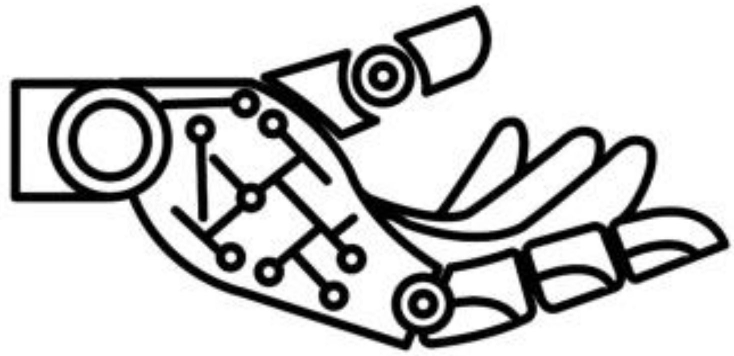
Prosthetic Hand



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EMPOWERED GRASP: MYOELECTRIC SMART EMBEDDED PROSTHETIC HAND WITH INTELLIGENT CAPABILITIES

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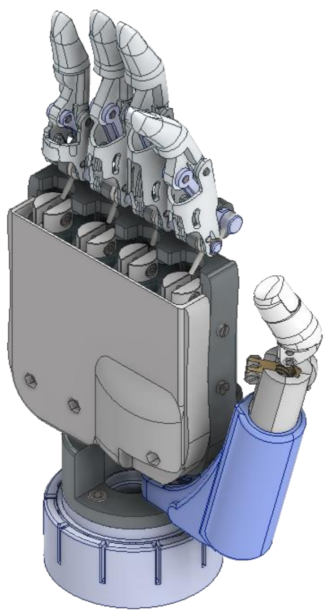

Mechatronics Engineering

Graduation Project Report

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DECLARATION

We hereby certify that this Project submitted as part of our partial fulfilment of BSc in ***(Mechatronics Engineering)*** is entirely our own work, that we have exercised reasonable care to ensure its originality, and does not to the best of our knowledge breach any copyrighted materials, and have not been taken from the work of others and to the extent that such work has been cited and acknowledged within the text of our work

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ABSTRACT

This paper presents the detailed development process of a prosthetic hand that closely mimics the anatomical structure of a human hand.

The aim goals of the project focus on the development of a myoelectric prosthetic hand utilizing an EMG sensor and to address the discomfort experienced by patients with upper limb defects by creating a more aesthetically pleasing and natural-looking prosthetic.

This paper also details several other key components. These include the mechanical design of the prosthetic hand, and its implementation. The development of an embedded microcontroller system to power its functionalities, and the tuning of parameters for optimal performance.

By incorporating these aspects into the project, it ensures not only the visual appeal and functionality of the prosthetic hand but also the efficient and effective operation of its various features.

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List of utilized standards:

- National Electrical Code (NEC)
- VDI 2206

1. Chapter 1: Introduction

Hand amputations or loss affect more than 3 million people worldwide, with over 75% of cases being partial amputations. This loss has a significant impact on the individual's functionality. While prosthetic hands offer a solution, their development has primarily focused on aesthetic aspects rather than functionality. However, advancements in biotechnology and robotics have paved the way for more sophisticated prosthetic hands. These modern devices are equipped with sensors and actuators, enabling motorized fingers and grasping movements. Unfortunately, these automated prosthetic hands are costly and not accessible to everyone in society.

Hand prostheses can be categorized into two types: mechanical and myoelectric. Mechanical prostheses are controlled by the human body, while myoelectric prostheses utilize electrical motors and electromyography sensors for control. The development of these prostheses presents challenges due to the intricate nature of the human hand system. The human hand has a high number of degrees of freedom (DOFs), with five DOFs per finger, resulting in a total of 25 DOFs. To address this complexity, prostheses are designed with under actuation, reducing the number of components required for construction. This approach helps to minimize weight and cost while maintaining functionality.

Traditional prosthetic hands typically have limited control capabilities, as they are controlled by a single input, restricting individual finger or joint control. EMG-based prosthetic hands, for instance, utilize electrical signals from two opposing muscle contractions to enable flexion and extension movements.

The advantages of myoelectric prostheses over body-powered devices include a reduction of harnessing, access to effortless strength and multiple grip patterns, and more natural hand movements. [10] An often-stated limitation of myoelectric is that they cannot get wet. That too has been overcome with recent advancements in waterproofing technologies for some terminal devices and elbows.

While these EMG-based prosthetic hands are aesthetically pleasing and cable-free, achieving more than two movements requires additional conditions, such as triggering or artificial intelligence techniques like pattern recognition and classification. Prosthetic hands designed for multi-finger movements often operate in a sequential order with time delays. Some prosthetic hands achieve finger movements by utilizing multiple contractions of the same muscle or alternating between muscle contractions to control different joint movements. These approaches enhance the functionality and versatility of prosthetic hands, providing users with a wider range of control options.

One of the most sophisticated and well-designed and intelligently controlled Myoelectric prosthetic hands designed so far is the “BeBionic” hand model by Otto-Bock. But the possibility for model to be accessible to everyone with limp loss is rather low as the price range for that model is around 30,000$ to 40,000$, which is quite the challenge to afford especially for people who suffer from amputations in the third world countries.

One of the advantages of the BeBionic hand is that it is able to perform various types of grips and motions with only 5 Motors utilizing linkage systems and springs in a certain combination of actuation to mimic a certain grip.

2. Chapter 2: Research

2.1. Historical Background

To really understand how far the field of prosthetic have come in the present, first you will have to look at the past,

FROM ANTIQUITY TO THE MIDDLE AGES: IRON HANDS

One of the earliest records of a prosthetic hand is described in AD 77 by the Roman scholar Pliny the Elder in his encyclopedia Naturalis Historia. After losing his one arm in the Second Punic War (218 BC-201 BC), the Roman General Marcus Sergio's received his prosthetic arm and was able to rejoin battle.

"Sergius in his second campaign lost his right hand… He had a right hand of iron made for him and going into action with it tied to his arm, raised the siege of Cremona…"

One of the most famous examples of early prosthetic hands is the iron hand of the German knight Goetz von Berlichingen.

After Goetz lost his hand at the Siege of Landshut in Bavaria (c. 1505), the craftsmen passively flexed the metatarsophalangeal joints, proximal and distal interphalangeal joints, interphalangeal joints and made him iron hands with outstretching fingers.

Figure 1 Illustration of the numerous components of Götz's medieval hand prosthesis

With the prosthesis tightened, Goetz was able to grip the reins, grab the weapon, and return to battle. The device was modeled as an extension of his battle armor rather than a human arm, and due to its weight, had to be attached to Goetz's armor with thick leather straps.

