Electronically Controlled Exoskeletal Hand

WPI

ECEH

Electronically Controlled Exoskeletal Hand

A Major Qualifying Project Report submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfillment of the requirements for the degree of Bachelor of Science

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Abstract

The aim of Electronically Controlled Exoskeletal Hand (ECEH) is to create a wirelessly controlled robotic hand that is actuated with a wearable exoskeletal controller that easily fits to a user's hand. The controller provides the user with haptic feedback that simulates the force the robotic hand encounters when grabbing an object. The team worked to create a functional wireless hand and controller at a fraction of the cost of similarly functioning robotic hands on the market. This system was designed to maintain a high level of functionality and precision, as well as incorporate extra capabilities like haptic feedback, wireless functionality, and real-time control. ECEH's goal is to bridge the gap of the industrialized robotic hand and end of arm tool (EOAT) market and general consumer through price point and capability.

Executive Summary

ECEH is a user-controlled wireless hand that will allow general consumers, as well as practical consumers (in the use of bomb defusal for example) to be able to enhance their lifestyle through the use of an industrial grade robotic hand. Creating a functional robotic hand with advanced features at the fraction of the cost of industrial grade EOAT will allow consumers to use this tool for everyday activities, like different household tasks to be able to complete multiple tasks at a quicker pace, or at the opposite end of the spectrum in dangerous activities, like use in outer space, bomb defusal, and more. The hand will be able to handle the majority of different grip types, as well as utilize haptic feedback so that users can feel and understand the amount of strength/force required for the object interacted with. ECEH will fit into two markets, hopefully to bridge the gap between the two, the EOAT and robotic hand/prosthetic arm market, where these markets have shown a steady upward trend with the introduction of Internet of Things (IoT) applications to the products. In a growing market comes competition, however with the functionality, price point and lack of competitors for this application, ECEH will fit into the market and be able to prosper.

To help fulfill the design requirements of creating a project that simulates human hand capabilities, ECEH consists of two separate systems: a controller and a robotic hand. The controller – which is operated by the user– consists of five servo motors used to simulate haptic feedback, along with ten constant force springs. These springs are used to back drive the cables that run along the fingers.

The robotic hand also consists of five servo motors and five potentiometers. The potentiometers serve the same purpose of tracking the motion of each individual finger, but the motors are used to mirror the user and controller. The robotic hand has five constant force springs that are used for back driving the cables that run along each finger. Each finger's cable is attached to a corresponding servo motor and pulls the finger closed when the servo motor is actuated from motion detected on the controller.

Controller movement is tracked using a series of braided Kevlar cable attached to spools and potentiometers; the spools allow for constant tension on the cables as they to retract. As the potentiometer rotates in either direction, the data is transmitted to the Arduino connected to the robotic hand and the finger associated with that potentiometer will move the exact distance of the controller in real time.

Once the robotic hand has attempted to match the position of the controller, but a rigid object is interfering with the actuation of the robotic hand, the data containing the stuck position of the robotic hand is transmitted back to the controller and causes the servo motor to back drive and cause tension on the cable attached to the fingers to signify that the hand cannot close anymore and attempt to imitate the forces on the controller.

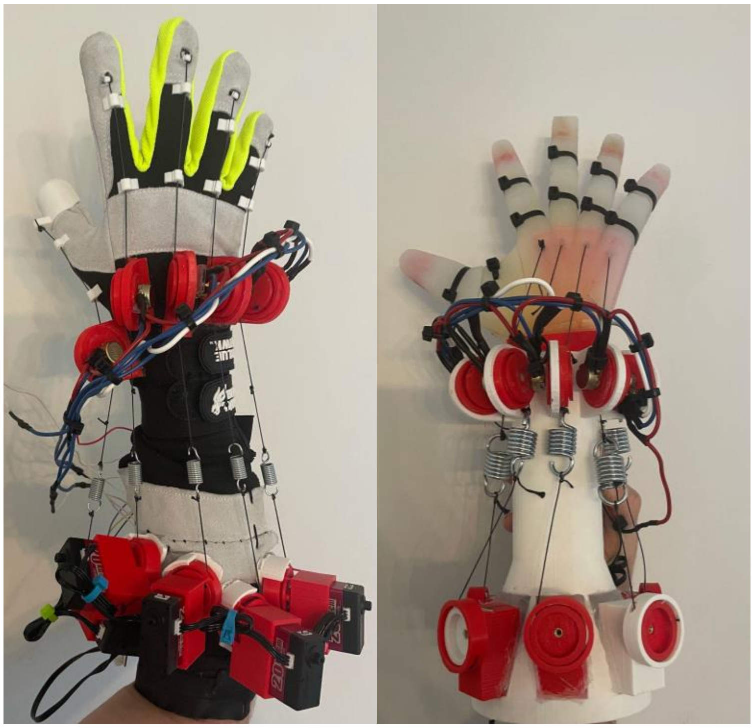
Throughout the testing of the design components, we were able to successfully integrate accurate motion control with all five fingers. This test was completed before the final assembly to ensure we had complete functionality before integrating it into the final assembly. Testing haptic feedback only required a single finger to test the proof of concept. We created a mounted system that simulated one finger for this test. The software for haptic feedback is a feedback loop that reads the potentiometer values on both the robotic hand and the controller and uses both values to lock the controller motors to the position of the robotic hand motors. With the success of this feedback loop, we were able to incorporate haptic feedback for all five fingers.

Despite not incorporating every aspect of our initial design goals into this project, our results show that we were able to achieve the goal of designing a system that can simulate and be controlled in real time with a wearable controller that attaches to a user's hand and forearm. We attempted to

implement wireless communication several times with several different methods, but unfortunately fell short of that design goal due to lack of reliable hardware and adequate time.

With the implementation of wireless communication, the application of ECEH can range anywhere from bomb defusal to weightlifting. If attached to a bomb defusal robot for example, a user can accurately control ECEH and use the necessary tools to help diffuse an explosive.

Our recommendations for the future of this project include implementing wireless communication and adding a wireless power supply to both the controller and robotic hand that is not too large but can safely and easily power its respective subassembly. The implementation of wireless communication will open the door for many applications of ECEH. Adding a safe and small power supply will allow for both the controller and robotic hand to move freely. This in turn can also increase ECEH’s application.



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CAD	David	Lucas
Soldering	David, Matt, Jack	
Electrical Testing	Jack	Matt, Lucas
Hand Unit Assembly	David	Matt
Silicone Molding	David	Lucas
Controller Unit Assembly	Matt	David, Jack, Lucas
SEA Design	Matt	David, Lucas
Mechanical Design	David	Lucas
Software Architecture	Matt	Jack
Electrical Architecture	Jack	Matt

1. Background

1.1 Prosthetic Hand

Due to its nature a prosthesis is normally defined as any device that supports, replaces, or corrects a body part [17]. With respect to our project the functionality of a prosthetic hand is to recreate the motion of a human hand. With this goal in mind, almost all prosthetic hands lack the ability to completely mimic the full capabilities of a human hand [17].

This section will cover a brief history of the prosthetic hand, as well as the general design of a typical prosthetic hand. The design section will look at several examples of current prosthetic hands and will look at the mechanical, electrical, and software aspects of prosthetic hands. We also will cover soft robotics and their application in relation to prosthetic hands.

1.1.1 History of the Prosthetic Hand

Prosthetic hands have been developed throughout history, first being recorded in Ancient Egypt. The first notable prosthetic being made for a general in the Roman Military in 77 AD allowed for the general to return to battle. From this point in history, prosthetics made more advancements in cable operation, where the use of the body plays into operation such as the movement of the shoulder on the opposite side would actuate the prosthetic. With the addition of electronics in the mid-1900s, advancements are still made to this day. Real time movement and added degrees of freedom are becoming the norm. This, along with the use of myoelectric designs, are the standard for most prosthetics being used today [29].

With the introduction of 3D printing, rapid prototyping, product cost, and accessibility have become much easier. And the two major types of hand prosthetics, cable operated and myoelectric can make advancements much quicker.

1.1.2 Soft Robotics in Prosthetic Hands

Soft robotics is defined as the use of compliant materials to fully structure or partially structure a robot [25]. This makes the actuation of a robot much simpler because the robot can be returned to its starting position by releasing power to the motors. This causes the use of electrical actuators on the opening motion of a robotic hand to be redundant and unnecessary. Soft robotics often involve the use of pneumatics. Pneumatics can be used to actuate different systems through the use of different gasses. Pneumatic pressure built up inside of the robot allows the robot to expand and contract to shape the objects it is trying to hold.

In the field of soft robotics many of the robots currently perform inherently non-repetitive tasks that require large amounts of variability between different tasks that the robot needs to compete, however this does come at a slight disadvantage as the robot is unable to perform these tasks as reliably as their harder counterparts. The advantages in certain scenarios vastly outweigh their counterparts as the compliance and flexibility of the robots allow them to adapt to many small spaces.

Figure 1 shows the Soft Anthropomorphic Manipulator (SAM), a soft robotic hand that uses elastic fingers and a series of cables for actuation in both extension and flexion. The soft fingers allow for the flexibility to grip many objects with odd shapes that many more rigid hands would be unable to grasp. The use of soft robotics in SAM also allows for the opening motion of the hand to be powerless; the hand will open itself due to the elasticity of the fingers.

Figure 1 SAM Soft Robotics Prosthetic Hand [28]

1.1.3 Cost of Current Prosthetic Hands

On the market today, there are numerous types of prosthetic hands, each with their own advantages and disadvantages. With more expensive hands comes more capabilities; ones that make it as realistic as possible. Many of the expensive hands use myoelectric technology, which uses electrical stimuli from muscles within the arm to control motors within the prosthetics. These are composed of multiple motors embedded within the hand, as well as a microcontroller connected to both motors and the surface electromyography (sEMG) technology, which is responsible for handling and inputting the electric stimuli from the muscles. Myoelectric prosthetics can range $20,000-$100,000. Less advanced prosthetic hands–like cable operated–are much cheaper than those with more advanced electronically controlled movements, generally ranging between $5,000-$10,000. These consist of simple cables and motors that control finger and wrist movements [23].

1.1.4 Design

The typical design of a prosthetic hand will bear a resemblance to a regular human hand with four fingers and a thumb. Depending on the need, prosthetic hands may include a wrist joint with similar or equal motion to a human wrist or a forearm that varies in length [18].

The Ottobock Bebionic 3 prosthetic hand, shown in Figure 2, has multiple degrees of freedom with 14 different grip patterns and hand positions [2].

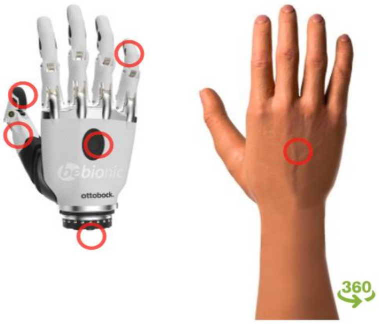

Figure 2 Ottobock Bebionic 3 Compared to a Human Hand

Each finger has its own motor that allows for natural coordinated grasp patterns. The hand also has proportional control that enables the user to adjust the speed and grip force when using the hand. Like this hand, our prosthetic hand design will handle individual finger motion. It will not necessarily have adjustable speed or grip force but will automatically adjust itself depending on the required amount of force to hold or manipulate an object.

One example of a common type of prosthetic is myoelectric prosthetics. Myoelectric prosthetic hands use muscle stimulation to control both the fingers and wrist. These types of prosthetics are less bulky but more invasive than prosthetic hands that are controlled by other means.

