provide a stable output voltage. Using an external linear voltage regulator will not only provide better stability and heat dissipation, but it will also offer a layer of circuit protection and is more easily replaced if it gets damaged. (See Figure 41)

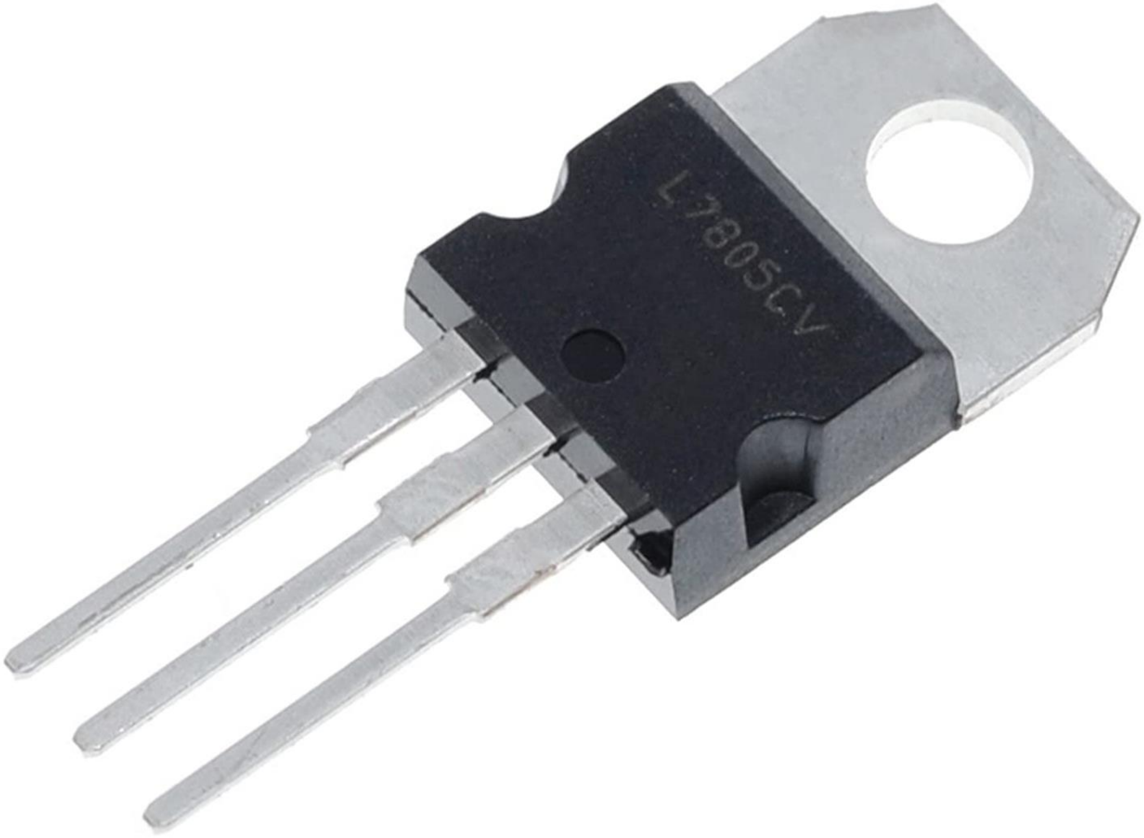


Figure 41: Linear voltage regulator

7.2.4 Base board design

A base board needed to be designed in order to mount the electrical components and the hand onto one solid piece. (See Figure 42)

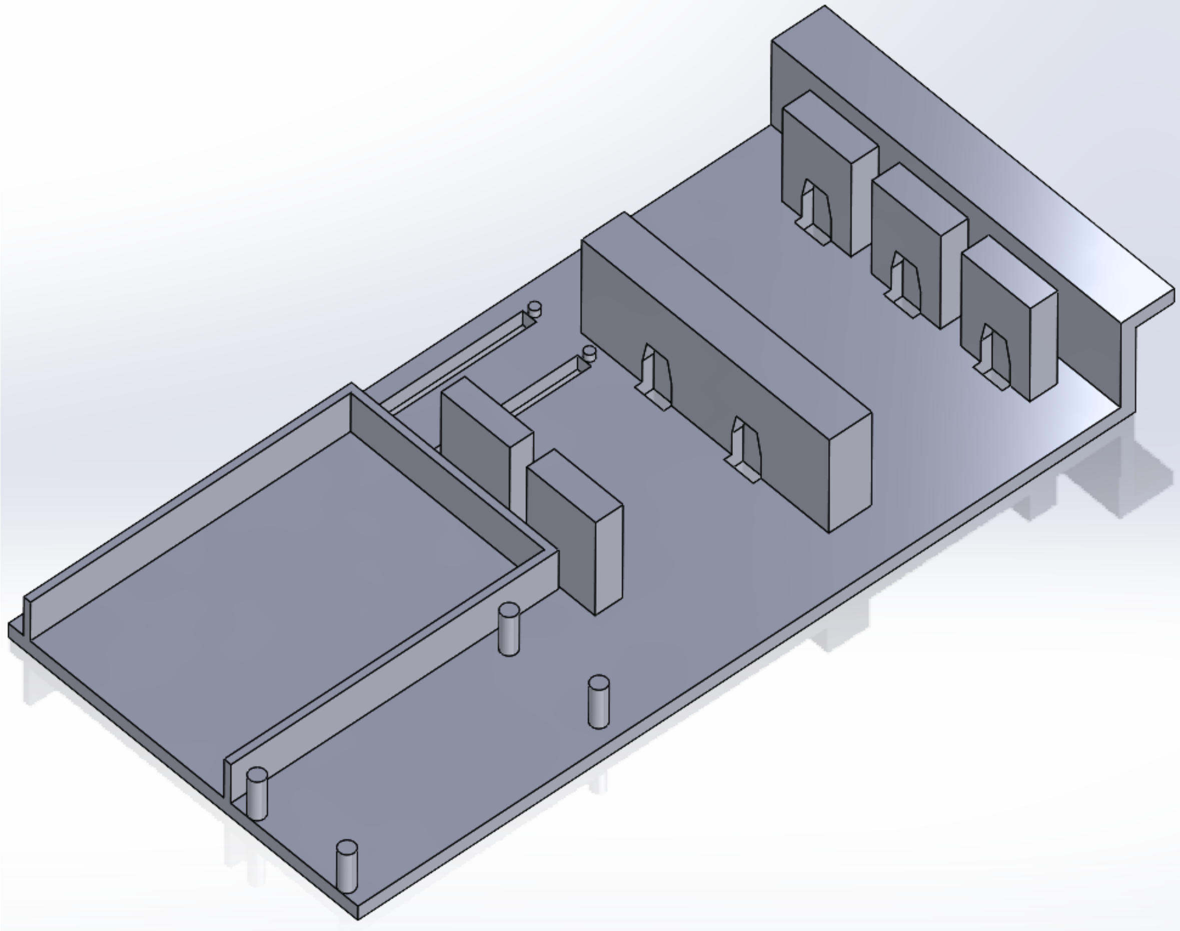


Figure 42: Base Plate (SolidWorks)

To accurately adjust the dimensions of the servo mounts, it was necessary to print multiple versions of this design. Each servo mount had a channel cut out so that their wire could be fed through to the other side without damaging the wire. (See Figure 43)