ITALIAN HISTORIAN AND PHYSICIAN PAOLO GIOVIO

reports that the Turkish pirate Horc Barbarossa lost his right hand in the Battle of Bugia with Spain (c. 1517) and received an iron replacement so he could continue the fight. Another example of an iron hand was that of a Dutch craftsman of Christian, Duke of Brunswick, who lost his left hand at the Battle of Fleury (c. 1622).

One of his first descriptions of a non-combatant prosthetic hand was by Italian surgeon Giovanni Tommaso Minadoi in the 1600s, who could take off his hat, unbuckle his purse, and even write with a quill.

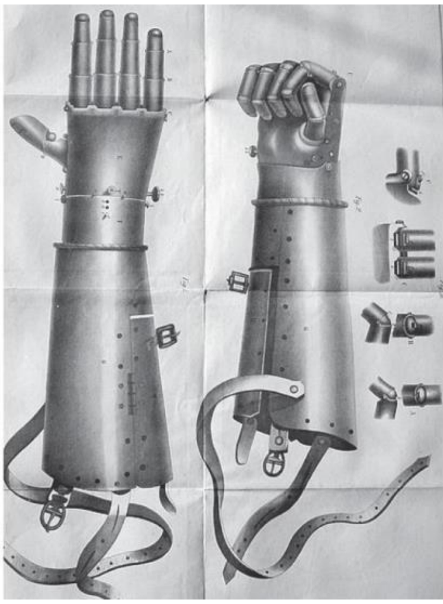

Figure 2 The iron hand of Götz von Berlichingen

IN THE 16TH century, French military surgeon Ambroise

hisparais drew the first detailed design of a spring-loaded prosthetic hand, called "le Petit- Rolin" after the craftsman who made it (figure 4).

Paré also donned his prosthetic arm for a humerus amputation (figure 3)

Figure 4 Ambroise hisparais spring loaded prosthetic hand.

Figure 3 Paré s prosthetic arm for a humerus amputation

Although heavy and requiring control by the intact hand opposite the amputee, early prosthetic hands successfully restored a knight's ability to hold a shield or weapon during combat.

BODY-POWERED PROSTHESES, TWO WORLD WARS AND THE CREATION OF DEDICATED PROSTHETICS ORGANIZATIONS

IN 1818, the concept of “automatic” body-powered upper limb prosthesis was developed by the German dentist Peter Buriff.

By transmitting tension through leather straps, Barif's device allowed the intact muscles of the trunk and shoulder girdle to initiate movement at terminals attached to the amputated stump.

For the first time, an amputee was able to manipulate prosthesis with fluid body movements rather than as a foreign object in itself. it changed. Shoulders with straps buttoned to pants.

His harness was threaded through loops to the opposite armpit and to the missing limb. Stretch with fused fingers.

IN 1916, German surgeon Dr. Ferdinand Sauerbruch published the design of a prosthetic limb that controlled the fingers by transmitting the movement of the muscles of the upper arm.

Figure 5 Sauerbruch's prosthetic hand design in the early 20th century

WORLD WAR I (1914-1918) caused an unprecedented number of casualties. In the United States (USA), the Amputee Rehabilitation Program was created to help more than 4,400 amputees, most (54%) of whom have upper extremities, regain their ability to work on farms.

and factories. it was done. The distribution of prostheses with sockets and universal attachment devices allowed attachment of a variety of working tools.

In 1917, the U.S. Army's Surgeon General issued a groundbreaking invitation for limb manufacturers to meet in Washington, DC.

This resulted in the formation of the American Limb Manufacturers Association, now the American Association of Prosthetics and Orthotics. In Canada, a national charter in 1920 recognized the need to support amputees, leading to the formation of the World War I Amputee Society, now known as War Amps.

DURING WORLD WAR II (1939–1945), improved shock management and antibiotics saved lives, but 3,475 upper limb amputees occurred in the United States. The enormous demand for prosthetic limbs led to the formation of the US Prosthetic Limbs Research and Development Committee in 1945 and the Canadian Association of Prosthetics and Orthotics in 1955. The thalidomide tragedy (1958-1962), which produced many children with short limbs, further fueled demand and investment in improved prostheses.

In 1948, the body-powered Bowden Cable Prosthesis was introduced, replacing the bulky straps with slim, robust cables. Despite new materials and improved craftsmanship, today's body-powered prosthetic legs are essentially adaptations of Bowden's design.

Durable, wearable, and relatively affordable, body-powered prostheses use terminal devices (most commonly two hooks) to change cable tension with sustained shoulder and body movements.

It provides users with an impressive range of motion, speed and power when manipulating the prosthesis Rather than requiring a healthy hand to control the prosthesis, both hands can be used simultaneously, allowing users to complete their tasks more efficiently.

Additionally, sensing cable tension allows the amputee to anticipate and adjust prosthesis position without visual feedback. Prolonged wear can be uncomfortable, complex motor.

tasks are restricted, and body-powered prostheses are widely used, although not human-like in appearance.

ROBOTIC TECHNOLOGY MYOELECTRIC PROSTHESES

In 1919, a German book titled Ersatzglieder und Arbeitshilfen (Limb Substitutes and Work Aids) contained conceptual designs for the first externally powered prostheses, using pneumatic and electric power sources. Unfortunately, these revolutionary designs were too complex to be feasible with contemporary technology.

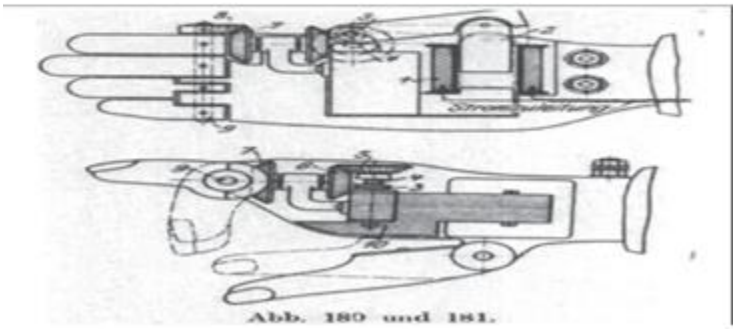

Figure 6 Electromagnetic hand prosthesis from 1919

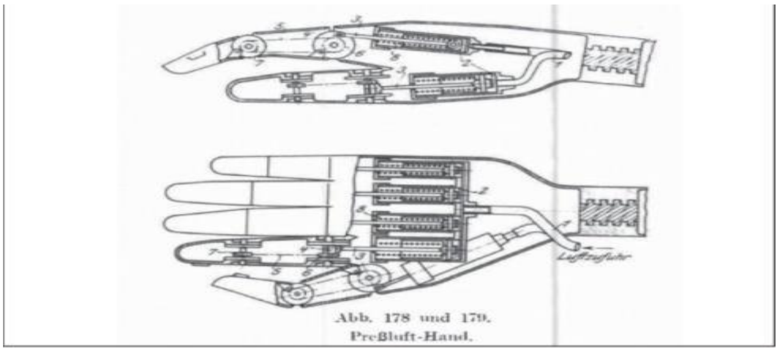

Figure 7 Early compressed gas-powered prosthetic hand from 1919

IN 1948, Reinhold Reiter, a physics student at the University of Munich (Munich, Germany), created the first electromyographic prosthesis, a device that amplifies surface electromyographic (EMG) potentials to drive motorized parts. Did. Reiter published his work, but it was not widely accepted, and this potentially groundbreaking invention was not commercially or clinically accepted.