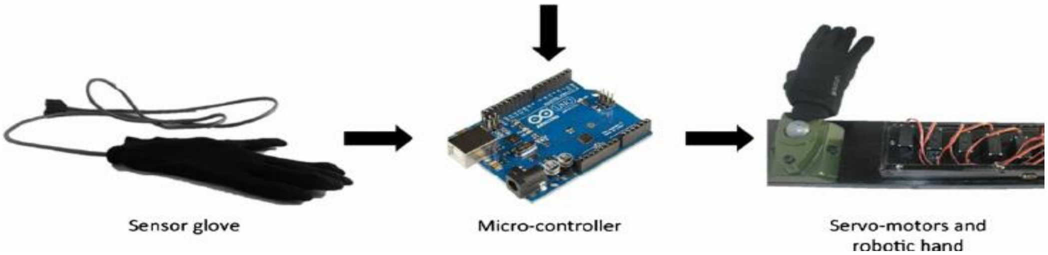

Figure 3 General Functionality of Controller, Microcontroller, and Prosthetic

Early designs of prosthetic hands used an on and off control scheme to actuate electronic terminal devices, wrist rotators, and elbows. Currently, prosthetic hands use programmable microprocessors. These microprocessors allow for easier control through the use of easily modifiable control options and thresholds, and more complex myoelectric characteristics. The integration of a microcontroller/processor within a prosthetic hand allows for easily accessible, manageable, and controllable functionality of the prosthetic itself. It creates automation between the electrical and mechanical components of the prosthetic and can allow it to be controlled by a user in addition to a remote. Data from sensors and motors within the prosthetic can be easily input into the analog and digital I/O pins embedded on the device, and in using these pins, the coded microcontroller can receive input and output of the peripherals in the prosthetic, allowing for easy control. To put it simply, the microcontroller embedded within the hand acts as the mainframe for the hand itself and is responsible for all connections and control of peripherals like motors, sensors and more. In having one device/area where all connections are established and controlled from, it is easily understood where each movement comes from and allows for easily programmable fixes/updates to the movement/control of the prosthetic.

As well as strictly hand function, the microcontroller can be easily switched with the use of the remote to control the movement of the wrist rather than the hand. It essentially allows for the use of a single device that controls the entirety of the prosthetic's functions, increasing the simplicity of the prosthetic tenfold. Figure 3 [5] shows the general functionality of a microcontroller, and its use in specific in this application [13].

The microcontroller that is embedded within the prosthetic itself once properly coded and assembled, is able to receive input from the sensor/controller glove, and then properly use the received data to actuate sensors and motors within the prosthetic to mimic the function of the controller [13].

1.2 Hand and Wrist Mechanics

In this section we will delve into the anatomy of the hand and wrist, while briefly touching upon the forearm. We will also discuss the degrees of freedom of the hand including all the fingers individually and the wrist. Next, we will present the average dimensions of the hand and wrist, which will be taken from the people we surveyed on campus. Lastly this section will discuss the many different grip and strength types of the hand.

1.2.1 Anatomy

The hand and wrist consist of 27 bones combined, 8 of the bones are located within the wrist called carpal bones are lined in two rows of four bones and are connected to the radius and ulna as well as to the hand (Figure 4). The connection point from the radius, ulna and the carpal bones creates the wrist joint allowing for the radial and ulnar deviations, flexion, and extension of the joint (Figure 5) [10]. The carpal bones connect to the metacarpals in the hand which are connected to the phalanges. The connection to the carpals to the five metacarpals creates the palm of the hand. The connection between the metacarpals to the phalanges of each finger, where each finger has three phalanges, and the thumb has two. Adding up to the 19 bones in the hand itself. Between each of the bones in the hand is articular cartilage allowing for movement and the location of each of the joints within the hand allowing for the flexion, extension, hyperextension, abduction, and adduction of the fingers (Figure 6) [24].

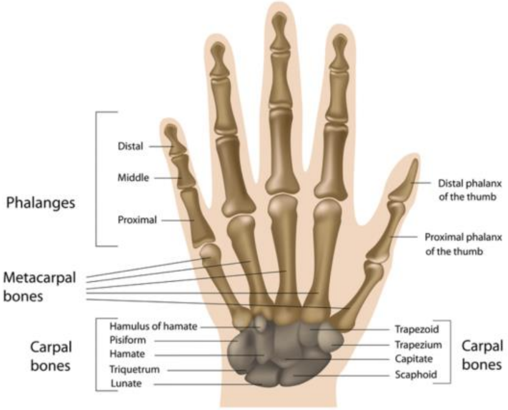

Figure 4 Bone Structure of the Hand [10]

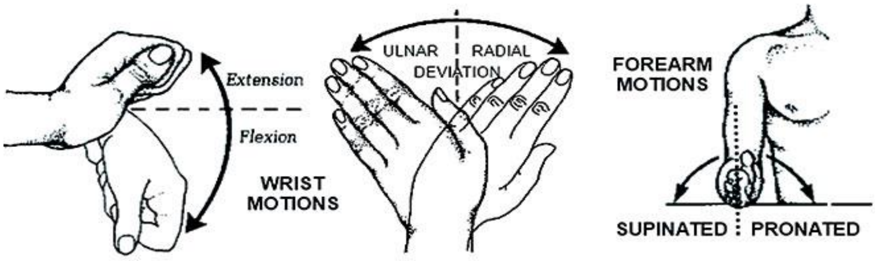

Figure 5 Movements of the Wrist Joint [12]

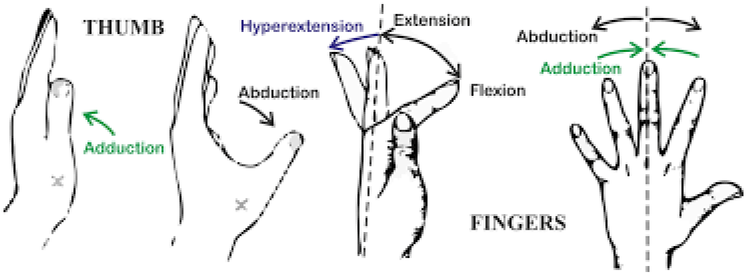

Figure 6 Movement of the Fingers [12]

1.2.2 Degrees of Freedom

A degree of freedom can be considered either rotational or translational movement by an independent variable of a system. The translational motion is along either the x, y, or z axis in a reference frame defined by the engineer. The rotational motion is around either the x, y, or z axis in a reference frame defined by the engineer as well. A particular variable of a system can have multiple degrees of freedom i.e. multiple axis rotations as well as multiple axis translations.

A normal human hand has up to twenty-seven degrees of freedom. Each finger has a total of four degrees of freedom, with each joint having its own degree of freedom. The thumb has five degrees of freedom. Each joint has its own degree of freedom, and the bottom joint has three degrees of freedom. The Joints that contain one degree of freedom are the Distal interphalangeal Joint (DIP) and the proximal interphalangeal Joint (PIP). Each bone in the finger has two connections to tendons that allow for the opening and the closing of the hand. One tendon is connected to the interior face of the bone while the other tendon is connected to the back of the bone to allow for the finger opening.

The average human wrist has six degrees of freedom, three of those degrees of freedom come from the translation of the arm, one come from the rotation of the forearm, and the last two come from the pitch and yaw of the wrist.

1.2.3 Dimensions

Table 1 gives the average length of different parts of the human hand based on measurements the team took from an individual with a large hand and an individual with a small hand. The averages of the two were taken to create a generalized list of measurements for an average human hand.

Table 1 Dimensions of the Average Human Hand

Part of Hand	**Average Length (mm)**
Index Length (tip of distal bone to bottom of proximal bone)	71.625 ± 8.917
Middle Length (tip of distal bone to bottom of proximal bone)	80.09 ± 8.301
Ring Length (tip of distal bone to bottom of proximal bone)	74.195 ± 8.478
Little Finger Length (tip of distal bone to bottom of proximal bone)	61.84 ± 3.691
Index Width	19.31 ± 0.071
Middle Width	18.89 ± 0.453
Ring Width	18.255 ± 0.05
Little Finger Width	15.965 ± 0.12
Thumb Length	61.51 ± 3.691
Thumb Width	20.55 ± 0.806
Hand Length	186.725 ± 17.70
Palm Width	85.505 ± 2.20
Palm Width to Tip of Thumb	152.385 ± 9.270
Tip of Little Finger to Tip of Thumb	207.28 ± 19.361
Length of Palm	107.77 ± 2.984

Thickness of Palm at Wrist	41.685 ± 3.373
Thickness of Palm at Fingers	22.78 ± 1.245

1.2.4 Grip Types and Strength

In discussing wrist mechanics, one of the most important pieces to take into account is the types of grips a human hand can perform, as well as the strength and force behind it. In conducting background research, the average grip strength of both men and women was able to be determined, also taking into account external factors, like age. It was found that the typical cylindrical grip strength is between 103-121 pounds, and the strongest end of this is men between 20-39, and the weakest in women aged 70 and older [11]. This is imperative to take into account, as the prosthetic hand must be minimally capable of performing tasks with this required force.

Following the strength of the grip, it is also important to review and understand the different types of grips necessary to full function of the human hand. This serves as the basis for all processes of the hand itself and ensures that it fulfills all basic requirements for the consumer. In conducting research into the different types of grips of the human hand, it was found that there are around seven (give or take) specific types of holds/grips that hands can perform and that are used in daily life [9]. They are as follows:

- Hammer/Cylindrical grip
- Baseball batter grip
- Precision grip (tip to tip)
- Lateral Prehension
- Key grip
- Hook grip
- Tripod (pen) grip

To begin, the first grip that was looked into was the hammer/cylindrical grip. This type of grip is used in holding things like a hammer, as seen below in Figure 7.

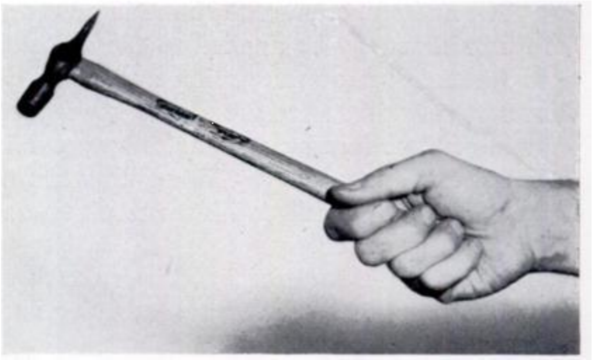

Figure 7 Hammer/Cylindrical Grip [16]

This type of grip is used to hold relatively small items in diameter and is a mix of a hold and a pinch-type grip, where the four main fingers wrap around the item, while the thumb sits atop for stability. The second type of grip researched was the baseball batter grip. This can be seen below in Figure 8.

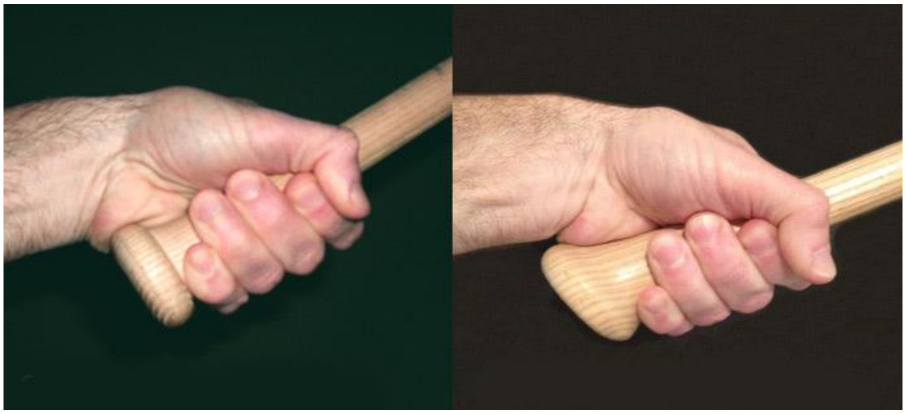

Figure 8 Baseball Batter Grip [26]

This type of grip is similar to the aforementioned cylindrical grip, however the thumb is used in the same way as the other four fingers, in a wrapping motion, whereas in the cylindrical grip, it is used more in a pinching function. The third grip detailed is the precision grip. This can be seen below in Figure 9.