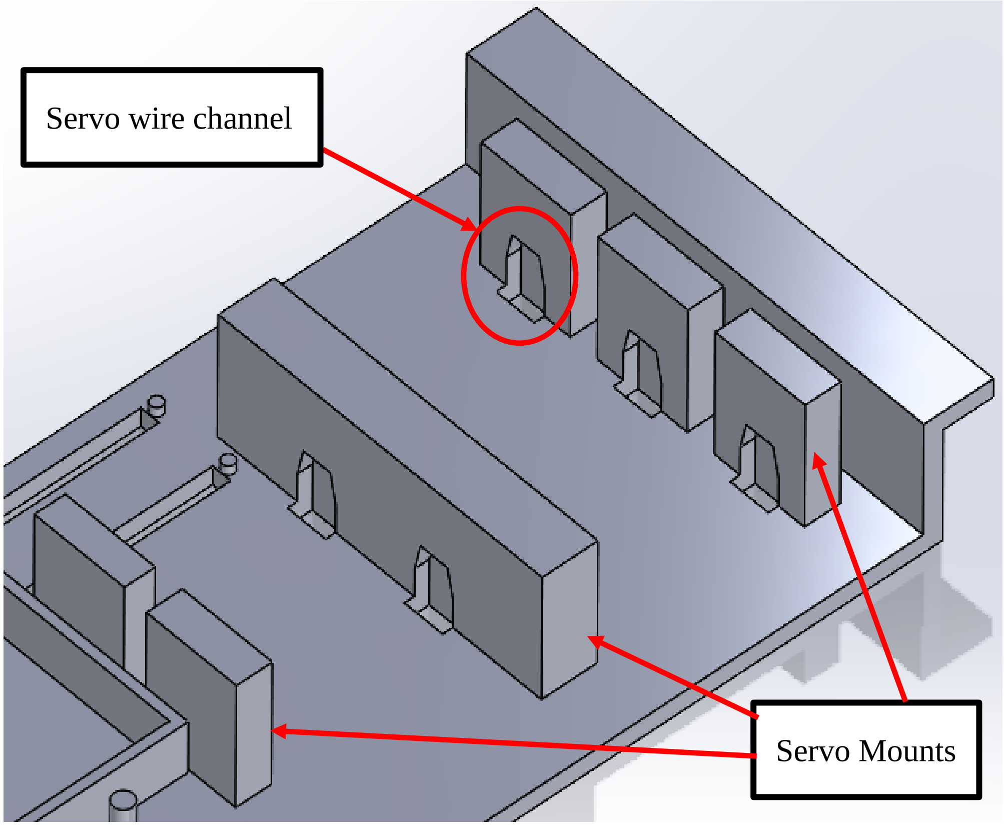


Figure 43: Base plate servo mount overview (SolidWorks).

There are standoffs for mounting the power distribution circuitry and the Arduino nano, as well as a section dedicated to the breadboard. (See Figure 44)

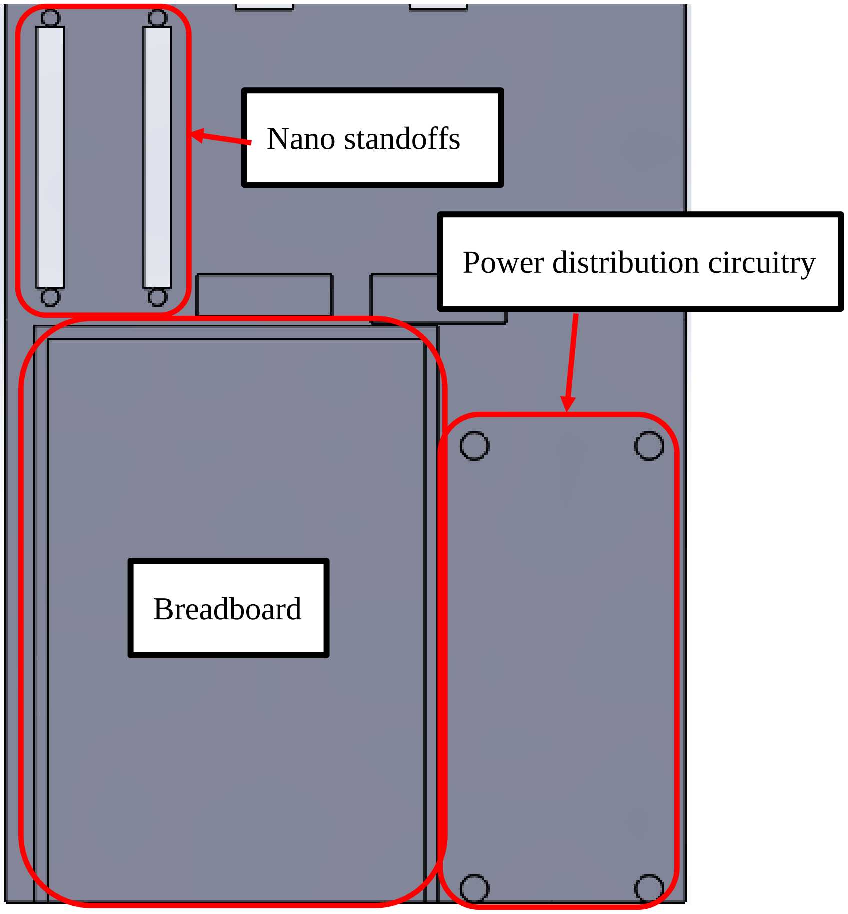


Figure 44: Base board power distribution circuitry, nano, and breadboard placement (SolidWorks).

There is also a raised surface for the hand to be mounted to, the surface is raised to make the string channels on the hand are moderately level with the servos.

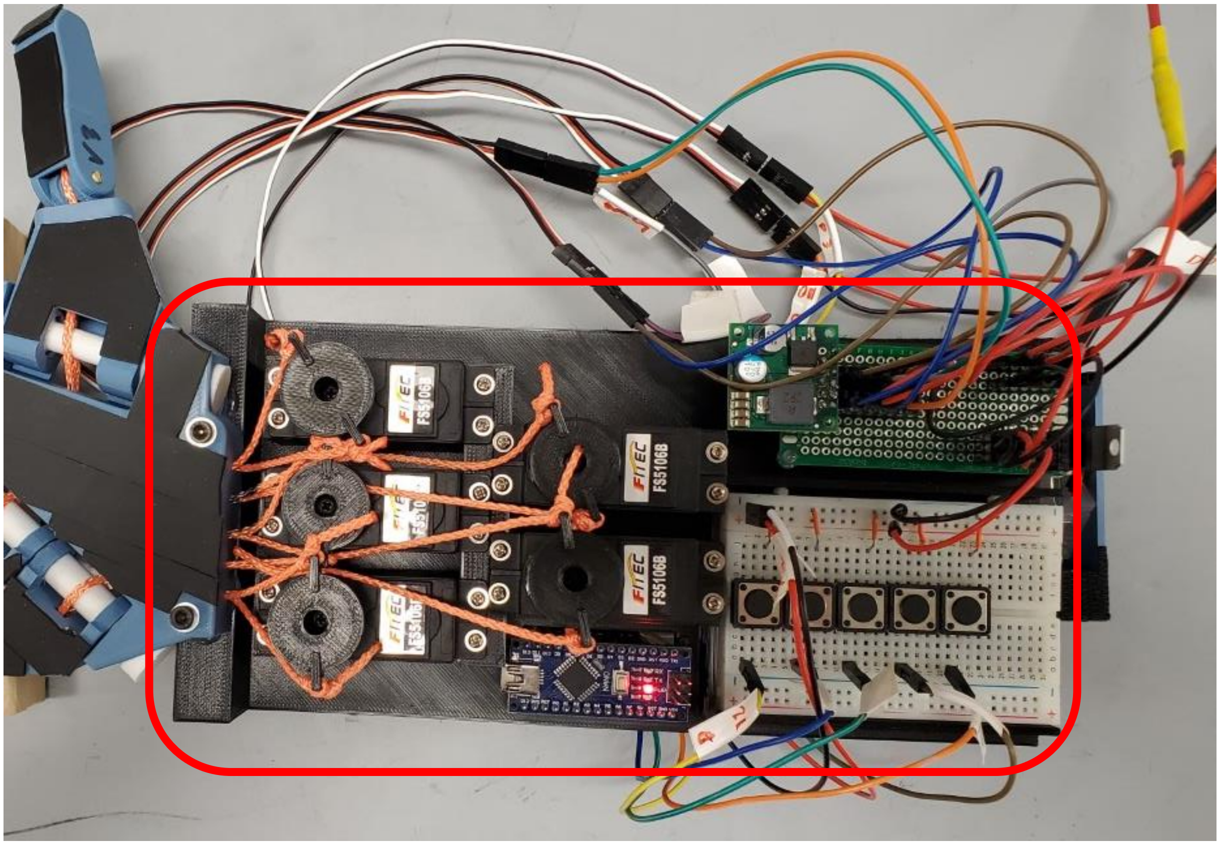


Figure 45: Base board implemented.