The first clinically significant myoelectric prosthesis was presented in 1960 by Russian scientist Alexander Kobrinsky. The use of transistors reduced bulk and made the device portable, and the battery and electronics were attached to a belt and wires connected to the prosthetic leg. The prosthesis was also fitted with flesh-colored rubber cosmetic gloves. This "Russian hand" was marketed in England and Canada, but had many problems: heavy, slow, weak clamping force, easily damaged cable connections, and electrical interference affecting reliability.

In the 1980s, myoelectric prostheses were used in rehabilitation centers around the world and are now a popular choice for amputees.

Improvements in materials have enabled lighter and more ergonomic designs, and power has evolved from compressed gas to rechargeable nickel-cadmium batteries.

Compared to body-powered prostheses, myoelectric prostheses offer superior comfort and aesthetics, no unsightly cables, and a wide variety of lifelike silicone palms and skin pad options. Moreover, signal detection is non-invasive to the skin surface and the surgical effort is comparable to that of normal limbs.

Control muscles vary according to the amputation level of the patient. For example, most sub-elbow (trans-radial) amputees use the preserved wrist flexors and extensors to control the prosthesis, whereas supra-elbow(trans-brachial) amputees also use the biceps and triceps. Incorporate and control the prosthetic leg.

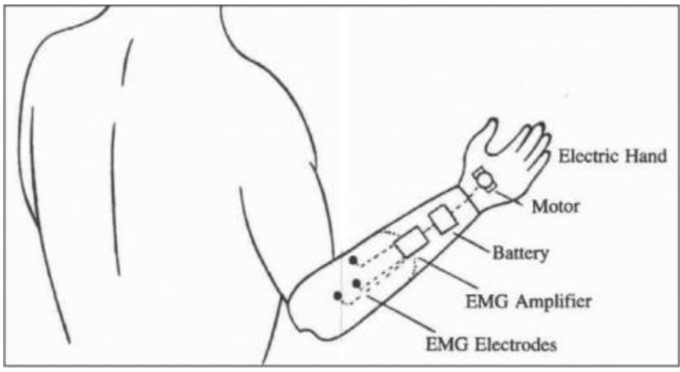

Figure 8 Myoelectric below-elbow prosthesis, controlled by electromyographic (EMG) potentials.

However, unlike body-powered prostheses, myoelectric prostheses are externally powered and require regular charging. Learning to isolate muscle signals can be cumbersome, require multiple phases of training, and may not be possible for complex movements that require simultaneous joint movement in fingers, wrists, and elbows.

There is a delay between the initiation of the motion command and the mechanical response, with small variations of: For example, electrode displacement or changes in skin conditions (such as perspiration) can disrupt the EMG signal.

Without sensory feedback, visual input must be constant, which is tedious, error-prone, and unnatural.

Cosmetic overlays are impressive for their realism, but durability is an issue, with users complaining of frequently changing gloves due to wear, cuts, and stains.

Osseointegration, the direct attachment of titanium attachments to living bone, eliminates the need for a cup and improves stability and comfort at the prosthesis-stump interface.

Osseointegration was developed by Swedish surgeon Per-Ingvar Brånemark in his 1950s, but it was his son Rickard Brånemark who pioneered its application to prosthetic limbs.

By providing stable fixation, Osseo-integrated prostheses increase the range of motion of amputees while eliminating socket-related problems such as chafing and sweating.

Due to the close connection between the prosthesis and the skeleton, users can also experience improved pressure and vibration sensations.

Between 1990 and his 2010, Brånemark's team fitted his 10 trans-radial and his 16 trans- humeral osseo-integrated prostheses. Only three patients failed to use the prosthesis later because of implant fracture, traumatic injury, or incomplete integration. It is a major constraint for more adoption of the integration.

Despite its widespread use, myoelectric technology is expensive and may not be covered by insurance plans. In the 1990s, terminal-equipped myoelectric prostheses for forearm amputees cost approximately six times as much as body-powered prostheses.

In Canada, a trans-radial electromyographic hand costs him $7,500 to $29,500, and a trans- brachial electromyographic prosthesis is up to $80,000. By comparison, a traditional body- powered prosthesis costs about $5,500.

INTUITIVE MYOELECTRIC CONTROL WITH TARGETED REINNERVATION

A major advance in intuitive control of prosthetic limbs is the technique of Targeted Motor Reinnervation (TMR), first developed in 2004 by Dr. Todd Kuiken and Dr. Gregory Dumanian, of America.

By rerouting severed (i.e., severed) peripheral nerves from the amputated limb to an intact surrogate (target) muscle, the EMG signal obtained from the target muscle is transferred to the muscle of the missing limb by the movement of the muscle. Provide input.

For example, when the median nerve is conveyed to the abdomen of the central pectoralis major muscle, given that the amputee "bends the fingers", the central part of the pectoralis major muscle is contracted, giving him a robust edge to close the prosthesis. An EMG is generated. Unlike traditional body-powered myoelectric prostheses, TMR is intuitive and allows patients to move multiple joints simultaneously.

Opening and closing the prosthesis while bending and extending the elbow increases the speed of execution of the task from 2 to 6 times his.

In addition to improved motor control, a recovery of sensation was noted in the skin overlying reinnervated muscles in early TMR patients. When the reinnervated skin was stimulated, sensations were experienced in the area of the body that the severed nerve had used for innervation. That is, amputees felt touched to specific parts of the missing limb.

This knowledge has extended the technique of targeted reinnervation to reattach sensory nerves to the main trunks of peripheral nerves.

A multidisciplinary team at the University of Alberta (Edmonton, Alberta) identified, isolated, and rerouted individual sensory nerve fibers from the median and ulnar nerves to target sensory skin areas away from reinnervated muscles. We have developed a variation of this surgical technique. This technique, known as fascicular target sensory reinnervation, creates individualized handheld spatial sensory maps over selected areas of receptor skin remote from the prosthetic interface. By incorporating a sensory feedback device, the patient can feel and regulate the amount of force exerted by the myoelectric prosthesis when manipulating objects. Preliminary results show discernible pressure sensation (up to 4 discrete levels of force with 75% to 85% accuracy), ability to grasp and release objects, and ability to discriminate size (mean [±SD] 93) have shown effective recovery. ±6% accuracy) and density (100% accuracy) without visual or auditory stimulation

Reported complications of targeted reinnervation procedures include increased cellulitis, seroma, and transient phantom limb pain. Surgery, hospitalization, prosthetics, and rehabilitation costs range from $150,000 to $250,000.