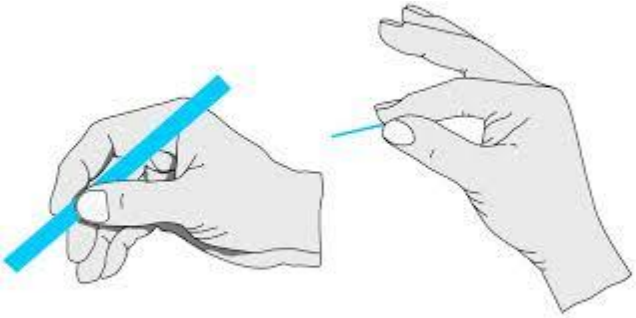

Figure 9 Precision Grip [15]

As mentioned in the name of the grip itself, this grip is focused on the function of holding small, lighter items, such as a pencil or a toothpick, and is a pinching-type grip. This grip is one of the more common grips and is especially prevalent in use in daily life. The next grip that is essential to human function is the tip-to-tip lateral prehension grip, shown below in Figure 10.

Figure 10 Tip to Tip Lateral Prehension Grip [8]

This grip is commonly used in daily activities, in performing tasks such as holding briefcases, suitcases, or soda cans, for example. It is important in this grip to note the common circumference of these items, to properly understand how the hand itself should wrap around the object. The average circumference of 12 fluid ounce cans is 9 cm, and this is the average circumference that the hand should be able to wrap around objects.

1.3 Wireless Controllers

Prosthetic hands that are controlled using wireless controllers use digital signal processing (DSP) in coordination with analog to digital converters (ADC) to drive the electrical components within. This revolves around the use of radio frequency (RF) techniques, in both emitting and receiving signals from the controller itself to the limb (Huang, 2000). The controller itself will emit a certain range of frequencies (in hertz) that the receiver will pick up to control the prosthetic [22].

These controllers use different filters within the receivers to be able to filter and receive the specific frequency emitted by the controller. These can be filters such as a second order Butterworth filter, a filter that limits the received signals to below 4 kHz (4 kHz low-pass filter) [20], allowing for a more precise control of the prosthetic [27]. By using this cutoff frequency of 4 kHz, it is easier for the prosthetic to determine the specific movement of the prosthetic [7].

1.4 Robotic End of Arm Tools

End of arm tools are pieces of equipment that interact with parts and components at the end of a robotic arm [1]. The equipment mounted to the robotic arm can be anything the user or designer desires. For example, a welding torch on the end of a robotic welding system. Grippers, claws, welding torches, force-torque sensors, material removal tools, collision sensors, and tool changers are just some of the many possibilities in the rapidly growing market.

1.4.1 Current Types of End of Arm Tools in Robot Applications

Currently, many of the end of arms tools can only be applied to one task. This is due to the design intentions of the consumer. The consumer would only need a welding robot for welding tasks and a material removal robot for removing material. Therefore, many end of arm tools are typically static in their application potential. Many of these tools are powered by hydraulics, pneumatics, electrically, or mechanically [4].

1.4.2 Adaptive Gripper End of Arm Tools

One specific type of end of arm tool is what is known as an adaptive gripper. This tool can have a variable number of grippers and can do multiple different tasks. Robotiq, a robotics company that specializes in grippers, creates many kinds of these adaptive grippers [21].

1.5 Series Elastic Actuators

A series elastic actuator (SEA) is a mechanical system that contains an elastic element, like a spring in series with a mechanical energy source. SEAs allow tolerance to impact loads, low mechanical output impedance, passive mechanical energy storage, and increased peak power output. Typically, SEAs are used to overcome the difficulty of modeling non-structured environments that coincide with high computational effort by applying them in compliant robotic grasping. Frequent decision parameters for the use of SEAs are power output, volumetric size, weight, efficiency, Back-drivability, impact resistance, passive energy storage, backlash, and torque ripple. SEAs are frequently used in rehabilitation and assistive technologies. This is in part due to the large reduction in peak power and energy requirements [14].

2. Introduction

2.1 Market Research

2.1.1 Problem Statement

Looking into the markets of end of arm tools (EOAT) and prosthetic hand markets, the closest two markets to the fit of ECEH, the team was able to determine many places for improvements in these products on the market, and as a result, there are no robotic hands within the current market that possess the following characteristics:

- Cost Effective: Lower cost for a robotic hand, however, still maintains impressive and functional capability
- Real-Time Remote Control Mimicking Capability

From these two indicators derived from market research, our group was able to come up with a plan to ensure that our product will not only be more accessible to the public by cost but will also fill the gap in the market for current robotic hands. ECEH is also to be accessible to jobs with dangerous applications, like bomb defusal squads. This will allow for a multi-purpose use, not only in specific situations.

2.1.2 Market Research

In completing research into the market of robotic hands/End of Arm Tools (EOAT), it was found that the market is relatively sizable, with global sales of $1.8 billion in 2018, and is set to continue to grow [6]. The market of EOAT tools has increased a steady 8% from 2013 - 2017 and continues to grow at a faster pace in the current age, surpassing $2 billion in global sales in 2019. [6]. To explain what an EOAT is, and why our product falls into this category, first the uses of the robotic hand must be examined. The primary purpose of the Electronically Controlled Exoskeletal Hand (ECEH) is to allow for consumers to use this product as an “extension” of their own hand, in that the robotic hand can be attached to any tool/surface as necessary to execute the action the consumer desires. In understanding this, EOAT are essentially grabbers, or claws (in the shape & form of a hand) that can be attached to any tool as desired by the consumer and can be controlled to achieve the desired function. It is important to note, that as this market continues to grow and develop, emerging trends have begun to take hold of the market, and the main one is access to the internet of things (IoT) [6] through the EOAT. This essentially means any wireless connection from controller to hand, or hand to internet, through Wi-Fi, Bluetooth, etc. Our product aims to fall into not only the EOAT market, but into this category in specific, and fill the void missing from current end of arm tools.

In researching the EOAT and prosthetic hand markets, three main companies and products that most closely resemble the aim/goal of our product, ECRH, were researched to be able to determine where ECRH can fill the gap for the consumer.

Figure 11 Robotiq, 3 Finger Gripper

The first product that was looked into was the Robotiq 3 Finger Adaptive Robot Gripper (Figure 11). This product is made for industrial use in robotic tools and has a ranging cost of $4-6 thousand per unit. The gripper is controlled by a joystick and is able to perform a majority of the possible grips mentioned earlier in the background, while also being able to hold a range of 5-22 pounds depending on grip [21].

The second product that was researched for comparison was the Hero Arm from Open Bionics (Figure 12).

Figure 12 Open Bionics, Hero Arm

The product is a myoelectric (nerve controlled) prosthetic arm, meant for use as a prosthetic. It is a 3D printed hand, weighing only 12 ounces, and is a full lower arm prosthetic (forearm down). The arm can hold up to 17.64 pounds, and costs $10-20,000 [3]. The arm is fully customizable to the consumers' choice and is able to form six different grip types.

The third and final product compared in the market research was the Zeus Hand from Aether Bionics (Figure 13), another myoelectric prosthetic arm that is marketed mainly as a prosthetic, however catered to daily use and function. The arm can apply a force of 150 Newtons, as well as hold up to 35 kg in a hook grip [19].

Figure 13 Zeus Hand from Aether Bionics

Through researching these different companies and products, there were two concrete factors that stood out between all current EOAT and prosthetic hands, and that is their definitive uses and costs. All the products listed above, and practically all within these markets currently only have one application; for prosthetic hands, it is to help those who have had amputations or only have the use of one arm, and for EOAT, all are used in industrial settings, as end pieces for industrial robots. With the increase in use of EOAT through the integration of IoT, industrial and other companies are making a push to bring robots into the workplace in place of part of the human work force, especially for dangerous environments. This is where ECEH can bridge the gap between these markets, as companies can utilize human-like end of arm tooling in areas where precision of the human hand is needed, but only robots can go.

The second of these factors is the costs of these products. The cheapest EOAT product that could be found was at a minimum $5,000, and for prosthetics, the cheapest electronic was $10,000. This as well leaves a large area to work with in terms of creating a low cost, enhancement product for consumers to purchase, that won’t set them back a small fortune. With advances in technology in recent years, the ability to create such a product for a normal, everyday consumer to aid in making their lives easier has become significantly applicable, in material costs and in technology, where ECEH will be able to bridge these aforementioned gaps for the consumers’ ease in their everyday activities.

In addition to these two major factors, other limitations of these products were able to be pulled from research into them, as well as a look into the application the team is aiming for with ECEH. The prosthetic arms are mainly myoelectrically controlled, without use of a controller, and the EOAT is controlled by a controller, however it is a joystick-type, which significantly reduces the amount of control users will have. As well, most of these products do not work in real time, EOATs generally have the motion of the controller, followed by the action of the gripper. While prosthetics generally do have a “real time” application, the majority found are slow, where the user will attempt to make that motion with the nerves in their arms, and the action will happen a few seconds following. ECEH seeks to have a near instantaneous reaction from controller to hand, with little delay in between.

In compiling this list of limitations of products currently available on the market, and in markets closest, it was able to be determined where ECEH will be able to find its place, attempting to bridge the gaps of these products, and bring industrial and limited use grippers and arms to general consumer use, at a fraction of the cost.

Based on growth of the robotic EOAT market in the past decade, it is promising that the market will continue to expand, especially through the increase in IoT application. This trend will allow for the market to cover other areas, like general consumers for example in the case of our product, where rather than strictly for industrial settings, consumers will be able to use their EOAT product for general daily activities.

2.1.3 Competitive Value Analysis of Products

With this, using the limitations mentioned above, and creating requirements for the product in this application, the team was able to create a weighted competitive value analysis table (Table 3). This table was weighed in terms of most important features to the customer, developed through market research. Products with a higher score ranked higher within the respective market for the criteria listed. Regarding the mass criteria, there are two separate weights due to the inclusion of two markets, *E* being EOAT market based, and P meaning prosthetic market based. A higher score within the criteria means a higher ranking in that area, and a lower score indicates that the product is worse in that area. Table 2 depicts the analysis:

Table 2 Initial Criteria and Respective Weights

Requirements	**Weights**
Cost	10
Movement Accuracy	8
Mass	4E/7P
Strength/Force Rating	9

Table 3 Weighted Competitive Value Analysis Table of Products

	Criteria					
Product	**Movement Accuracy**	**Mass**	**Strength Rating**	**Cost**		
Weight	8	4E/7P	9	10	**Raw Score**	**Weighted Score**
ECEH	6	8	7	9	29	245
Robotiq EOAT	8	7	6	6	27	176
Open Bionics Hero Arm	8	5	9	3	25	210
Aether Bionics Zeus Hand	8	6	9	3	26	217

From this analysis, it can be determined that ECEH will rank the highest in the market based on the criteria listed above, where the criteria were chosen in terms of importance not only in the market, but to the consumers themselves.

2.2 Product Requirements

2.2.1 Customer Requirements

After completing the market research, the team was able to define the customer requirements for the project.

1. Wireless control between the controller and robotic hand.
    a. Wireless Bluetooth control over a distance of greater 10 meters.
2. Easy to use controller.
3. Controller provides accurate and precise movements for the robotic hand.
4. Robotic hand achieves near strength of the human hand.
5. Robotic hand achieves near movement of the human hand.
6. Product is affordable.

These requirements were determined from research of the EOAT and prosthetic hand markets respectively, and into those products within these markets that closest resembles functionality and detail of our product. It was apparent through research into these products that there are a few discontinuities in capabilities that these products offer as well as base standard requirements that the product must have for consumers, and these offered in the ECEH, as listed above.