8 CONCLUSION

8.1 REQUIREMENTS MET

The prototype bionic hand shall…

√ Use individual servos to actuate the index, middle, ring, pinky, and thumb.

√ Weigh no more than 3 lbs.

√ Use a lithium polymer battery as its main power source.

X Hold a full 700 mL bottle of water (approx. 2 lbs.).

√ Be equal to or within the size constraints of an average sized human hand.

In general, this project fulfills most of the requirements, except for one. Although the prototype can technically lift and hold a water bottle, it falls short in the ability to grasp the bottle in a satisfactory manner. Therefore, it wouldn't be appropriate to say that the prototype fulfills the fourth requirement of holding the 700 mL bottle of water.

8.2 FUTURE WORK

This project was originally meant to be a prototype bionic prosthetic device. However, due to time constraints, as well as other limitations, the scope of this project had to be significantly scaled back. Currently this project serves as a proof of concept that will be further developed into a fully functioning prosthetic device through multiple future project iterations. With this in mind there is a substantial amount of future work that can be done to turn this into a fully functioning bionic prosthetic hand.

8.2.1 Immediate improvements

There are some immediate improvements that could be made to the device that will improve the device’s current function. One such improvement is fixing the thumb, which currently has limited capability to grab objects with a larger circumference, such as the water bottle. As discussed previously, when the thumb closes it pushes the water bottle out of the way instead of wrapping around it to grasp it. This issue could be resolved by adjusting the thumb’s position to face straight up, rather than being rotated slightly forward. Increasing the degrees of freedom in the thumb could also improve its functionality as well.

Another immediate improvement that could be made to the device would be introducing grip patterns to the device. This would allow the device to assume a fully clenched fist or pinch grip when a pushbutton is pressed, rather than just moving a single finger. By combining this improvement with an update to the code that enables the pushbuttons to activate the servos upon being pressed and release them upon being pressed again, testing the device's capabilities would become much easier.

8.2.2 Myoelectric sensors and pressure sensors

Incorporating myoelectric sensors will dramatically increase the device functionality by replacing the pushbuttons used to control the fingers. Myoelectric sensors are muscle sensors that can sense the electrical impulses that occur in a muscle when it is flexed. This would allow an amputee to control the device by simply flexing certain muscles in a specific manner. Unlike pushbuttons, myoelectric sensors would give the user variable control over the servos, giving the user a more precise control over the device. Thereby enhancing the device’s functionality.

Also, incorporating pressure sensors in the fingertips of the device would provide haptic feedback to the user, letting them know how hard the hand is grasping an object. Combining the use of the pressure sensors with the variable controls of the myoelectric sensors will dramatically increase the functionality of the device for the user. They will be able to precisely control the servos based on the feedback from the pressure sensors, allowing them to pick up delicate objects without breaking them.

8.2.3 Arm socket and wrist joint

An arm socket is a critical component in the design of a wearable device for an amputee. It can provide a secure and comfortable attachment point for the device, allowing the user to move around without fear of the device falling off. Therefore, a well-designed arm socket would be an exceptional upgrade to the overall functionality and usability of the device.

In addition to the arm socket, incorporating a wrist joint into the device can enhance its functionality. Designing a wrist joint for the device will also increase the functionality of the device. This would make it easier to perform various tasks and activities like adjusting it to hold a cup. Overall, designing a wrist joint for the device is a valuable addition that can improve the user's experience with the device.

8.3 LESSONS LEARNED

The development of the bionic prosthetic device also provided important lessons for future projects. The team learned that 3D-printing can be a challenging process, requiring attention to detail and careful calibration of the printer as well as knowing the printing capabilities of the printer. Pull up/pull down resistors were also identified as a necessary component for controlling servos to negate floating voltage values. Using engineering calculations to double check feasibility was found to be an important step in ensuring the device would work as intended. Not only do calculations provide a baseline of operation, they also can information on which components would actually work in the design. Additionally, anatomical accuracy is not always necessary if it hinders the function of the device. Although the thumb may look naturally placed, it fails to grasp wider objects. Lastly, fuses are a key safety feature for protecting circuitry when powering a device using a battery because if something goes wrong with the power supply, the fuses are destroyed and not the crucial electronic devices. These lessons will be important to consider when further improving the device and developing future prosthetic projects. It's clear that the team overcame many challenges and gained valuable insights that were instrumental in achieving the project's accomplishments.

8.4 ACCOMPLISHMENTS

Throughout the development of this prototype bionic hand, significant accomplishments were made in various areas. A full in-depth CAD model was created using SolidWorks, where complex geometries make up the foundation of the design. One example of this being the channels for each of the strings to be fed through. 3D-printing was also utilized to create various components of the device, making the fabrication process faster and more efficient. Additionally, the device has demonstrated the ability to pick up and hold various objects, a crucial aspect for its potential use as a prosthetic limb. The team, with the help of Dr. Chlebowski, also developed a power distribution system to power the device using a single battery, further simplifying the device's operation. Lastly, programming the servos to function properly was an important accomplishment, as it enables the device to perform its intended movements and functions. Overall, these accomplishments represent significant progress towards creating a functional and effective bionic prosthetic hand.

8.5 FINAL WORDS

In conclusion this project aims to address the problem of upper limb amputation using a bionic prosthetic device. There was a lot of research that went into this project that proved greatly beneficial. Even though this was just a non-wearable prototype there was still a lot that needed to be done and challenges to overcome. The hand has shown that it meets all but one of the requirements and can hold multiple objects of various sizes. Also, because this project is meant to be a prototype that will be eventually turned into a fully functioning prosthetic device, there is a substantial amount of future work that can be done to this device to improve its functionality. For instance, adding muscle sensors and an arm socket to the device would turn the device into a prosthetic that could actually be used by an amputee. Additionally, pressure sensors and a wrist joint would also improve the devices functionality. Overall, this project has demonstrated great potential for advancing the field of prosthetics and improving the lives of those with upper limb amputations.

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APPENDICES

Appendix A: Mechanical subsystem Breakdown

Appendix B: Electronic subsystem breakdown

Appendix C: Software subsystem breakdown

Appendix D: Schedule

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Appendix G: Mechanical block diagram