Although still in the early stages of development, more than 40 of her patients have undergone targeted reinnervation worldwide since 2011.

2.2. Current day Research and Overview

Background investigation was done to make sure we were making informed decisions before jumping right into the development phase. We looked into the following areas to achieve this:

- Prosthetic devices
- Prosthetic hand with myoelectric sensor
- Human Hand Anatomy
- Amputations
- Different popular Prosthesis models comparison

2.2.1. PROSTHETIC DEVICES

In medicine, a prosthesis is defined as an artificial device that replaces a lost part of the body due to trauma, disease, or congenital disease. prosthesis that replaces part of the arm between the elbow and wrist is called a trans radial prosthesis, also known as a "BE" prosthesis.
for lower extremities. These devices can be functional or simple looking, depending on their intended use.
Physically challenged individuals who require a device that is durable, reliable, and strong due to manual work a simpler prosthesis such as a hook may be selected. On the other hand, some individuals who are prepared sacrifice functionality for a more natural- looking prosthesis can opt for cosmetics.
A prosthesis (also called cosmesis) as shown in (Figure 9).

Figure 9 Personalized Cosmetic Prosthetic Hand by Sophie de Oliveira Barata

The advancements in prosthetic technology have revolutionized the choices available to individuals with upper extremity amputations. These options cater to various functions and purposes, providing amputees with a range of possibilities.

There are three distinct types of powered prosthetics available:

1. Body powered: In this type, the prosthetic is controlled by the movement of the user's body. For example, a cable may be connected from the shoulder to the prosthetic hand, allowing the hand to activate as the user moves their shoulder.

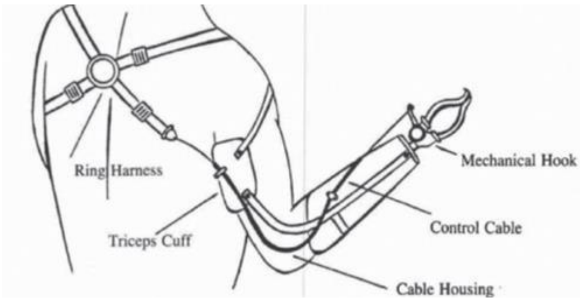

Figure 10 Typical Body Powered Trans radial prosthesis.

2. Motor powered: These prosthetics utilize buttons or switches to control movement. For instance, a prosthetic hand may have dedicated buttons to articulate the wrists and fingers, enabling the user to grip objects with precision.

3. Myoelectric powered: This cutting-edge technology enables prosthetic limbs to be powered by electrical signals transmitted through electrodes placed on the user's skin. These signals, generated by the user's muscles, are harnessed to control the movement of the prosthetic limb.

The myoelectric powered prosthetics represent a significant advancement in prosthetic technology, offering a more intuitive and seamless integration with the user's body. This innovation holds great promise for enhancing the functionality and quality of life for individuals with limb loss.

2.2.2. *Myoelectric powered Anthropomorphic Prosthetic Devices*

- Brief:

Anthropomorphic prosthetic devices aim to replicate the natural appearance and functionality of human limbs for individuals with limb loss. Myoelectric powered prosthetics utilize electrical signals generated by the user's muscles to control the movement of the prosthetic limb. In some cases, they even use lights, vibration motors, or other interfaces to provide user feedback.

Figure 11 Anthropomorphic Prosthetic Hands Showing bebionic (left), i-LIMB Ultra Revolution (center), i-LIMB Cosmetic Cover

- Definition and Key Features:

Myoelectric powered anthropomorphic prosthetic devices are advanced technological solutions that integrate sensors, electrodes, and microprocessors to interpret and utilize the electrical signals produced by the user's residual muscles. These signals are captured by surface electrodes placed on the skin, enabling precise control of the prosthetic limb's movements, including finger articulation, wrist rotation, and grip strength modulation. To operate the device, muscle contraction triggers one of the preloaded grip patterns. The pattern may vary from 14 to 24 depending on the model.

- Cost:

It is important to note that myoelectric powered anthropomorphic prosthetic devices generally come with a higher price tag compared to other types. This is due to the advanced technology, sophisticated components, and precision engineering involved in their development. The cost may vary depending on factors such as the complexity of the prosthetic limb, customization, and additional features.

- Why would I opt for a Myoelectric prosthetic device?

There are several compelling reasons to choose a myoelectric powered anthropomorphic prosthetic. Firstly, these devices offer enhanced functionality, allowing users to perform a wide range of movements with increased precision and control. The utilization of muscle signals provides a more natural and intuitive limb movement experience. Additionally, myoelectric powered prosthetics offer versatility, as they can control multiple joints and grip patterns, enabling users to adapt to various activities and environments. The realistic appearance and functional capabilities of myoelectric powered prosthetics can also have positive psychological effects, improving self-esteem, body image, and social integration for individuals with limb loss.

2.2.3. *Human Hand Anatomy and grip patterns:*

In this section we will be looking further at the human hand anatomy and bone structure while also highlighting some of its functionalities and grip patterns.

2.2.3.1. Anatomy:

The human hand is widely recognized as one of the most intricate and multifaceted mechanisms in nature. Comprising 27 bones and possessing over 20 degrees of freedom (DOFs), it enables a wide range of dexterous movements and precise manipulations.

These DOFs are governed by a complex system of tendons and ligaments, which act as actuators and limiters.

The control of hand movements is orchestrated by the human brain through the integration of the nervous system. This intricate network allows for almost instantaneous and highly efficient communication between the brain and the hand [1]. The brain sends signals through the motor cortex, which are then transmitted via the spinal cord to the peripheral nerves that innervate the muscles and tendons of the hand [7]. This neural control system enables precise and coordinated movements, facilitating activities ranging from delicate object manipulation to robust gripping.

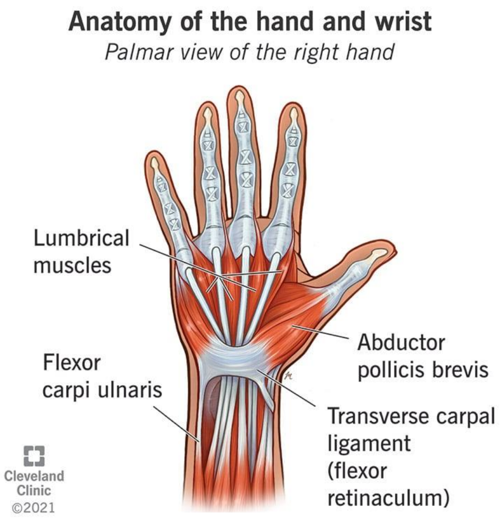

Figure 12 Human Hand anatomy

The efficiency and speed of this neural control system have been the subject of extensive research. Studies have shown that the human brain can rapidly adapt and optimize motor commands to achieve accurate and efficient hand movements [6]. The integration of sensory feedback from the hand, such as proprioception and tactile information, further enhances the precision and effectiveness of the control system [5].