The first of these requirements is the wireless control, with emphasis on a range of at least 10 meters. Wireless control is a staple in many EOAT and prosthetics, however in many cases, the control is done close by, as vision of the object is necessary. However, in tackling everyday activities, maybe such as turning lights on or making breakfast while a user is in another room doing something else, being able to control the hand from another room is part of what will make ECEH a standout competitor, as wireless controlling a hand from a separate part of your house/apartment/etc. could immensely improve the general lifestyle for those with the product. The second requirement for ECEH is that the controller is simple to use and doesn't involve a difficult setup or difficulty in use. The plan is to essentially have the hand and controller connect once powered on, and as soon as that connection is established, to be able to simply move your hand within the controller and have the robotic hand mimic it, without any difficult setup or assembly of the controller. As well, a definite requirement for the system is that the controller provides accurate and precise movements, and that the robotic hand is capable of mimicking that movement to a highly accurate degree. This is incredibly important for the system, as certain objects, such as paper or something of that thinness, requires a precise touch, and without the precision of the system, handling something like that that is seen commonly in everyday activities would not be very functional for the system's purposes. Requirements four and five as well are both closely linked together, as the point of ECEH is to essentially be able to extend the capabilities of your own hand to another place. With this, it is functionally necessary that the system can achieve near strength and possible movement of the human hand. The final requirement is affordability of the product, which was a huge issue within the current EOAT and prosthetics market. All items seen on the market were at a minimum $5,000, which is far too much for the average consumer to spend on an item. And while these items were mainly for industrial use, or use in limb replacement, this leaves room for a low-cost alternative that bridges these two markets, a hand extension for use in enhancing everyday life, that will not set consumers back an immense amount of money. Based upon these requirements, the team moved into researching and selecting components that would fit the needs of these requirements once assembled.

2.2.2 Product Specification

Based on the product requirements listed above, a general base structure for components could be determined on both an electrical and mechanical scale. The product will consist of the following specifications:

Electrical

1. Motors
2. Microcontroller
3. Movement Tracking Peripheral

Mechanical

1. Cables
2. Springs
3. 3D Printing Material
4. Bowden Cables

Electrical

The first device that will be necessary for the project are the motors. The motors within the hand will be responsible for driving the motion of both the robotic hand and the haptic feedback on the controller. The second necessary component in the project is the microcontroller. The microcontroller within the product will essentially act as the “brain”, or central mechanism, and is responsible for handling all connections to peripherals, such as the motor inputs, controlling the communication module in reception and transmission of signals, reading the inputs from the rotary encoders for movement and haptic feedback, and will make use of code to handle and actuate all of these inputs. The third electrical component in the project will be the communication module. The communication module is responsible for handling all message transmission and reception, which in the case of this project will be sending and receiving all command messages for movement from signals from the peripherals (encoder and motors) to be able to have functional movement and haptic feedback as a result of the microcontroller reading and decoding signals from the peripherals, and transmitting and receiving specific command messages for movement between the two, since they will work in tandem with each other to mimic movement and feel of the object held. The final component in the electrical side of the project will be the movement tracking peripheral. This component is responsible for movement tracking within the controller and hand both, to allow for the mimicking of movement between motors, to not only provide base movement amounts from controller to robotic hand, but to work backwards from robotic hand to controller to be able to provide haptic feedback, knowing how far the robotic hand has moved, and whether or not it is experiencing and external force that should be felt.

Mechanical

For the mechanical side of items, the product will consist of five major components, being cables, springs, the 3D printing material, and a soft material exterior (Figure 14). The cables used within the project will be used to control the movement of the fingers and wrist, attached to the servo motors, and will be run through each finger for capable motion. As well, the cable will be attached to the potentiometers within the hand for this movement, to be able to measure the distance that the cable moves. The springs within the system will be used in the series elastic actuator, in being able to supply haptic feedback for the system. These springs will be connected to the cables to elongate and stretch them to measure their deflection. The 3D printing material is more straightforward, the team will be utilizing a 3D printer to create the robotic hand and necessary components and creating a CAD model that can house all components, both mechanical and electrical will be a necessary requirement. The final component, the soft material will be coating the exterior of the hand, this will increase the friction of the hand and the objects it grabs, and will return the hand to a neutral position, allowing for the hand to operate with one set of motors for flexion.

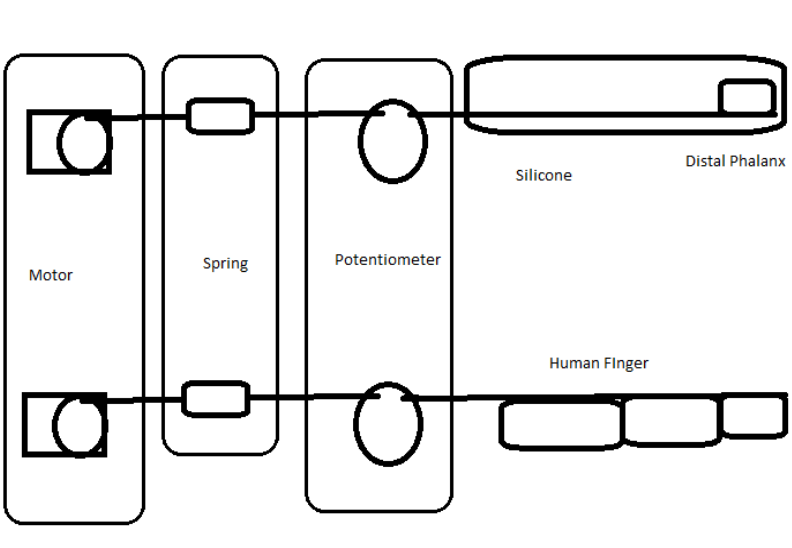

Figure 14 Single Finger Cable Schematic

Theoretical Calculations

As the MCP joint of the fingers in the robotic hand have minimal to no movement, we are neglecting the applied forces on an object that will be grabbed. Because of this, our main focus will be on the applied forces at the PIP and DIP joints in the fingers. In the human hand, the FDS and FDP tendons are used in flexion of the finger, but the team has decided to move forward with using one cable for flexion, and the force exerted by the cable will equate to the applied force at the tip of the finger. This section will show all the theoretical calculations in order to actuate the fingers in the robotic hand and the external forces at the joints.

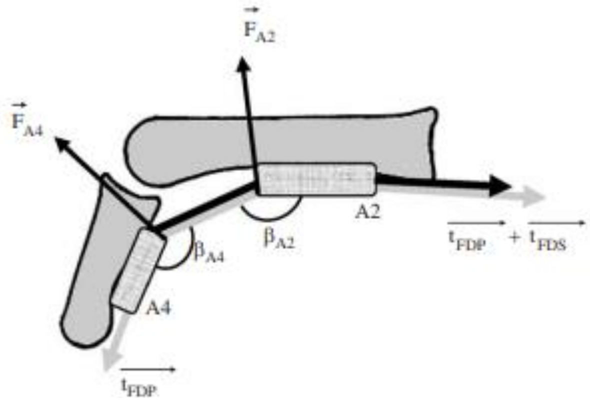

Figure 15 Single Finger Force Diagram

As there is only one cable used for actuation, the applied force at the fingertip is equal to that of the tension on the cable, represented by t_{FDP} in Figure 15, and for our calculation purposes will be represented as t_{cable}.

Normal forces exerted externally at the DIP and PIP joints are calculated in terms of the angle of the joints during prehension with the given equations:

Equation 1

$$F_{A2} = 2(t_{cable})\cos\left(\frac{\beta_{A2}}{2}\right) \qquad (1)$$

Equation 2

$$F_{A4} = 2(t_{cable})\cos\left(\frac{\beta_{A4}}{2}\right) \qquad (2)$$

The final equation utilized in this section is the torque calculation equation to determine the radius needed from the center of the axle of the servo motor to achieve the applied forces at the fingertips.

Equation 3

$$\tau = rF\sin\theta \qquad (3)$$

Equation 4

$$r = \frac{\tau}{F\sin\theta} \qquad (4)$$

Results of theoretical calculations

Using the DIP and PIP joint force equations and the found values regarding the variables used in the equations, the Table 4 consists of the variables input into MATLAB code to calculate the forces applied to the joints in the finger during prehension at maximum load.

Table 4 Finger Applied Forces at Maximum Joint Angle

Finger:	Applied force at fingertip (n):	tcable (n):	maximum angle at PIP joint (deg):	maximum angle at DIP joint (deg):
index	105.9363	105.9363	148	120
middle	148.3109	148.3109	148	120
ring	110.1738	110.1738	148	120
little	63.5618	63.5618	148	120

With the attached MATLAB code, the force exerted at the joints is graphed against the range of movement of the joints from 0° at fully open, to the maximum angle for each finger, at full flexion/extension:

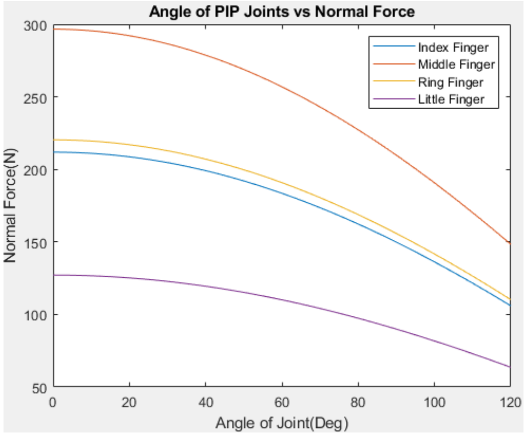

Figure 16 Angle of the Joint vs. Normal Force in the PIP Joints of Each Finger

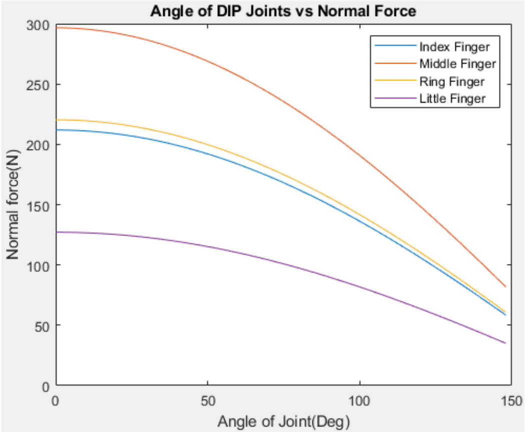

Figure 17 Angle of the Joint vs. Normal Force in the DIP Joints of Each Finger

For the torque calculations using Equation 4, The servo has a torque value of 3.1kg-cm which equals .304006 N-m. The values of t_{cable} listed in Table 5 are used for the force and the angle at which the force is applied is 90°. The radius at which the force must be applied at the servo motors for each finger is listed in the table below.

Table 5 Finger Lengths

Finger:	Radius (mm):
index	2.869
middle	2.05
ring	2.759
little	4.783

Software

The software was structured to fulfill the goal of accurate motion control as well as sensitive haptic feedback. We needed to design our software to seamlessly provide both of these initial customer requirements. Both the robot hand and the wearable controller require their own microcontroller which meant each microcontroller needed its own source code. The source code for each microcontroller needed to read information regarding position tracking, while simultaneously being capable of writing information relating to motion control and haptic feedback. Due to the similarity between the requirements each microcontroller contained, the source code was similar for both the robotic hand and the wearable controller.

3. Methodology

3.1 Project Objectives

Many of the applications for this EOAT would lie in job fields where using a human could be either too dangerous or cost too much to make it safe for a human to enter. One prime example of this would be bomb defusal. Our device would allow for a robot to take the place of a person's hand, eliminating nearly all risks towards the user while still providing an accurate medium for completing the task at hand.

Another potential capability for the ECEH would be as a cost-effective substitute for many of the more technical and costly myoelectric prosthetic models. While the application would be limited, this would allow for the wearer to put the controller glove on their opposite hand and have our prosthesis mimic that hand's movement.

3.2 Design Approach

Our design approach focused on iterations. This iterative design method allowed for rapid prototyping and analysis of successful components. Our iterations were broken down between electrical, mechanical and software, where each was integrated into each other and tested for compatibility.

3.2.1 Electrical Design Choice & Iterations

The following sections describe the different electrical iterations the ECEH went through when creating our final prototype.