Appendix H: Functional Block Diagram

Appendix I: Servo Calculations

Appendix J: Code Flowchart

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APPENDIX A

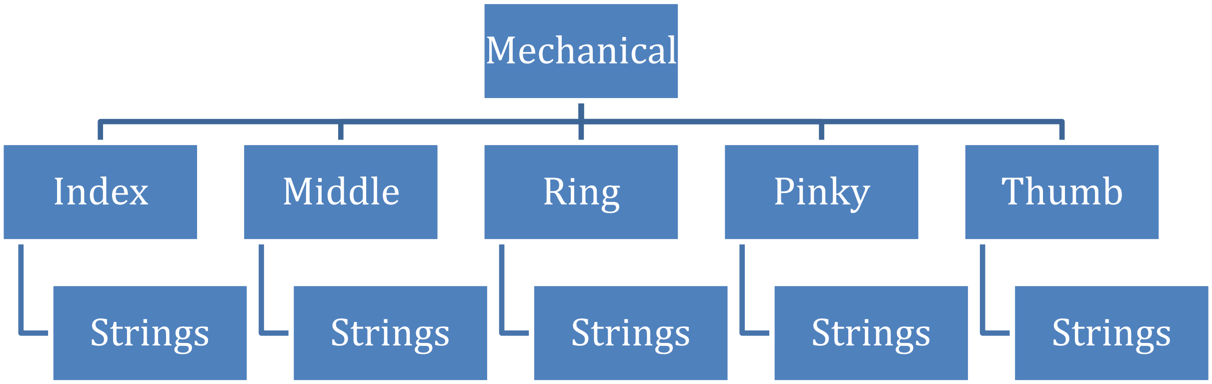


Figure 47: Mechanical subsystem breakdown

APPENDIX B

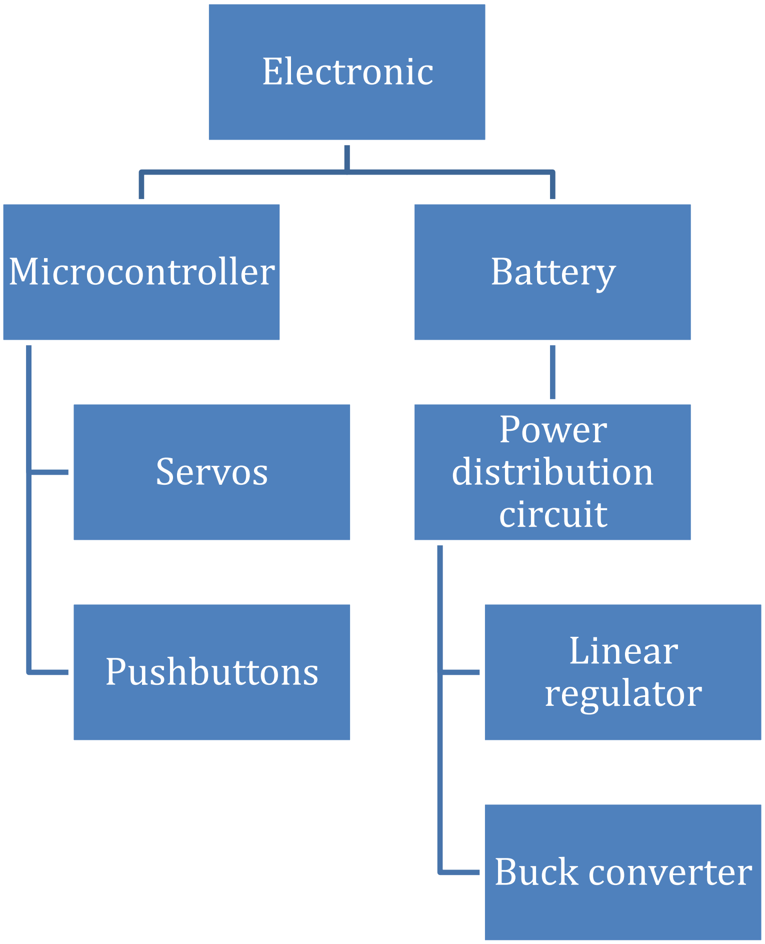


Figure 48: Electronic subsystem breakdown

APPENDIX C

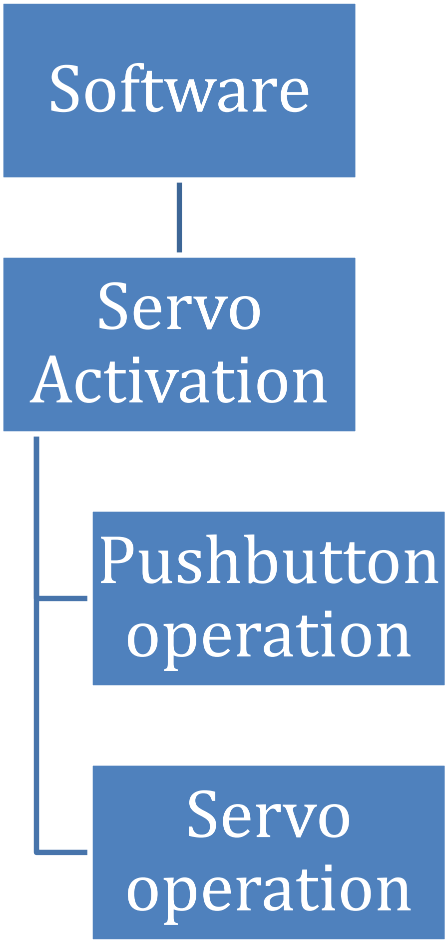


Figure 49: Software subsystem breakdown

APPENDIX D

Table 4: Senior Design Schedule

Schedule	
Task	Date
Fall 2022 Semester	
semester begins - think about project	8/22/2022
read senior design reports	8/23/2022
preliminary literature review	9/1/2022
library instruction on literature searches	9/12/2022
In depth literature review	9/15/2022
Project proposal 1st draft	9/30/2022
Work on project requirements	10/1/2022
Requirements due	10/3/2022
Revise project proposal	10/6/2022
Project proposal final draft due	10/7/2022
Start working on oral presentation	10/9/2022
Start developing preliminary designs	10/10/2022
finalize oral presentation	10/12/2022
oral presentation due	10/17/2022
finalize preliminary design	11/11/2022
preliminary design review oral presentation	11/14/2022 - 11/16/2022
start working on pre-senior design report	11/21/2022
finalize pre-senior design report	12/5/2022
turn in pre-senior report	12/7/2022
Spring 2023 semester	
Contact advisor to arrange weekly meetings.	1/9/2023
begin working on senior design report	1/10/2023
begin critical design	1/10/2023
finalize Solidworks files for fingers and palm	1/15/2023
Degree Works page review	2/3/2023

finalize critical design	2/7/2023
critical design review	2/9/2023
finalize electronic component selection	2/10/2023
test fit fingers and palm update drawings if needed	2/10/2023
construct final fingers and hand assembly	2/12/2023
Begin programming electronics	2/10/2023
begin working on senior design presentation	2/12/2023
Parts ordered	2/12/2023
Parts received	2/14/2023
Tested servos functionality	2/15/2023
Began writing code for servos and pushbuttons	2/15/2023
Began writing project info for Kuban’s shared drive	2/20/2023
Lifelong Learning quiz	2/22/2023
Ordered new servos	2/25/2023
Received new servos	3/1/2023
Program Info to shared drive	3/1/2023
Names, Emails on invite list in drive	3/1/2023
Be able to actuate servos using push buttons	3/10/2023
2-week grace period (do nothing for project) (spring break)	3/10/2023 - 3/17/2023
Servo Base plate constructed	3/18/2023
Servos mounted on to base plate	3/18/2023
Power regulator circuit constructed	3/20/23
Buck boost converter ordered	3/20/23
Buck boost converter circuit constructed	3/22/23
Begin assembling the full prototype	3/25/2023
Preliminary Project Poster to Shared Drive	3/24/2023
Senior design presentation reviews complete	3/31/2023
1st draft report due to advisor	4/6/2023
Finalized Poster to shared drive	4/13/2023
Finalize presentation	4/19/2023
Senior design presentations	4/21/2023

2nd draft of report due to advisor	4/24/2023
Present poster	4/27/2023
Complete CATME Survey	4/27/2023
Complete Exit Survey & Interview	4/27/2023
report final draft due to advisor and shared drive	4/27/2023
final report submitted to SOAR	4/27/2023