2.2.3.2. Bone Structure:

Taking one step deeper to sub muscular level that the human hand is a remarkable example of intricate bone structure that enables its remarkable functionality. Comprising 27 bones, the hand is divided into three main regions: the carpal bones in the wrist, the metacarpal bones in the palm, and the phalanges in the fingers.

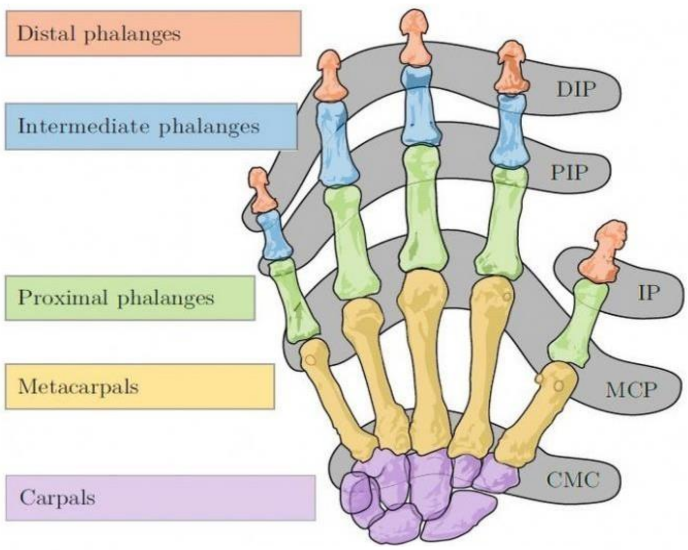

Figure 13 Joints and bones of the Human Hand

- The carpal bones, eight in total, form the wrist and provide stability and flexibility to the hand. These bones are arranged in two rows, with the proximal row consisting of the scaphoid, lunate, triquetrum, and pisiform bones, and the distal row consisting of the trapezium, trapezoid, capitate, and hamate bones.
- The metacarpal bones, five in number, extend from the wrist to the base of the fingers. These bones are long and cylindrical, with a slight curvature, and are numbered from the thumb (first metacarpal) to the little finger (fifth metacarpal). The metacarpals provide support and stability to the palm, allowing for grip strength and fine motor control.
- The phalanges, the smallest bones in the hand, make up the fingers. Each finger (excluding the thumb) consists of three phalanges: the proximal phalanx, the middle phalanx, and the distal phalanx. The thumb has two phalanges: the proximal and distal phalanges. The phalanges are connected by joints, allowing for the flexion and extension of the fingers, as well as enabling a wide range of movements, such as grasping, manipulating objects, and performing intricate tasks.

2.2.3.3. Human hand grip patterns:

The human hand, as the complex machine that it is, can perform a large number of different grasps during different daily living activities or more specific ones, for example related to specific configurations during sport or grasps that require greater precision, for example when handling hazardous materials.

The AHAP is the Anthropomorphic Hand Assessment Protocol which is a tool that provides a measure for quantifying the grasping abilityof artificial hands and allows to compare different hand designs. The AHAP uses 25 different objects from the Yale-CMU-Berkeley Object and Model Set (YCB set)], and it involves grasping with 8 of the most relevant human grasps and 2 non-grasping postures. Figure 14 shows the YCB set of objects.

The grasping ability and the comparison between different hands is made thanks to the Grasping Ability Score (GAS), which is a numerical score based on the performance of the

Figure 14 YCB objects set.

hand prototype throughout the different tasks. This benchmark allows us to demonstrate improvements to newer designs with respect to previous ones.

The different grasps that are performed during the AHAP are the following ones:

- Hook (H) Figure 15 (a)
- Spherical grip (SG) Figure 15 (b)
- Tripod pinch (TP) Figure 15 (c)
- Extension grip (EG) Figure 15 (d)
- Cylindrical grip (CG) Figure 15 (e)
- Diagonal volar grip (DVG) Figure 15 (f)
- Lateral pinch (LP) Figure 15 (g)
- Pulp pinch (PP) Figure 15 (h)

Additionally, as mentioned before, there are 2 non-grasping postures which are also assessed:

- Index pointing/pressing (IP) Figure 15 (i)
- Platform (P) Figure 15 (j)

a

b

c

d

e

f

g

h

Figure 15 Human hand common grasps

i

j

Comparing these Grip patterns with the 14 grip patterns offered by the Bebionic model shows how much different modes or poses a human hand can really take to perform numerous tasks without you even realizing and also goes to show how far the prosthetic field has come in order to ease the performance of daily tasks to people with amputations or disabilities. The main patterns offered by the bebionic model are:

Active Index Grip

Column Grip

Finger Adduction

Finger Point

Hook Grip

Key Grip

Mouse Grip

Open Palm

Pinch Grip

Power Grip

Precision Closed Grip

Precision Opened Grip

Relaxed

Tripod

Figure 16 BeBionic Grip patterns

2.2.4. Amputations:

In this section we will be discussing Different amputation types, causes, and Phantom pain:

2.2.4.1. Amputation types

Upper limb amputation is a medical intervention that can be necessitated by various factors, including cancer, trauma, fractures, and malformations. The level at which the amputation is performed directly affects an individual's ability to perform different actions and tasks, as well as the type of medical assistance required.

Amputations are classified based on the specific location where they occur along the upper limb. These classifications include trans phalangeal amputation (at the level of the fingers), trans metacarpal amputation (at the level of the metacarpal bones), trans carpal amputation (at the level of the carpal bones), wrist disarticulation (at the wrist joint), trans radial amputation (at the level of the forearm), elbow disarticulation (at the elbow joint), trans humeral amputation (at the level of the upper arm), shoulder disarticulation (at the shoulder joint), and forequarter (interscapulothoracic) amputation.

To provide visual clarity, Figure 17 illustrates the different levels of upper limb amputations and their corresponding names based on the specific part of the extremity where they occur.