Microcontroller Iterations

The first of the electrical iterations the team went through was the microcontrollers. The team needed a microcontroller that was capable of handling all of the inputs required of the sensors and motors in terms of processing speed and communication speed, as well as able to supply enough current for the peripherals being run off of it.

The first of the microcontrollers tested was the Arduino Nano 33 BLE Sense. This microcontroller had integrated Bluetooth, which was responsive, accurate, and fast, as well as a small form factor for incorporating into the mechanical design. Through testing, it was quickly noticed that despite the reliable and useful Bluetooth, the microcontroller only had 3.3 Volt (V) inputs, which caused issues in incorporating the sensors we had purchased and wanted to begin testing, due to the 5V inputs being incompatible with the impetus of the controller. As well, the Arduino only had one serial bus line which did not fit the requirements necessary of the system.

The second iteration of the microcontroller was the Arduino Mega 2560. The team chose this microcontroller due to the multiple serial bus lines and 5V input/outputs which fit the needs of the system. As well, following iterations of motors and sensors, we chose a microcontroller that had an abundance of digital I/O pins, as well as analog due to the quantity of sensors that the team was fashioning into the system.

Peripheral Motion Tracking Iterations

There were a few choices for the team to make regarding the peripheral that was responsible for handling the movement of the motor, specifically its accuracy and integration into the project, for both movement of the robotic hand, as well as movement of motors for feedback in the controller. The team looked into many different options for this control: flex sensors, IMUs, gyroscopes, rotary encoders and potentiometers

The first of the choices was the IMUs, a device that measures and sends an object's force and angular rate, and depending on the IMU, sometimes the orientation of the object in space (like a built-in gyroscope). This would allow the team to take the readings from the sensor and translate it through code to the motors to mimic the movement of what the sensor feels. While this is exactly what the team was looking for in a peripheral to control movement, incorporating this component into the haptic feedback was likely to prove difficult, as it would likely make the motors fidget and not as smooth as the team was looking for, as well as the sizing of the component and prices being too large for the scope of the project.

The second choice that the team was experimenting with were gyroscopes, a sensor used to be able to track relative position of the object attached to in an XY or XYZ plane. The team ordered a couple of gyroscopes to test out for use controlling hand movement, but was met with a couple obstacles, the same as the IMU sensors in incorporating into the haptic feedback, as well as the gyroscopes implementation. The gyroscopes ordered were to be soldered onto a PCB, which would require using a significant amount of space within the hand and controller respectively, and respective of price, were relatively pricey in finding one that would satisfy the accuracy requirements of the project. Combining the two difficulties presented from the gyroscopes, the team decided to find another option.

The third option that the team explored were the flex sensors, which upon bending the sensor, for example attaching it along each finger and closing fingers, would create a measurable increase in resistance that could be mapped through code to the movement of the motors to match exactly the bend the sensor experienced. The sensors tested were the SEN-10264 flex sensors, which had 5V inputs and a variable resistance from 25kΩ unflexed - 100kΩ fully flexed. While perfect for mapping the movement of the motors in their easy integration into the fingers, incorporation to the haptic feedback portion of the project was deemed difficult, especially in running the system backwards from robotic hand to controller, since the sensors were to be worn on the controller. As well, the sensors themselves produced a large amount of noise which would commonly cause the values expected for the movement of the motors to be heavily skewed and inaccurate. A final notion with these sensors is their durability. Following testing them for a few days, the sensors began to break due to repeated use, and their accuracy along with it.

The fourth option that the team eventually decided on were rotary encoders, which track linear movement of an attached item (such as a cable/wire/spring) and map the movement to a certain number of ticks experienced by the component. This component fits the design in many different ways, as for movement of the motor, the movement can be tracked to the amount of ticks experienced by the encoder, to any degree of movement necessary, as accurately as the encoder will allow (amount of ticks per degree of movement). As well as basic movement control, the team was able to find a haptic feedback system in a series elastic actuator, where with the use of springs and a lever arm, are able to use the rotary encoder to measure the deflection and lengthening of the spring to understand the force/torque the hand and motors within the hand are undergoing, allowing the system to be back driven to the controller for use in haptic feedback. The first of the rotary encoders tested for proof of concept into the system was the PEC-12R. These were basic quadrature rotary encoders with 24 pulses per revolution (ppr) and 5V inputs, where it was mapped to the motor through software so each tick of the encoder (1/24) would move the motor around 15°, and at the 24th tick, or a full revolution, the motor would have spun a full 360°. These worked relatively well through testing, producing the proof of concept for movement between sensor and motor that the team was looking to achieve, however their durability quickly became compromised through repeated use, beginning to skew the accuracy of the project. Following the success in this proof of concept, the team purchased and moved forward with E4T encoders, which were similar quadrature encoders, however at a higher price point. These encoders boasted a 360 ppr count, as well as 5V inputs, where each degree the motor moved could be mapped through software to each tick on the encoder, providing much more smooth and clean movement. While accurate and useful within the project, the team quickly noted that to incorporate five of these into the system would require a lot more processing power than our microcontroller had. This would then require the team to incorporate a separate processing chip for the encoders alone to be able to read and send values in real time between the controller and hand. Due to time constraints and difficulty in using the chip in software, the team decided to move forward with the final option because of the increasing difficulty of using the encoders.

The Final option the team decided to use for movement tracking were potentiometers. The potentiometers have very accurate readings, and the team only needs readings up to approximately 270° and the potentiometers gave far more smooth movement between hand and controller compared to the rotary encoder and flex sensors. These sensors had 5V inputs and a variable resistance up to 10kΩ and were very easily incorporated into the mechanical aspect of the project. These were simply integrated into a unison 5 volt and ground line throughout the system, as well as simple mapping between sensor reading and motor movement, making them the best choice within our electrical system for use.

Wireless Communication Module Iterations

The final of the electrical iterations is about the wireless communication modules. Although not implemented in the final design, the group performed research and tests to help prove the proof of concept using wireless communication in future more improved versions.

The first of the modules tested was the Arduino Nano 33 BLE Sense. This Arduino had an integrated Bluetooth function with a range of 1-2 meters. The connection was easy to set up and establish through use of integrated Arduino libraries, and connection speed was quick and reliable. However, for reasons stated prior regarding functionality of the microcontroller, the team moved on from this option,

The second set of testing was with the HC-05 Serial Wireless Module. This module required only a transmit and receive pin on each Arduino, as well as the 3.3V input and ground for connection. The supplemental code was easy to implement to get the components up and running, with a range of about 1m during initial use, however through testing of these components, the team found faulty connection issues with dropped connections for periods of time, as well as issues with the modules continually resetting after being connected and set to certain speeds/linked with certain devices. Performing these tests took longer than initially expected and were never resolved despite long hours of troubleshooting. The team did further external research to determine if there was any way to fix the current issues, and through this research, the team found that it was highly likely that a defective module was received. The component was reordered a few other times, and the same issues occurred.

3.2.2 Electrical Architecture & Design Process

Single Finger Prototype

To begin designing the robotic hand and controller alike, the team began with modeling the layout of the two pieces, and their structure, in a top-level block diagram, seen below Figure 18.

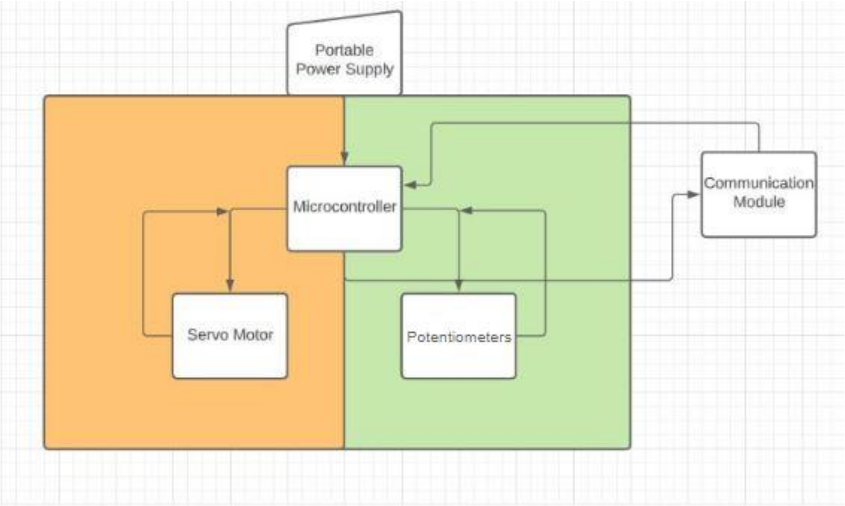

Figure 18 Top Level Block Diagram of Single Finger Prototype

Following our basic component selection of items necessary in the product (as seen above in Section 2.2.2), we moved into the layout of the selected parts and their connections/compatibility with each other, as generally, the components, regardless of specifications, have the same pinout in connecting to each of the other components, and will be subject to change throughout testing the capabilities of the product itself as a result. We began with a single finger prototype, which was the same for both the robotic hand itself and controller as well. All components are powered from the external power supply due to the requirements of the components, described above.

As seen in Figure 19 below, the schematic of the single finger layout of electrical components can be seen, all components have the voltage in pins supplied by the external supply, with all ground pins connected to a universal ground.

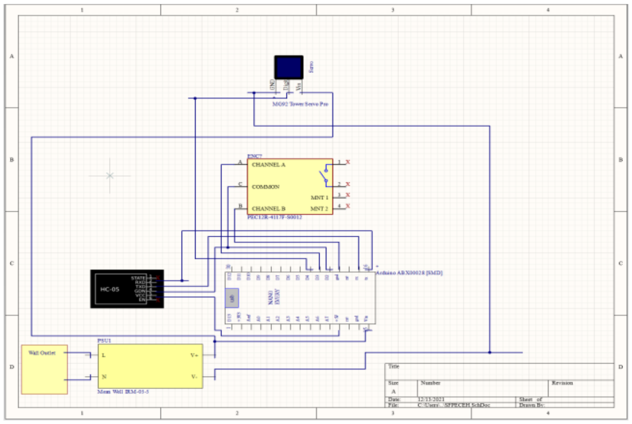

Figure 19 Schematic of Single Finger Prototype

The servo motor has three pins, two of which are ground and voltage, with the final connected into the fourth digital I/O pin (D4), which is a pulse width modulated (PWM) pin. For the rotary encoder, Channel A is connected to D3, a digital I/O pin, the common pin is connected to D2, and Channel B is connected to the ground on the Arduino. The extra pins on the rotary encoder are mounting pins, as well as a momentary push button, which will not be used within this structure, so they are left unconnected. The communication module (HC-05) is a Bluetooth module that is connected to the receiving (Rx) and transmitting (Tx) pins of the Arduino, as well as the ground and 5V supply. The Rx pin of the module is connected to the Tx pin of the Arduino, and Rx of the module to Rx of the Arduino, as a receiving or transmitting pin on one device must connect to its opposite pin on the device being connected to.

Five Finger Prototype

Following a successful prototyping of a single finger system, the team worked to scale the single finger to the full hand, encapsulating all five fingers and their movement. The final iterations of each electrical section and software was combined and integrated into the final mechanical design. As seen in the two Figures below (Figure 20 & Figure 21), the top-level block diagram of the flow between the two systems, as well as the electrical schematic for both sides are relatively simple in design.