APPENDIX E

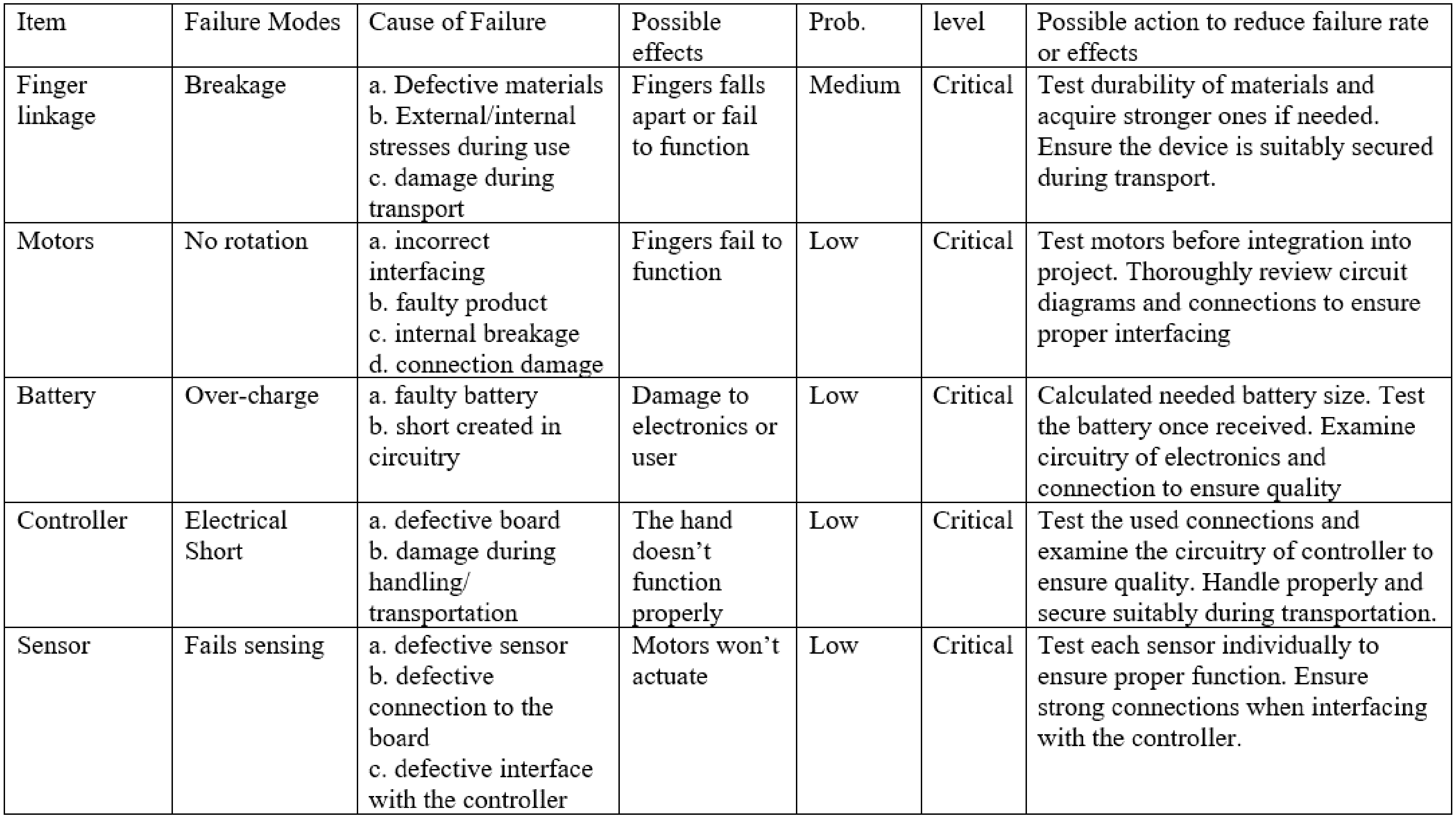
Table 5: Project budget

Budget		
MAX Project Budget = $500		
item type	Item	max allowed price
Electronics	Arduino nano	$30
	Servos	$25
	Sensor	$100
	Battery	$30
	LED indicator	$10
	Pack of jumper wires	$7
Misc.	3d printing	$100
	Hardware	$15
	String	$5
	Subtotal	$332
	For emergencies	$168
	Total	$500

Table 6: Cost analysis

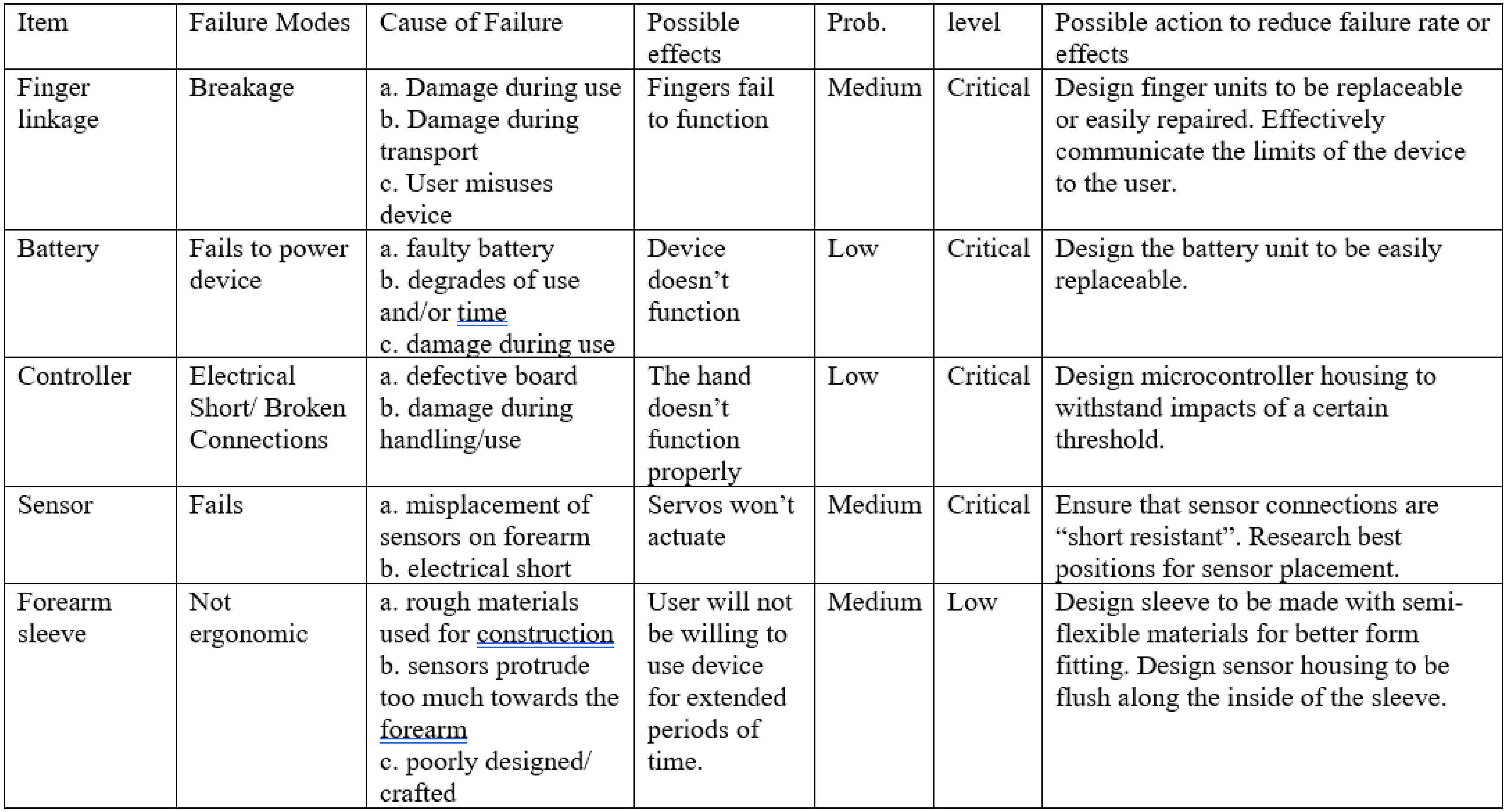
Final cost		
Item	**Quantity**	**Cost (USD)**
Arduino Nano	1	$12.99
Servos	5	$69.75
Battery	1	$49.99
Wires	120	$6.98
Buttons	20	$8.99
Breadboard	1	$5.99
Strings	1	$6.48
Buck Regulator	1	$48.58
Subtotal:		$209.75
Sales Tax:		7%
Total:		$224.43

APPENDIX F



Item	Failure Modes	Cause of Failure	Possible effects	Prob.	level	Possible action to reduce failure rate or effects
Finger linkage	Breakage	a. Defective materials b. External/internal stresses during use c. damage during transport	Fingers falls apart or fail to function	Medium	Critical	Test durability of materials and acquire stronger ones if needed. Ensure the device is suitably secured during transport.
Motors	No rotation	a. incorrect interfacing b. faulty product c. internal breakage d. connection damage	Fingers fail to function	Low	Critical	Test motors before integration into project. Thoroughly review circuit diagrams and connections to ensure proper interfacing
Battery	Over-charge	a. faulty battery b. short created in circuitry	Damage to electronics or user	Low	Critical	Calculated needed battery size. Test the battery once received. Examine circuitry of electronics and connection to ensure quality
Controller	Electrical Short	a. defective board b. damage during handling/ transportation	The hand doesn't function properly	Low	Critical	Test the used connections and examine the circuitry of controller to ensure quality. Handle properly and secure suitably during transportation.
Sensor	Fails sensing	a. defective sensor b. defective connection to the board c. defective interface with the controller	Motors won't actuate	Low	Critical	Test each sensor individually to ensure proper function. Ensure strong connections when interfacing with the controller.