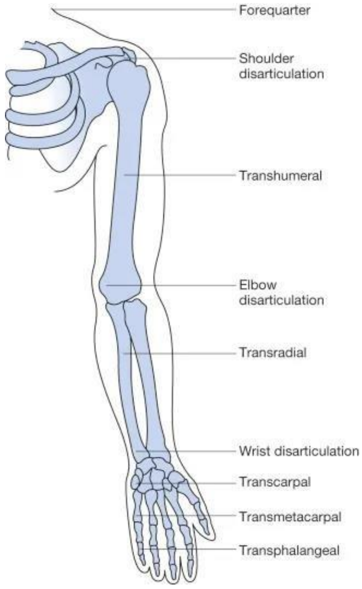

Figure 17 Amputation levels and names

2.2.4.2. Causes:

Amputations can occur due to various factors, but some of the most common causes include:

1. Traumatic Injuries: Severe accidents, such as car crashes, industrial mishaps, or combat-related injuries, can lead to the loss of a limb.
2. Vascular Disease: Conditions like peripheral artery disease (PAD) or diabetes can result in poor blood circulation, leading to tissue damage and the need for amputation.
3. Cancer: In some cases, the removal of a malignant tumor may require amputation to prevent the spread of cancer cells.
4. Infections: Severe infections, particularly those that affect the bones and tissues, may necessitate amputation as a life-saving measure.

5. Congenital Defects: Some individuals are born with limb abnormalities or structural deformities that may require surgical removal.
6. Severe Burns: Extensive burns that cause irreparable damage to the affected limb may require amputation.

2.1.4.3. Phantom Pain:

Amputation of the upper limb can have significant emotional, psychological, and functional consequences for individuals. One of the notable consequences is the occurrence of phantom pain, characterized by the perception of pain originating from the missing limb. Initially, researchers believed phantom pain to be a solely psychological condition. However, subsequent investigations have revealed that this pain is indeed real and originates from alterations in the spinal cord and brain pathways involved in pain processing. These findings highlight the complex nature of phantom pain and its physiological underpinnings, emphasizing the need for comprehensive approaches in managing and treating this condition.

Some experiments carried out with hand prostheses demonstrated that the embodimentof these artificial hands could help to reduce the phantom pain.

2.2.5. *Different popular Prosthesis models comparison:*

Table 1 Popular prosthesis models comparison

Model	**Miquelangelo**	**i-Limb**	**Be Bionic**	**Sensor Hand**	**Vincent Hand**
Characteristic					
Developer	Otto Bock	Touch Bionics	Otto Bock	Otto-Bock	Vincent Systems
Weight, gr	510	599	500	500	410
Operating voltage, V	11.1	7.4	7.4		6–8
Battery type	li-ion	Lithium polymer	li-ion		li-Pol
Battery, mAh	1500	1300–2400	1300–2200		1300–2600
N° Actuators	2	6	5	1	6
Type of actuators		DC motor with worm gear	DC motor head screw	DC motor	DC motor worm gear
Active fingers	3	5	5	2	5

Model	Miquelangelo	i-Limb	Be Bionic	Sensor Hand	Vincent Hand
Characteristic					
Force, N	70	100	140	100	60
Movement control	EMG, 4channels	Mobile app, EMG	Sequential EMG	EMG	Single trigger EMG
Movement command	Switching	Double and triple impulse	Co-contractions		Switch signal Co-contractions Double impulse
Feedback	NO	NO	Audible bip vibrations	NO	Vibrations

2.3. Actuation:

2.3.1. Under actuation

Advancements in prosthetic component research have propelled the development of sophisticated mechanisms that aim to replicate a diverse range of grasping and hand movements akin to those exhibited by natural human hands. The realm of anthropomorphic artificial hands can be classified into two primary categories: fully actuated hands and underactuated hands. While the human hand boasts around 23 to 25 degrees of freedom (DOFs) in its kinematic chain, fully actuated artificial hands require a substantial number of actuators to emulate these intricate movements. These actuators can be positioned within the hand or on the forearm, facilitating independent finger flexion and thumb motion. The incorporation of such actuation capabilities opens up a multitude of possibilities for various gripping techniques and precise control. Nevertheless, it is worth noting that fully actuated hands come with a complex control interface and tend to be heavier compared to their underactuated counterparts. For example, the Shadow Dexterous Hand (depicted in figure 18) encompasses 20 motors, rendering it more comprehensive in terms of functionality but also more intricate in its configuration.

Figure 18 Shadow Dexterous Hand

On the other hand, underactuated prototypes offer distinct advantages in terms of space, weight, and cost reduction by minimizing the number of components required. The fundamental principle behind underactuation is to achieve a high degree of freedom (DOFs) with fewer actuators. For instance, instead of employing six motors to control the flexion of five fingers and the abduction/adduction of the thumb, certain prototypes utilize a single motor for finger flexion and another for thumb movement, or even incorporate manual mechanisms.

Ongoing research is centered around the exploration of differential mechanisms to develop efficient underactuated systems and enhance their designs. These mechanisms enable force adaptation and distribution across multiple fingers, accommodating various finger positions. The systems are engineered to evenly distribute forces on both sides of the mechanism, enabling it to rotate and continue exerting force even if one of the moment arms is obstructed. This adaptation is rooted in the diverse array of grasps that both human and prosthetic hands can perform, as elucidated in previous sections of the AHAP (Anthropomorphic Hand Analysis and Performance).Advancements in prosthetic component research have propelled the development of sophisticated mechanisms that aim to replicate a diverse range of grasping and hand movements akin to those exhibited by natural human hands. The realm of anthropomorphic artificial hands can be classified into two primary categories: fully actuated hands and underactuated hands. While the human hand boasts around 23 to 25 degrees of freedom (DOFs) in its kinematic chain, fully actuated artificial hands require a substantial number of actuators to emulate these intricate movements. These actuators can be positioned within the hand or on the forearm, facilitating independent finger flexion and thumb motion. The incorporation of such actuation capabilities opens up a multitude of possibilities for various gripping techniques and precise control. Nevertheless, it

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There are different types of mechanisms that allow differential under actuation which are based on the following principles:

- Pulleys and tendon system (a)
- Whiffletree mechanisms (b)
- Gear differentials (c).