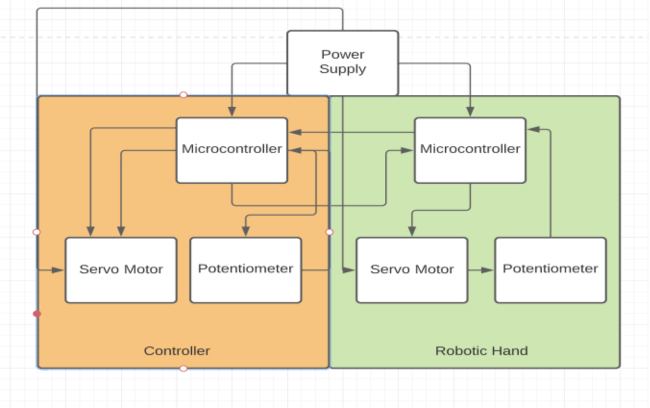

Figure 20 Top Level Block Diagram of Five Finger Prototype

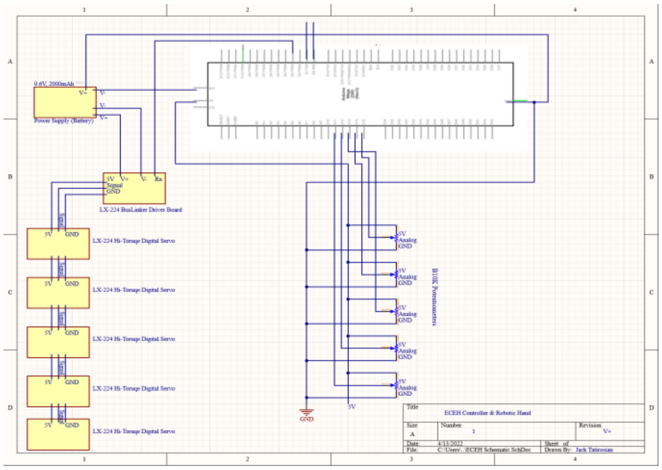

Figure 21 Schematic of Five Finger Prototype

The microcontrollers and motors are both powered from the power supply, supplying 5 volts to both the Arduino Mega as well as the motor driver board. The motors are connected to each other through a serial bus system, where each motor has its own address to receive motion commands from the Arduino. The first of the set of motors on each hand are connected to the driver board, and the driver board is connected to the Arduinos 5V and ground lines, as well as the receiving pin of the driver board into the serial3 transmit pin of the Arduino. The potentiometers are connected in series to a 5 volt and ground line from the Arduino, and each is connected to its own analog pin to accurately read the values for position tracking. Finally, each of the Arduinos are connected to each other through the serial lines on the Arduino mega for communication between the two. These were further tested for proof of concept including a discrete message structure to ensure the data being sent was accurate from finger to finger or being able to know which finger was read and accurately send over the data and move the motor for that specific finger.

3.2.3 Mechanical Design Choice & Iterations

Motor Iterations

The team decided to make use of servo motors within the project. Servo motors were chosen for a few main reasons: sizing, relative torque, and positional movement at 360°. For sizing, the team needed the motors to be as small as possible to be able to house eight of them, one for each finger, and three for the wrist within the controller and robotic hand, while still maintaining the ability of having enough torque to be able to functionally pick up, hold, and use in everyday activities. As well as this, regarding the accuracy of movements, the team needed a motor that was able to be controlled positionally, to a precise degree.

While stepper motors fit this bill and were able to take advantage of speed control and other factors, it was too difficult to find one that fit the sizing and torque requirements that the team needed. This is why servo motors were decided upon, as they could be accurately controlled in position, and were able to output a relatively large amount of torque, 3.1 -13 kg/cm., at a small sizing, ranging from 20mm by 20mm., to 40mm by 40 mm. The largest size (40x40) was equal to the same size of the smallest stepper motors that the team could find, however the torque output of the stepper motors was significantly smaller at this size than the servo motors found, which allowed the team to move forward with servo motors as the choice of motors.

Servo Motor Choice

The first servo motor chosen for actuation of the robotic hand was the Tower Pro MG92B. This motor initially proved to fit within the design constraints as it was a low-cost motor supporting position control with sufficient force output. The MG92B has a Stall torque of 3.1 kg-cm, providing exactly 148.3901 N at the tips of each finger if the actuation takes place from the motor horn itself. Through testing, it was determined that the MG92B was not controllable past 180° of rotation, and with the addition of the elastic soft material for opening of the hands, would no longer suffice for force outputs.

The next and final choice for the servo motor was the LX-224. This motor has a stall torque of 20kg-cm and rotation of 240°. With the increased stall torque, these motors are able to output 300 N of force with the same sized motor spool as the MG92B allowing for the team to increase the size of the motor spool to account for the cables being used. This increase of torque also overcomes the force provided by the soft material encapsulating the hand while still providing the 148.3901 N of force requirements in the tips of the fingers. Additionally, the increased range of motion to 240° allows for position control far enough to fully actuate the robotic hand as needed.

Robot Finger and Joint Iterations

The first design for the fingers on the robotic hand consisted of PLA Hinge style joints and fingers (Figure 22). These were entirely fabricated with PLA, and the joints would require actuation for both flexion and extension as there is no elastic material to assist with actuation. Although these fingers were very rigid and had exceptional strength, they would require the addition of a second actuation system for mechanical extensor tendons as well as the initially planned flexor tendons.

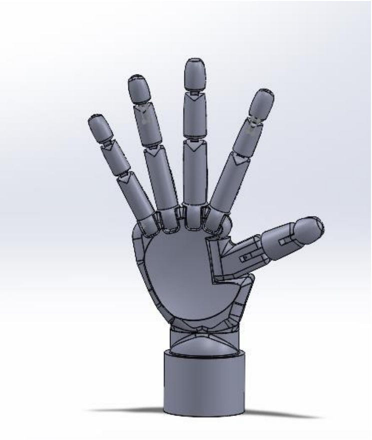

Figure 22 CAD Design of Hinge Style Finger

The next iteration of fingers and joints within the robotic hand was the Silicone-Rubber Joints and PLA Fingers (Figure 23). These consisted of the same PLA finger segments but replaced the joints of the fingers with Silicone-Rubber joints. The silicone rubber joints were created by filling a PLA mold of the joint with a two-part silicone rubber solution and left to cure for 8 hours. These silicone rubber joints provide the required force to open the hand fully after tension is released on the mechanical flexor tendons returning the hand to the rested position and removing the need for an extensor tendon system. The main issue regarding this design is that with the PLA, it is a low friction material and will not provide sufficient friction between the robotic hand and objects to grab as well as the silicone-rubber joints slip out of the fingers when the fingers actuate.

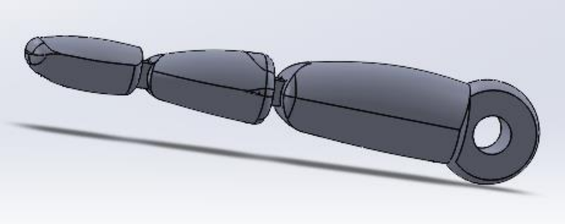

Figure 23 CAD Design of Silicone Joint Style Finger

Following the friction issue with the PLA fingers, the team then moved onto the third iteration of the gingers with a silicone encased PLA finger and silicone joint system (Figure 24). This maintained the overall structure of the precious iteration with the silicone-rubber joints between the fingers. Once the robotic hand was assembled, it was placed within a mold that contained space around the hand to be filled with silicone rubber to encapsulate the hand within the silicone and left to cure for approximately sixteen hours. This removed the issues regarding both the friction between the robotic hand and objects and the slippage of the silicone rubber joints between the fingers. This iteration came with its own problems as the void of space between the PLA fingers was filled with the silicone-Rubber and inhibited actuation, leading to incision being made between the segments of the fingers to allow for actuation but was not enough room for the robotic hand to close entirely.

Figure 24 CAD Design of Encased Silicone Style Finger

The team's final iteration of the fingers and joints were simple Silicone Fingers and Joints (Figure 25), which removed much of the PLA segments within the hand, the middle and proximal phalanx were removed in all of the fingers and the distal phalanx was suspended with wooden stages within the mold itself with the only connection to the rest of the hand being the Kevlar lines. This was then molded in the silicone rubber and set to cure. Once the silicone-rubber was cured, incisions were made at the distal and proximal interphalangeal joints to remove excess material and allow for actuation as mentioned in the previous iteration. This iteration removed much of the actuation issues that were seen in the previous iteration but still retained the benefits of the silicone encapsulation. The main issue of this iteration was that there were frictional issues regarding the silicone-rubber fingers and the Kevlar cable where the fingers would not return to a resting position once tension was removed from the cables and require a minute external force to return the fingers to the rested position.

Figure 25 CAD Design of Silicone Style Finger

Cable System

There were many decisions for the team to make in determining a design for the mechanical aspect of the product, including finding proper components that would function properly in conjunction with each other. The process of design for the hand is explained in further detail below.

The cables that the team has decided to move forward with braided Kevlar lines. This is because of the repetition of movement and applied forces that will act upon the cables can cause the cables to stretch, ruling out materials such as fishing line which will stretch over time a considerable amount. In terms of the strength of the line that is used, the maximum non-thumb force is 141.3109 N which translates to 31.757 pounds of force. With the thumb having just about over twice the force output of the middle finger, the 100-pound test braided Kevlar line is the ideal component as it is resistant to stretching through repeated use and has a high enough force capacity to be used for the hand.

These cables were tested first as the main portion of the control for the hand. The first iteration contained a simple cable spool and motor system (Figure 26). This system was very easy to design and implement in our project. It was very quick to prototype as well as low cost. However, this system did not allow for any haptic feedback, like we wanted in our final iteration, so we then moved to the series elastic actuator design. The initial SEA design was indicative of the average SEA, with a loop and two springs attached between the potentiometer and motor on both sides of the loop (Figure 27). This design worked well to provide the haptic feedback that we were looking for in our robot, however the need for a looped cable to be run to each motor-potentiometer pair was met with great difficulty spatially. Therefore, for the final design of the cable system of the ECEH, we decided on using half of the SEA v1. This half, now known as SEA v2, allowed for less space to be taken up by the sea and allowed for easier implementation of the SEA into our design (Figure 28).

Figure 26 Simple Cable System

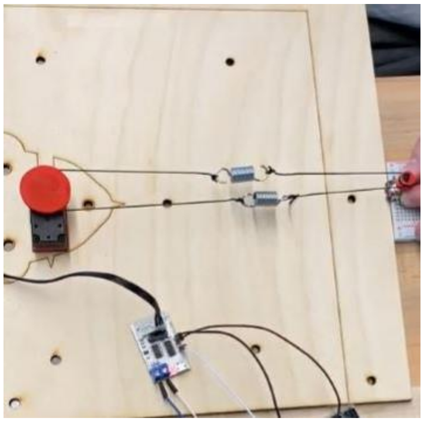

Figure 27 SEA v1

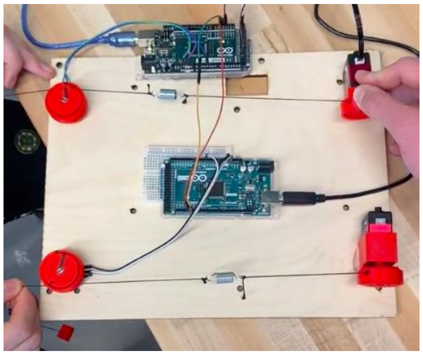

Figure 28 SEA v2

In order to select the springs needed for the application in the series elastic actuators for both the hand and the controller a spring with enough force to properly support the force of the human grip without deforming was needed, however this spring also needed to be able to have a small enough pound per inch ratio to be able to be sensed at a small scale. This scale was determined to be about the pressure it takes to break an egg with the finger as they are quite fragile. The springs then needed to be small enough to be able to fit inside of the palm so they could not be longer than 2 inches, in order to attain these goals two springs were selected that would fit concentrically inside of one another. This allowed for one spring to be able to support the full force of the human grip while the other was used for minute force detection as force begins to be applied.

The 3D printer material needed for the hand is Polylactic Acid (PLA), an environmentally friendly material that is recyclable through various means. This material must suffice for multiple conditions such as low friction material will not be needed as originally intended since there will be use of the Bowden cables within the hand itself. Second, the material must be strong enough to withstand the maximum applied force along the tips of the fingers, 148.3901 N in the four other digits and approximately 200N in the thumb. With a tensile modulus of 50 MPa, PLA suffices for the pressure applied at the tips of each finger. Finally, the material must be low cost as that is one of the largest parameters for our project.