Table 6: FMEA before end of Senior design.



Item	Failure Modes	Cause of Failure	Possible effects	Prob.	level	Possible action to reduce failure rate or effects
Finger linkage	Breakage	a. Damage during use b. Damage during transport c. User misuses device	Fingers fail to function	Medium	Critical	Design finger units to be replaceable or easily repaired. Effectively communicate the limits of the device to the user.
Battery	Fails to power device	a. faulty battery b. degrades of use and/or time c. damage during use	Device doesn't function	Low	Critical	Design the battery unit to be easily replaceable.
Controller	Electrical Short/ Broken Connections	a. defective board b. damage during handling/use	The hand doesn't function properly	Low	Critical	Design microcontroller housing to withstand impacts of a certain threshold.
Sensor	Fails	a. misplacement of sensors on forearm b. electrical short	Servos won't actuate	Medium	Critical	Ensure that sensor connections are "short resistant". Research best positions for sensor placement.
Forearm sleeve	Not ergonomic	a. rough materials used for construction b. sensors protrude too much towards the forearm c. poorly designed/ crafted	User will not be willing to use device for extended periods of time.	Medium	Low	Design sleeve to be made with semi-flexible materials for better form fitting. Design sensor housing to be flush along the inside of the sleeve.

Table 7: FMEA after end of Senior design.

APPENDIX G

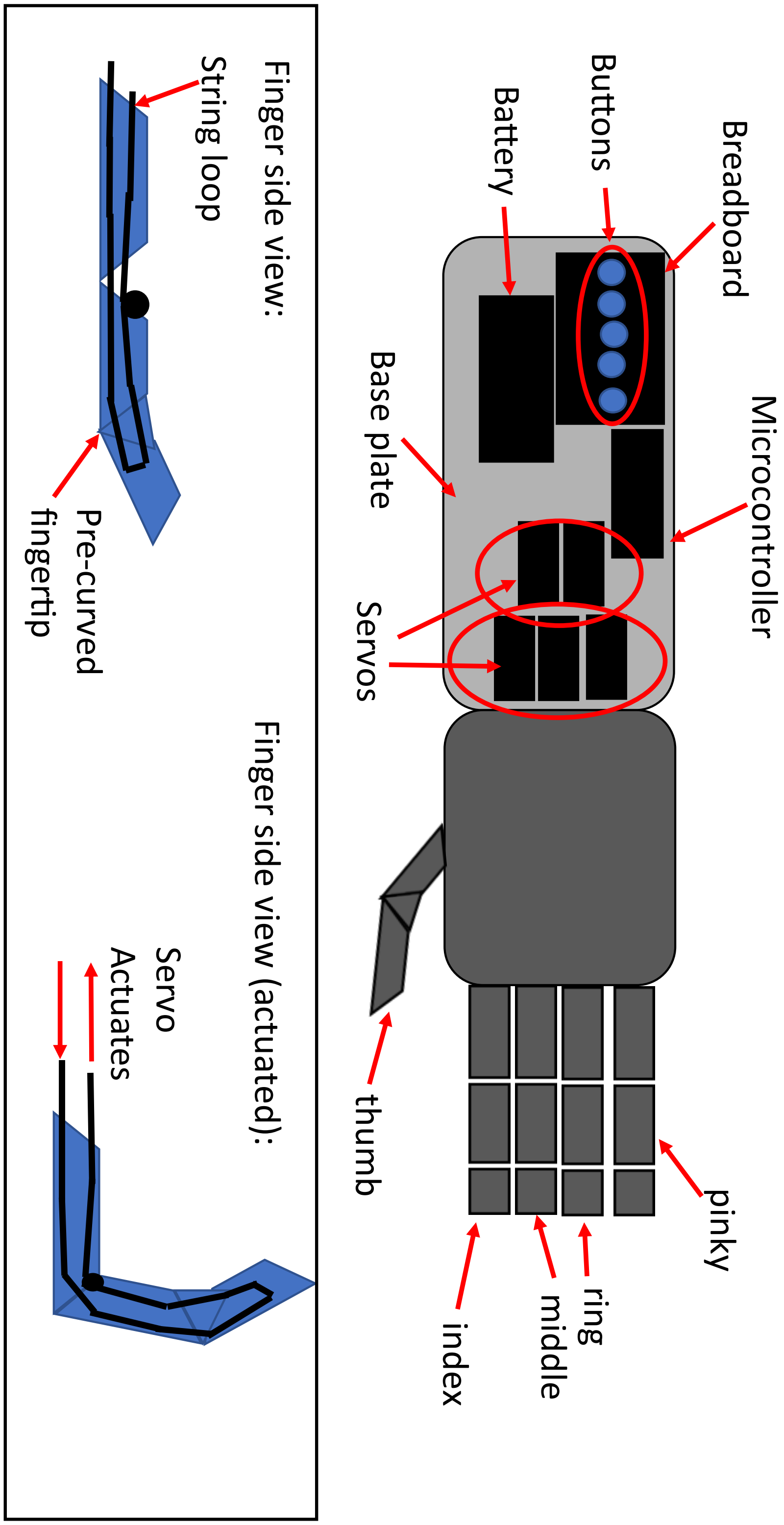


Figure 50: Mechanical Block Diagram.