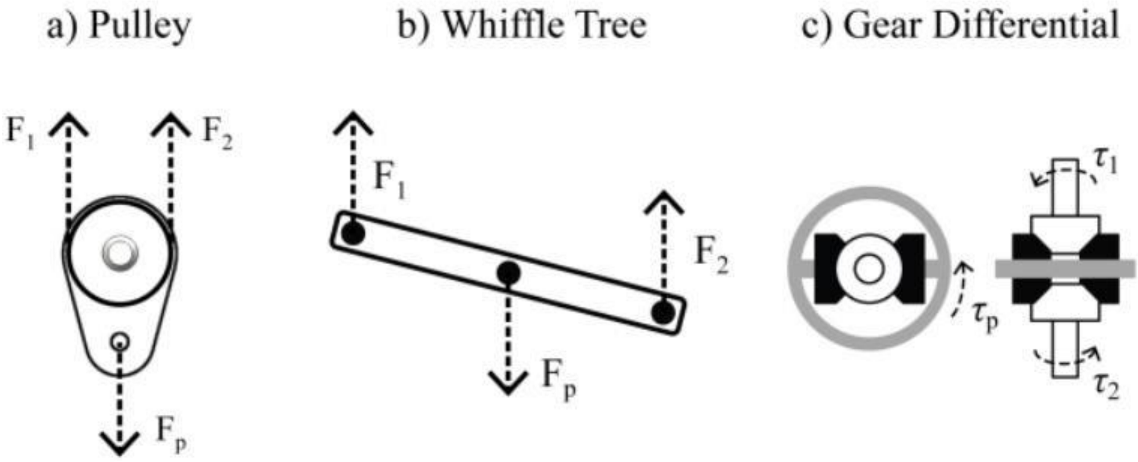
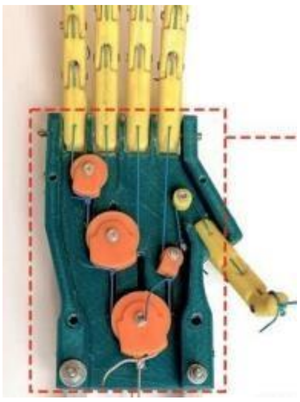


Figure 19 Differential under actuation systems

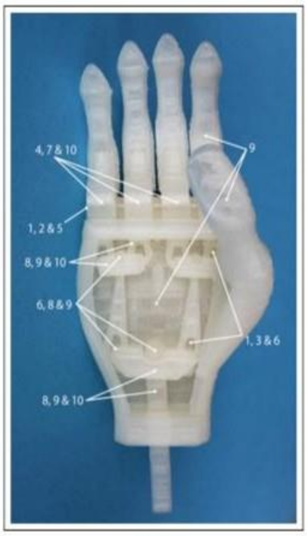
An implementation of these mechanisms using different differential under actuation is shown in the following models:

- (a) shows a pulleys system made out of 3D printed material.
- (b) shows a whiffletree mechanism made out with linkages and withno need of assembly after printing the prototype
- (c) shows a whiffletree mechanism working with tendons and pivots.

(a) Esposito pulleys system



(b) Whiffletree mechanisms with linkages



(c) Whiffletree mechanism with cords

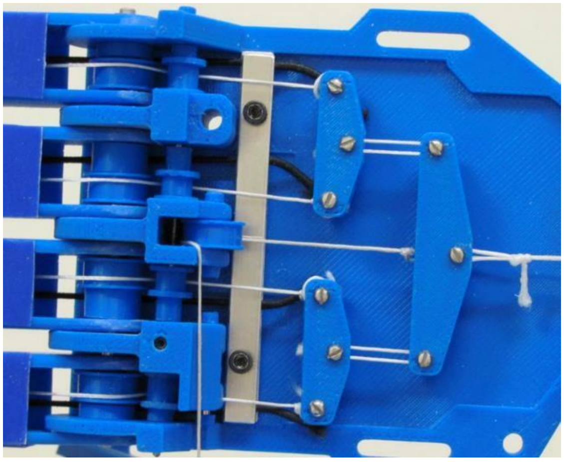


Figure 20 Different under actuation mechanisms

Within the existing literature, various designs have been proposed that leverage the functionality of the aforementioned mechanisms by combining them synergistically to achieve an optimal solution. Typically, a popular combination involves integrating the whiffletree mechanism with a pulley system, as depicted in Figure 21. This amalgamation allows for the utilization of the respective advantages offered by both mechanisms. For instance, it enables the distribution of forces characteristic of the whiffletree mechanism while simultaneously capitalizing on the friction reduction facilitated by the incorporation of pulleys. Additionally, there are alternative mechanisms, such as the modular system showcased in Figure 22, which amalgamate sliders, pulleys, and pivots to uphold the same underlying principle.

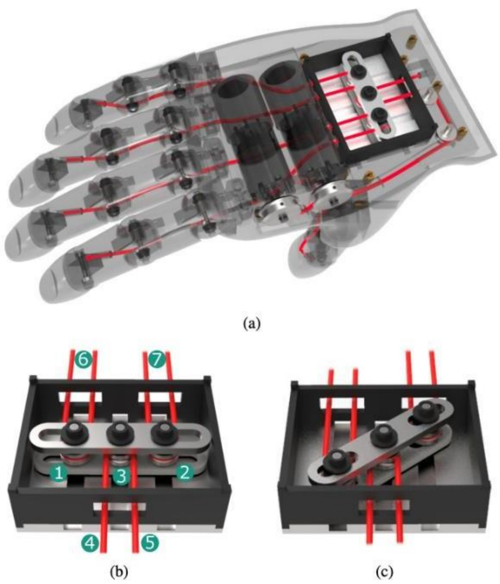


Figure 21 Pulleys and slider mechanism

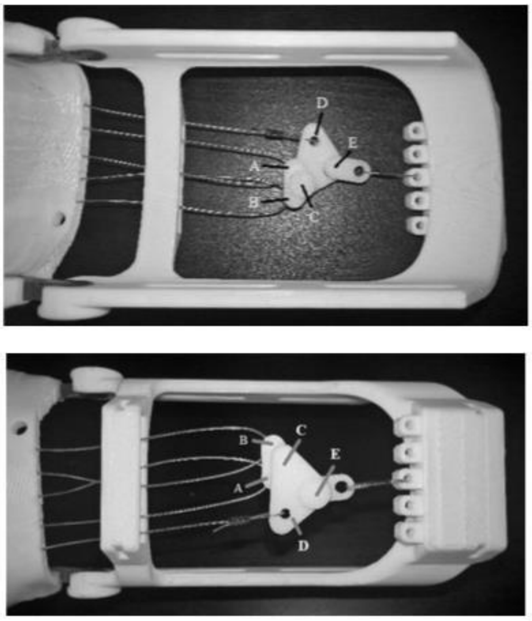


Figure 22 Modular System

2.3.2. Finger under actuation

The concept of under actuation extends beyond the entire hand and encompasses each individual finger within it. Each finger can possess its own underactuated nature, achieved by utilizing a single cable as a tendon to actuate the degrees of freedom (DOFs) of its various joints.

In this specific scenario, the under actuation of each finger revolves around employing a single cable to induce flexion in both the proximal and distal phalanges that constitute the finger.

The primary objective of finger under actuation aligns with the broader goals of under actuation in general, which is to achieve a configuration with fewer actuators than DOFs. This reduction in the number of actuators can be accomplished through mechanisms such as pulleys or links that facilitate pulling and the use of springs to restore the phalanx to its resting position.