3.2.4 Software Choice & Options

Control/Feedback Loop

This project will be using the Arduino IDE and Arduino Libraries. Since the microcontroller is an Arduino brand microcontroller, using Arduino's IDE provided the team with an easy way to interface with the microcontroller. The flowchart in Figure 29. represents the control/feedback loop the software is structured around.

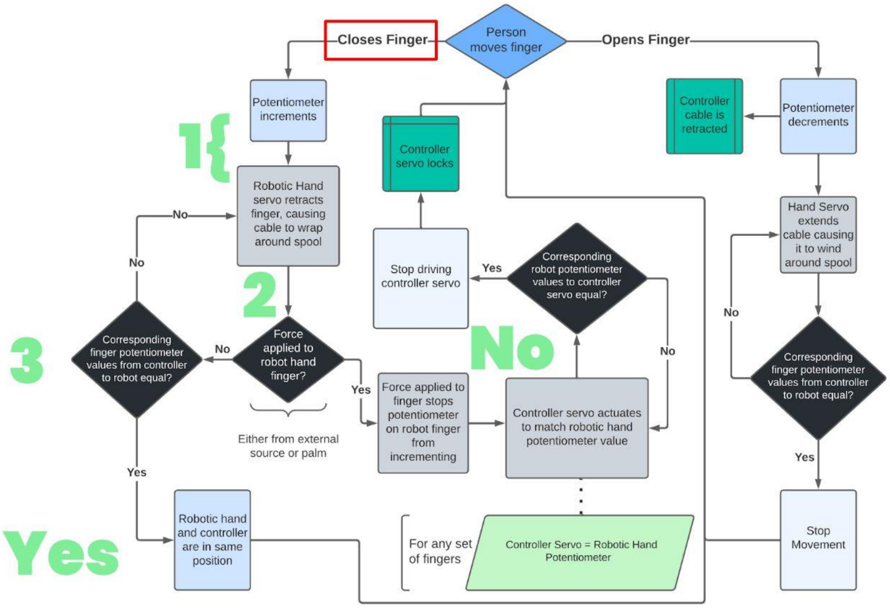

Figure 29 Control Feedback Loop Flowchart

Once a user moves their finger while wearing the wearable controller regardless of direction, the software will follow the same sequence:

Sequence of Motion Control

1. Track wearable controller position from potentiometers
2. Actuate robotic hand to match controller

3. Track robotic hand position from potentiometers
4. Return robotic hand information to wearable controller for consideration

This sequence alone is enough for accurate motion control. The integration of haptic feedback is where the software and flowchart branches. On step 4 of the Sequence of Motion Control in the software, one of two things can occur: The robotic hand will feel a force due to it grabbing an object or hitting an obstruction, or the robotic hand will not feel a force due to a lack of an object or obstruction. If we were to begin at section 3 in the flowchart, we see the flowchart branches off into two different directions.

The first, “Yes”, represents the situation in which the wearable controller and robotic hand are in the same positions known from comparing the potentiometer values. In this case, no action is taken that will deter the software from following the Sequence of Motion Control. This path also lets us know that the robot hand is not being obstructed in its motion. In other words, both the user controlling the robotic hand and the robotic hand itself can move freely.

Next, we have the “No” path. This path represents the situation in which the wearable controller and the robotic hand are not in the same positions. We were able to detect this by comparing the values of the robotic hand potentiometers against the values of the wearable controller’s potentiometers. If the values were not within a specified tolerance of each other, then the following sequence happens:

Sequence of Haptic Feedback

1. Communication from the wearable controller to the robotic hand ceases
2. Wearable controller servo motors are actuated to robotic hand potentiometer position
3. User can no longer close their hand further than the position of the robot hand

The Sequence of Haptic Feedback repeats itself until the user begins to open their hand. When the user begins to open their hand, the potentiometer values on the wearable controller will then start to match the potentiometer values on the robotic hand and the Sequence of Motion Control begins again.

System Architecture

Figure 30 represents the entire system architecture for the ECEH project.

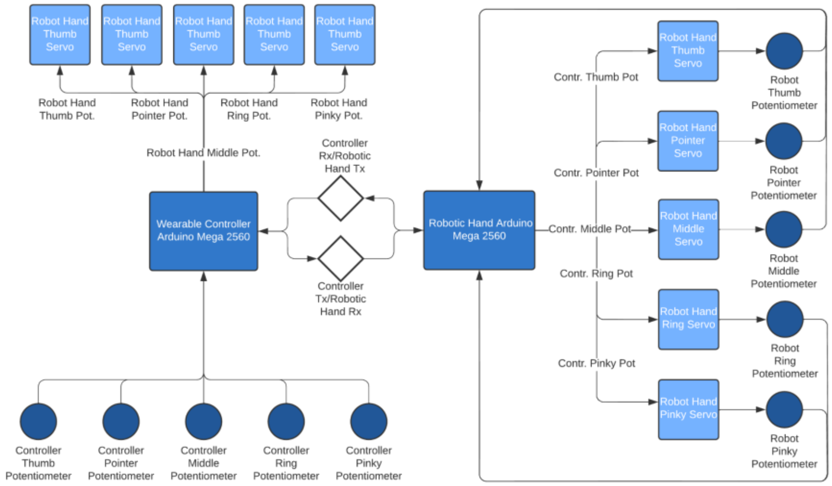

Figure 30 System Block Diagram

As seen in the Control/Feedback Loop Flowchart, the ECEH carrying out any tasks is dependent on a user moving their finger while wearing the controller. Once this occurs, all five controller potentiometer values are transmitted from the Wearable Controller Arduino Tx Serial pin. This pin is used for transmitting data from the host Arduino to–in this case another Arduino–a corresponding Rx line that is used to receive data being sent from a Tx line. Once the five potentiometer values are sent from the controller to the Robot Hand Arduino, the values are then assigned to each corresponding finger's servo motor. When the servo motors are actuated, the robotic hand potentiometer values change and are then read on the Robotic Hand Arduino and sent to the Wearable Controller Arduino by using the Robotic Hand Arduino's Tx pin and the corresponding Rx pin on the Wearable Controller Arduino.

Assuming the potentiometer values on the controller were different from the potentiometer values on the robotic hand, the following would occur. The robot hand's potentiometer values are then sent to the wearable controllers' servo motors. Once the wearable controller servo motors actuate to the correct position, the process repeats until the system is shut down.

3.3 Testing

Through our many design iterations, we were able to conduct several tests that helped us achieve our final prototype and fulfill our initial design goal. Much of the testing involved achieving motion control and haptic feedback with only one finger. This was to ensure the concept was achievable. Once we were able to prove the functionality of one finger, we could then apply that functionality to the entire hand.

Single Finger Motion Control with SEA v1 and Rotary Encoder

Our first successful test of the single finger theory incorporated an early prototype which used the Arduino Mega 2560s, our initial rotary encoders, the LX-224 Servo Motors, and the first version of our SEA. In the video titled "Single Finger Motion Control with SEA v1 and Rotary Encoder"[1]., we can see that when the rotary encoder is spun (located at the bottom of the screen), the servo motor actuates, rotating the SEA. The jumpy motion seen in the video is due to the low-quality rotary encoder. This test provided us with an insight into how the communication between the position tracking peripheral device and a servo motor would function.

Single Finger Motion Control with SEA v2 Between Two Arduino Mega

Our next main test was very similar to the first. This test also was for single finger motion, but instead used the SEA v2, the B10K Potentiometers, and two Arduino Mega 2560s. In the video titled "Single Finger Motion Control with SEA v2 Between Two Arduino Mega"[2] We can see the controller SEA (bottom) being actuated by pulling the cable. When this happens, the controller potentiometer inside the spool (bottom left spool) is then sent from the wearable controller Arduino to the robotic hand Arduino. Once received, the servo motor on the robotic hand actuates to the position of the controller potentiometer and retracts the cable. When the person pulling the cable on the controller SEA releases pressure, the cable retracts due to the constant force springs inside of the spools with the potentiometers. This in turn causes the servo motor to actuate and mirror the position of the controller's

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[1] See supplementary files for details

[2] See supplementary files for details

potentiometer. We found this test to be very successful and allowed us to move on to integrating all five fingers.

Five Finger Motion Control Between Two Arduino Mega

Our final test was motion control of five fingers. This test was similar to the previous in that all of the hardware was the same but differed in the quantity of components and the lack of the fully assembled SEA v2. We felt it unnecessary to include the SEA v2 since we already proved its functionality in the previous test. This test was solely used to test whether or not individual motion control of all five fingers was possible with the current module prototypes. As seen in the video titled "Five Finger Motion Control Between Two Arduino Mega"[3], the potentiometers are spun by a team member which in turn actuate the corresponding servo motor. Each potentiometer and servo are actuated individually, then multiple servos are actuated simultaneously. With the success of this test, we were able to ensure the integration of accurate motion control into the final prototype.

Bluetooth Communication Tests

During our testing and prototyping of the wireless communication, we conducted several different tests. The first test, which used two Arduino Nano 33 BLE Sense microcontrollers, involved using example code provided from Arduino to communicate the data being read on one microcontroller's gesture sensor to the other using Bluetooth. This test, which was successful, assisted us in developing our foundation for wireless communication which involved creating our data structure as well as the sequence of receiving and sending data values.

The other main Bluetooth test we conducted used the HC-05 Serial Bluetooth modules. This mainly involved ensuring connection on startup and sending and receiving potentiometer values from one module to another. Unfortunately, due to the modules' quality, we were unable to get consistent results from this test. The HC-05 modules would connect consistently on startup but would lose connection frequently. Additionally, the data being sent back and forth would often get jumbled due to the low data speed capabilities the HC-05 possessed.

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[3] See supplementary files for details

4. Results

4.1 Final Design Prototype

Through our many module and design iterations, our team was able to integrate all of the components and structure we intended to use to create both the wearable controller and the robotic hand (Figure 31).

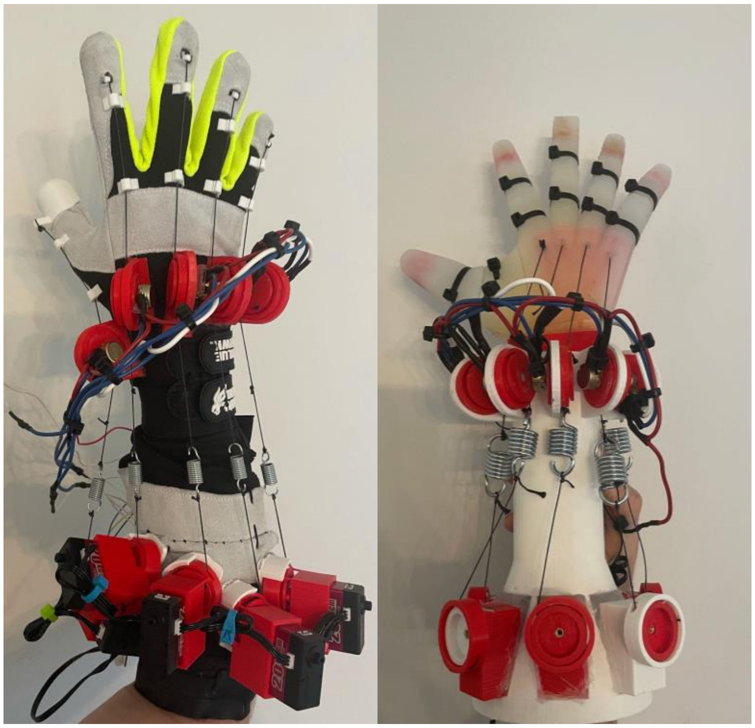

Figure 31 Final Prototype of Wearable Controller (Left) and Robotic Hand (Right)

The mechanical components on both systems were successfully designed to allow for accurate motion control and present the foundation for the integration of haptic feedback. The design also allows for strong forces to be applied to any object the robotic hand can grab. The LX-224 Servo Motors provided us with plenty of force to both close the fingers and exceed our initial requirement of at least 148.31N of force for the strongest finger.