APPENDIX H

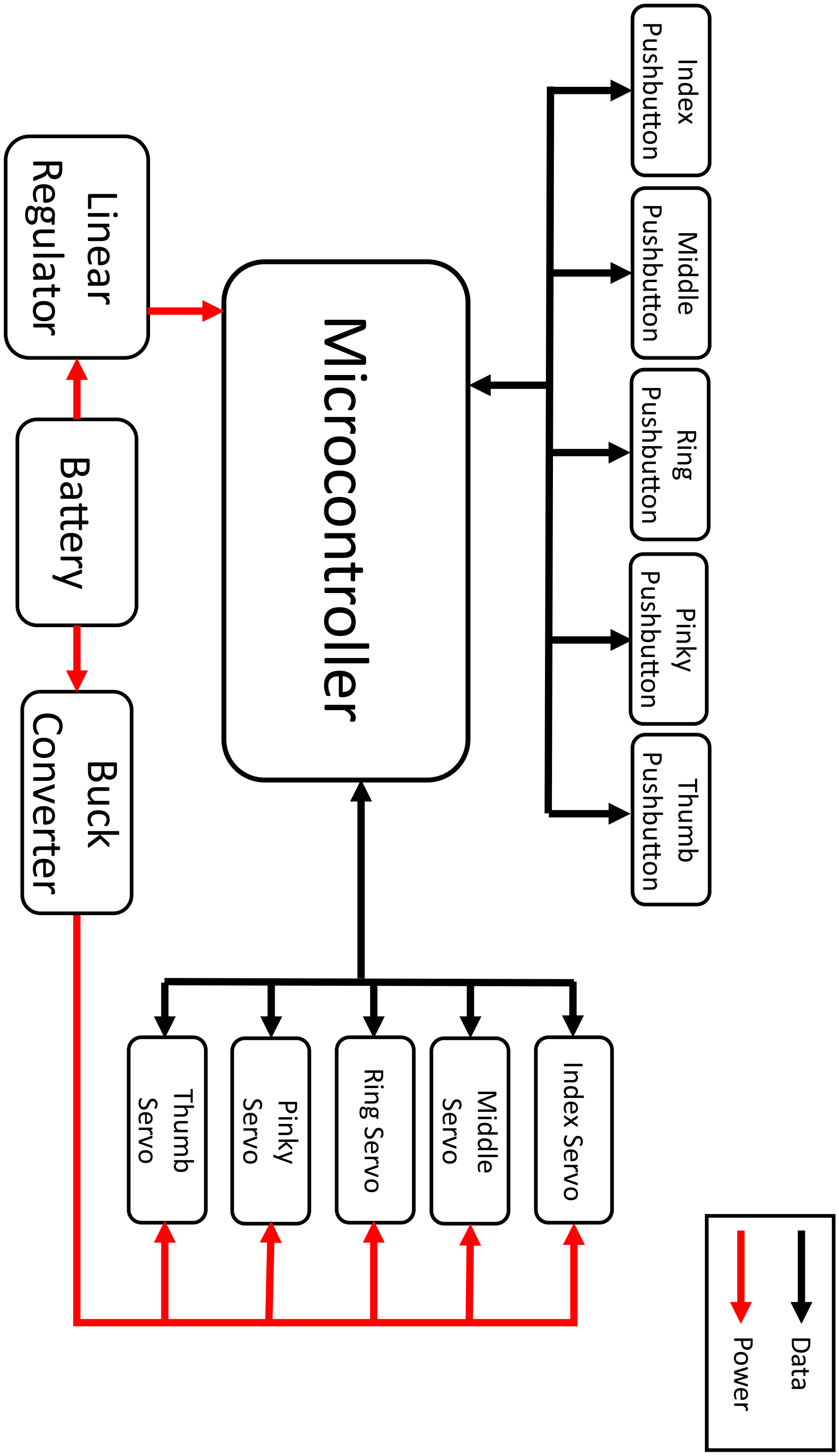


Figure 51: Functional Block Diagram.

APPENDIX I

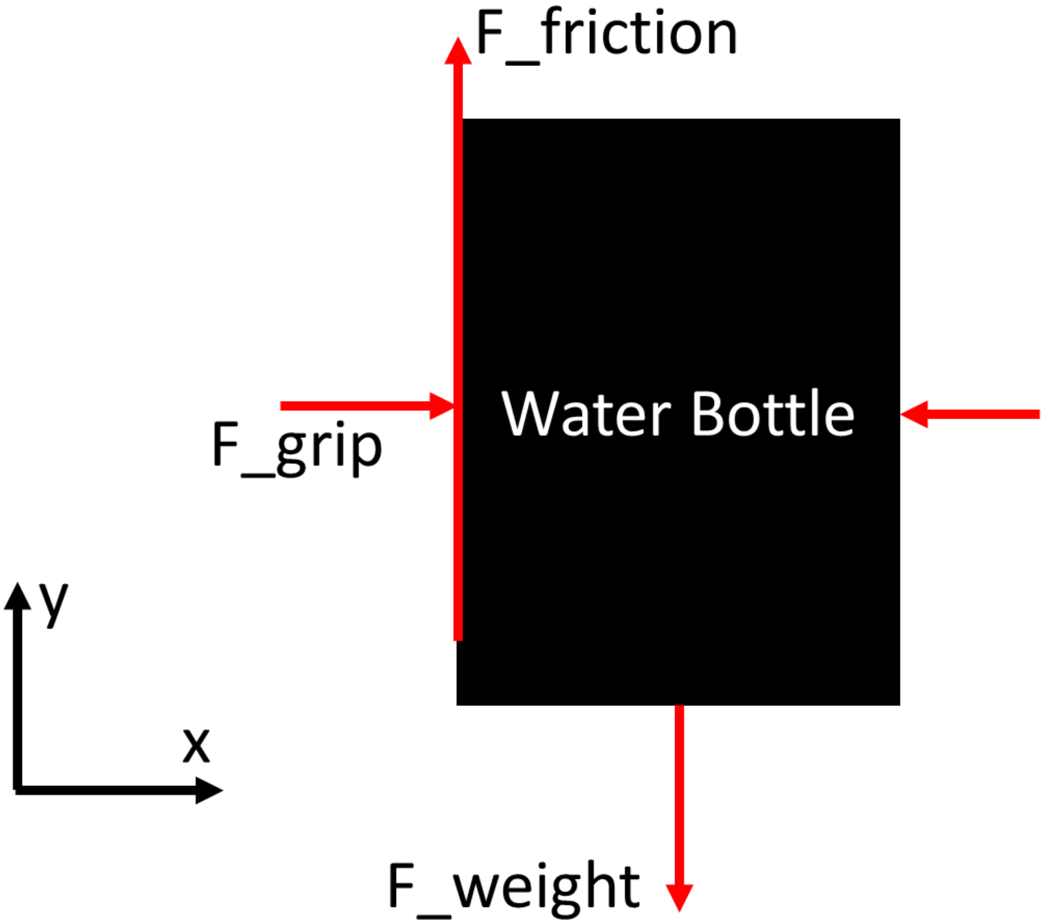


Figure 52: Water bottle free body diagram

Grip force required to hold the bottle of water:

$$\Sigma F_y = F_f - F_w = 0$$

$$\Sigma F_y = \mu F_{grip} - m * g = 0$$

$$(.05)F_{grip} - (.907185\, kg) * \left(9.81\frac{m}{s^2}\right) = 0$$

$$F_{grip} = \left(\frac{(.907185)(9.81)}{.05}\right)$$

$$F_{grip} = 17.7N$$

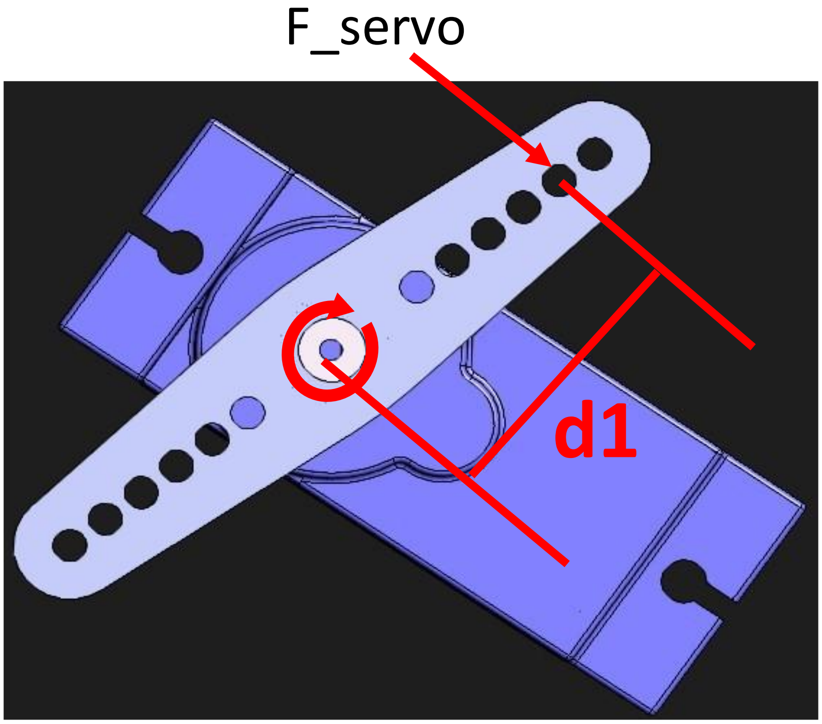


Figure 53: Servo diagram

The force that the servo imparts on the string when activated:

$$F_{servo} = \frac{\tau}{d_1}$$

$$F_{servo} = (.1969064\ Nm\ )/(.010\ m)$$

$$F_{servo} = 19.69\ \mathrm{N}$$

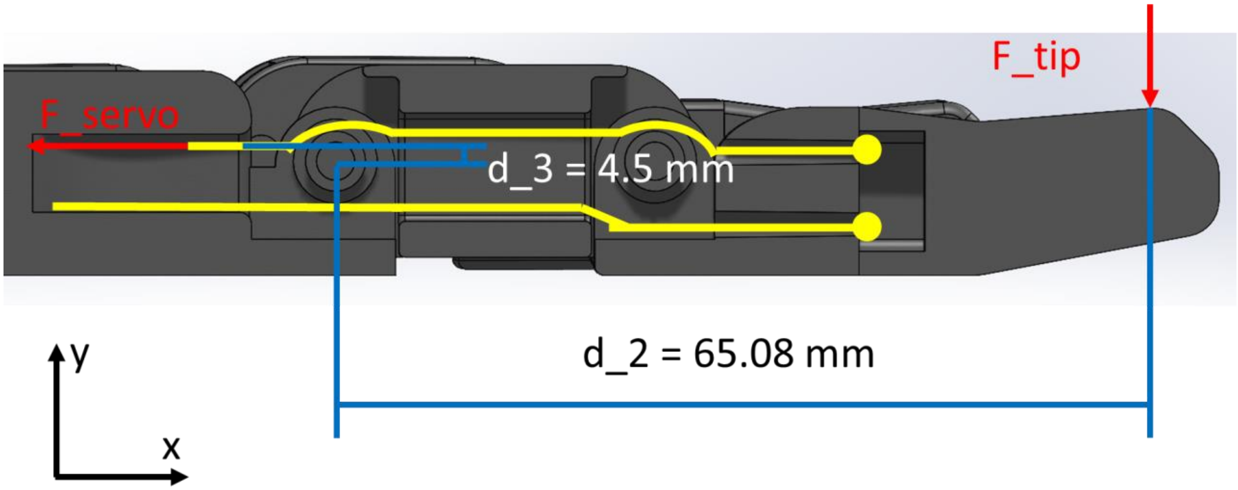


Figure 54: Finger diagram

Force generated at the tip of each finger:

$$F_{servo} * d_3 = F_{tip} * d_2$$

$$(19.69\ N)(.0045\ m) = F_{tip} * (.06508\ m)$$

$$F_{tip} = \left(\frac{(19.69\ N)(.0045\ m)}{(.06508\ m)}\right) = 1.36\ N$$

FITEC FN5106B servo calculation:

$$F_{servo} = \frac{\tau}{d_1}$$

$$F_{servo} = (.589\ Nm)/(.010\ m)$$

$$F_{servo} = 58.9\ \mathrm{N}$$

$$F_{servo} * d_3 = F_{tip} * d_2$$

$$(58.9\ N)(.0045\ m) = F_{tip} * (.06508\ m)$$

$$F_{tip} = \left(\frac{(58.9\ N)(.0045\ m)}{(.06508\ m)}\right) = 4.07\ N$$

If the force generated by each finger is 4.07 N then the total grip force of the device using the new servos would theoretically be 20.36 N.

APPENDIX J

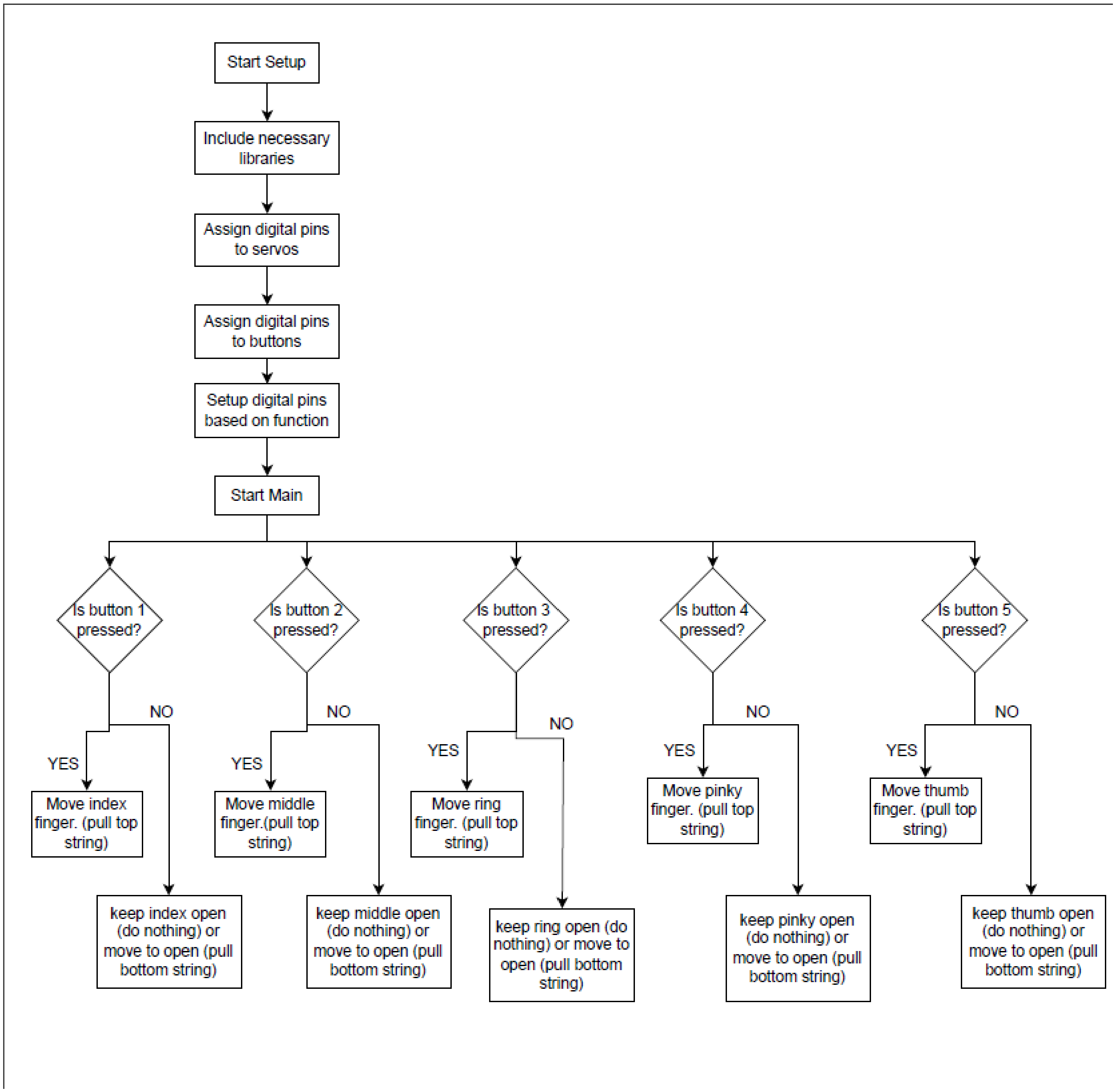


Figure 55: Flow Chart to outline code logic.

APPENDIX K

Table N.1, Design Factors Considered

Design Factor	Page number, or reason not applicable
Public health safety, and welfare	This does not apply due to the fact that in is a prototype that will not be available to the public.
Global	This does not apply due to the fact that in is a prototype that will not be available to the public.
Cultural	Mentioned on Pg.1
Social	Mentioned on Pg.1, Addressed on Pg.6
Environmental	Mentioned on Pg.1, Addressed on Pg.11
Economic	This does not apply due to the fact that in is a prototype that will not be available to the public.
Ethical & Professional	This does not apply due to the fact that in is a prototype that will not be available to the public.
Reference for Standards	This does not apply due to the fact that in is a prototype that will not be available to the public.