The potentiometers, Arduinos, and servos were all easily combined and integrated into the final system while simultaneously providing us with accurate position tracking and motion control. The Arduino Mega 2560 provided us with the proper number of both analog and serial bus ports to achieve both haptic feedback and motion control. All the components were low cost but still effective, enabling us to keep to our second customer requirement.

The software's final architecture was effective in reading and communicating data with the Arduinos, despite having a simplistic structure. The readings were consistent and accurate for all the potentiometers as well as the writing of values to the servo motors. The software was debugged easily debuggable and individualized each finger to prevent compilation failure due to single finger changes. This allowed us to change the code of a single finger as needed without a cascade of failures from the rest of the source code; both on the wearable controller and the robotic hand.

If you refer to the video entitled “Motion Mirroring Test”[4], we present one of our most successful tests. In the video, one of our team members moves each of their fingers one-by-one while wearing the controller. The robotic hand then moves in the same motion for each finger and then our team member creates a fist, causing the robot hand to actuate to a fist as well. When the index finger moves individually, there is a fair amount of binding that occurs in between the silicon material and the cable on the robotic hand. This is the cause for the lack of opening from that finger along with any of the other fingers that don’t fully open. That being said, the servos on the robotic hand do actuate to the correct position, which means that the motion from the controller is still being simulated by the robotic hand.

In the video entitled “Hand Grabbing Can”[5], the robotic hand can be seen grabbing a soda can. This video allows us to say with confidence that the robotic hand can hold objects when a person uses the controller to actuate the robotic hand. This was a big step for us in our initial goal, and we feel that it will provide sufficient evidence to support the success of our proof of concept.

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[4] See supplementary files for details

[5] See supplementary files for details

5. Cost Analysis

With regards to the pricing and cost of ECEH in comparison to those competitors on the market, one of the main goals of the project was to create a cost-effective alternative to robotic EOAT, as well as limb enhancement/replacement products on the market. As spoken about in the market research, most products within these markets that most closely resemble ECEH range in price from $3,000-$20,000 for higher end prosthetics and EOATs. In this section, the cost of components and resulting price point of ECEH will be explained in further detail.

5.1 Bill of Materials (BOM)

Beginning with the bill of materials, all of the components within each system and their respective costs were tallied and compiled together to understand the cost to make ECEH on a component basis. The BOM is as seen below in Table 6.

Table 6 Bill of Materials (BOM)

Component	**Amount**	**Cost**	**Total Cost**
LX-224 Serial Bus Servo	10	$17	$170
Arduino Mega 2560	2	$41.80	$83.60
B10K Potentiometers	10	$1.30	$13.00
Silicon Molding	1	$22.94	$22.94
Controller Glove	1	$6.99	$6.99
Kevlar String	1	$0.90	$0.90
Stranded Core Wire	1	$13.00	$13.00
3D - Printer Filament	1	$18	$18
LX-224 Driver Board	2	$24.00	$48.00
Springs	10	5.5	55
Misc (Super Glue, etc.)	1	$10	$10
			441.43

In the table above it can be seen that the cost of all of the components, both mechanical and electrical, totaled up to $441.43. This exceeded our expectation of making a low-cost alternative, as this allows us to price the cost of the system below $1000, a significant cut in price compared to those currently on the market for industrial and commercial use. In the following section the team will go into the pricing evaluation of ECEH, its price point, comparison to competitors, as well as the return on investment (ROI).

5.2 Pricing & Return on Investment (ROI)

To begin pricing ECEH, the team first began determining what it would take to recover the costs of product development. The goal in pricing ECEH would be to make profit and at a minimum break even on the sales of the product. In order to analyze our ROI, the team first had to identify our initial investments (cost of components), as well as our fixed costs (labor, etc.)

As stated in the previous section, the team had a cost of the product at $441.43, which was determined from the sum of the components in our BOM. This cost covers the price to manufacture and make the product on a component level. With this, we wanted to keep the price of the system under $1,000, however still keep a modest price on the product. Being able to retain a minimum of 20% profit for both our group, as well as any potential distributors, brought us to a selling price of $750. This allows us to keep the margins of the product on the slim side, keeping ECEH as a low-cost alternative to EOATs and limb enhancement products, while still being able to generate enough profit for a successful ROI. Including labor and tools used to create ECEH over the course of the year, we were able to determine our fixed costs. The team projects the fixed cost of researching and developing ECEH to be $400,000. With these metrics identified, the team was able to produce a graph of the ROI of ECEH, seen below in Figure 32.

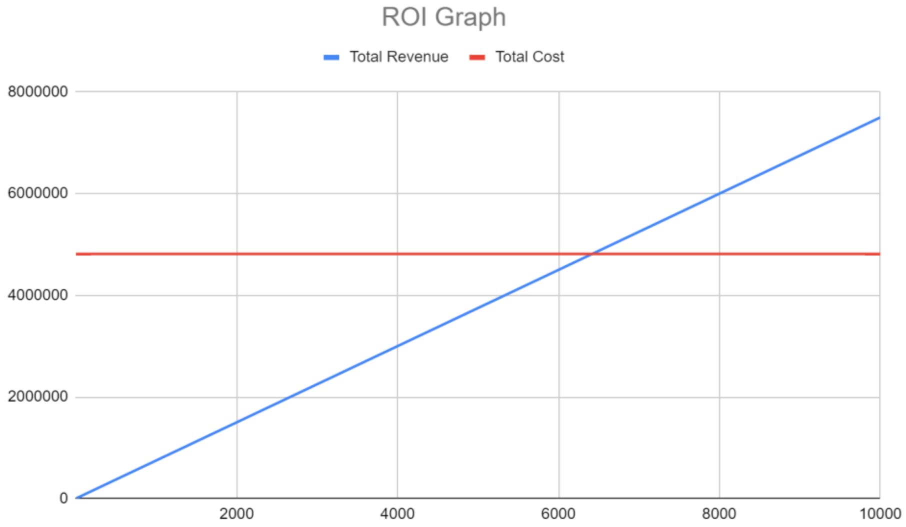

Figure 32 Graph of Projected Return on Investment

In producing about 10,000 units, the team would have costs of $4.81 million to manufacture all of the units. With this, and the selling point of $750, it would require the team to sell about 6,314 units to break even on the cost, with the following 3,684 units being left for pure profit. From the graph we used the following formula to determine our ROI:

Equation 5

$$((750 - 441.43) * N - 400000)/(441.43 * N + 400000) \qquad (5)$$

With this, our return on investment depends on our sales, and whether we are functionally able to sell 6,314 units. If the product becomes a popular buy for industrial or commercial consumers, our ROI will be far larger.

6. Failure and Hazard Analysis

6.1 Failures

Throughout the process of creating our proof of concept for ECEH, we encountered many difficulties, of which we had to continually improve upon and learn from to continue to make solid progress. Many of these failures and issues came from small mishaps in electrical connections, as well as issues in 3D printing, and silicon molding.

To begin with the electrical failures, we first began with the Arduino Nano BLE Sense 33. With our group's experience in using Arduino nanos, the group Figured that this specific version of the nano had the same specs as the others, just with integrated Bluetooth. After faulty readings and testing of sensors with it, the group came to the realization through research that the board was only capable of 3.3V inputs and signals. The boards had been used to the point with 5V signals that there was definite damage to the board and some of its ports, which essentially meant we had to move on to a new microcontroller or purchase new ones. Another item on the electrical side was with the potentiometers through testing. There were many points throughout the project that the team would finish research and testing for the day, unplug all the electrical components, and come back the next day, where upon reconnecting the pins on the potentiometers, the 5V input and ground pins would be swapped accidentally due to changing the orientation of the potentiometers. This resulted in a couple blown potentiometers, which were only noticed through continual testing, as the values began to skew largely.

On the mechanical side, issues in prototyping mainly stemmed from failed 3D prints, as well as incorrect fashioning of the silicon mold. Many times, throughout the mechanical iterative design process, there were new 3D parts being printed for the system. These parts typically had long print times; upwards of 10+ hours. The team would let these print overnight so that in the morning they could be tested and used. However, several times throughout this process, the print would fail at around 3-4 hours in. This is a difficult item to keep in mind when prototyping, however it is important to keep in mind while printing, so that these can be solved quickly and efficiently, rather than waking up to a failed print. The second issue on the mechanical side came with the silicon molding. Like the 3D printer, molding silicone took a long time to finish, at a max of a couple of days at points due to the thickness of the mold, and following pulling the mold out, a few times the team noticed that adjustments should have been made prior to molding, with regards to the 3D printed fingers and string within the mold, however it was near impossible to modify the mold once it had finished curing. Due to this, the team had to perform multiple molding and curing processes on the system, which used up a significant portion of the time we had planned on testing the system further with.

While these failures are unfortunate in terms of the timeline of the project, they serve as good places to learn and improve upon for future iterations of the project, so that these may be taken into account to avoid.

6.2 Potential Hazards

Some of the potential hazards the team noticed throughout the prototype of ECEH are mostly with regards to the number of electrical items on the user/consumer's arm and hand. Making sure that all wires are properly connected, with no stray ends is a must, as at full tension from the motors, the user could have upwards of 12 amps coming from the system attached to their arm, which is unsafe in many different ways to the user. To combat this, it must be made entirely sure that all the wires are properly and securely fastened, as well as blocked away from potential contact with the user's skin.

As well as this, it had to be made sure that the motors used for haptic feedback were properly calibrated, as if there were large skews in data on the controller side motors, the strings would pull back on the user’s hand with a large force, causing potential harm to the user due to the strength of the motors. To combat this, the team worked through the software to iron out all issues regarding false readings or spikes in readings to avoid this hazard.

7. Conclusions and Recommendations

7.1 Conclusions

Our team was able to create a successful proof of concept for real time motion control from controller to robotic hand, as well as the foundation for haptic feedback through research and development of the system. We feel that we achieved our initial design goal, both with our prototype as well as through our research. The prototype allowed us to achieve the accurate motion control, low cost but effective, ease of use, and strength customer requirements. Our research and testing provided us with a foundation for both integrated haptic feedback and wireless communication. With that, we can confidently say we achieved our customer requirements and our design goal through our proof-of-concept prototype of the ECEH.

7.2 Recommendations and Future Work

Despite our success, there is still room for improvement. We believe we have fulfilled our initial goal of designing a system that can mimic the motion of a human hand and provide a user with haptic feedback. Together, we decided that the potential future improvements should include – in order from most to least important:

1. Back Driving Fingers
2. Reliable Wireless Communication
3. Wrist Feature
4. Compact System

The first and most important improvement we feel should be added to the ECEH, is the capability of back driving the fingers. We attempted to implement a method of doing so, but unfortunately were unable to due to time constraints. With the ability to back drive the fingers, the system will be able to function at a higher level than it currently operates. This is because the ECEH will be able to mimic the human hand motion more accurately, as well as have the ability to grab and release multiple objects within one test.

Next, we feel that the implementation of wireless communication is very important for the application of the ECEH to both the industrial and commercial world. The very basis of our project is that the ECEH can be used when a person should not. This involves the ability to work at a distance. Therefore, for the success of the ECEH from a market standpoint, the implementation of reliable wireless communication is essential.

Our next recommendation is to add a wrist feature to the ECEH. This wrist feature would allow even more accurate motion which would in turn increase the application of the ECEH to different tasks and jobs. A wrist feature would also cause the robotic hand to be even more interactive with the user and provide more sensitive and accurate haptic feedback if haptic feedback were to also be implemented in the wrist.

Finally, we recommend that with the additions of the previous three recommendations, the system remains as compact as possible. We understand the difficulty of attempting to fit all the components required for the ECEH within an “arm sized” attachment for both the wearable controller and the robotic hand. With the potential additions of a wrist feature, wireless communication, and a system for back driving the fingers, the ECEH will definitely become much bulkier than it currently is. For practical application, the ECEH needs to be easily equipped and transported so as to not provide a user with more difficulty than doing it without ECEH.

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