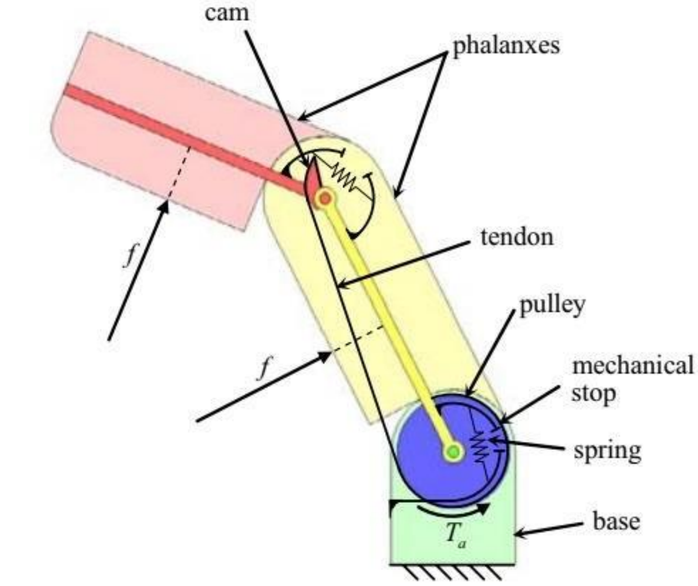


Figure 23Under Actuated finger schematic

2.3.3. Hand under actuation

When considering hand under actuation, the objective is to maximize the number of degrees of freedom (DOFs) while minimizing the required actuators, as previously discussed in the broader context of under actuation. This entails utilizing a single mechanical or electric actuator, such as a motor or pulling system, to facilitate movement across multiple fingers. Various mechanical systems, including the utilization of links as previously mentioned, can be employed to achieve this goal. Figure 24 exemplifies a professional illustration showcasing motor-activated tendon actuation with four degrees-of-actuation (DOAs).

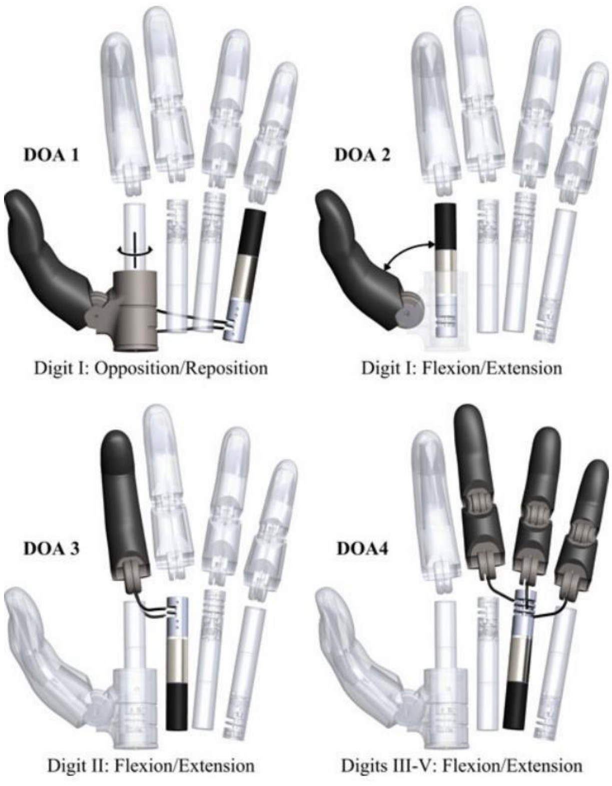


Figure 24 Underactuated hand with 4 DOFs

3. Chapter 3: Groundwork

3.1. Guideline and production plan:

The project is executed in adherence to the stringent quality standards set by our Supervisors in the Mechatronics Department Faculty of engineering Ain Shams University, as well as the V model of the VDI 2206 Guideline for the design of mechatronic systems, ensuring optimal performance and compliance with industry best practices.

The V Model:

Throughout The development of the product, we will be following these stages to assure a systematic framework for managing the entire product lifecycle, from concept and design to testing, assurance of properties, And production.

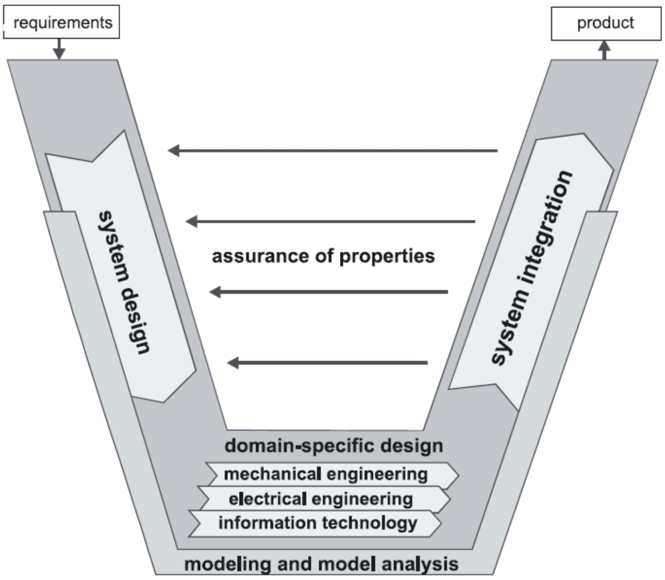


Figure 25 V Model VDI 2206

- Requirements:
  To develop a prosthesis that is both smart and cheap while maintaining the quality of performance
- System Design:
  The Product is to mimic the functionality of the human hand in motion and grips while keeping a human hand aesthetic. Also, it needs to be portable and electrically operated via batteries so that it's portable and not wired for portability.
- Domain specific design:
  The design and implementation of each field of engineering for the product will be carried out in detail separately, each in its concerned domain.
- System integration:
  The assembly process of the subassemblies of systems mechanically and electrically into the whole system within the requirements criteria
- Assurance of properties:
  Each Design process is constantly checked and evaluated to verify and validate the meeting of requirements for the product.
- Modeling and model analysis:
  The described phases are flanked by the modelling and analysis of the system characteristics with the aid of models and computer-aided tools for simulation.

3.2. Requirements:

3.2.1. Objective*:*

The Goal of this project is to Design and manufacture a prosthesis utilizing linkages and mechanisms to be able to perform various ranges of motion for a 5 DOF prosthetic that is both effective and cost efficient.

- The prosthesis is to be visually appropriate and of matching proportions to that of a real human hand.
- The material of the prosthesis hand should be durable and resistant to climate effects (Does not melt in the heat or dissolve under rainwater etc...)
- The product is to have 5 Actuators each to a single DOF for the hand while other joints are to be actuated by links connecting it to the original motor-actuated joint.
- The thumb must be able to change orientation to mimic the human thumb opposition and reposition.
- Having a 5 DOF type of prosthesis in its nature creates an objectively "light" prosthetic, another objective of the project is to maintain that lightness in weight and not overload the prosthetic with heavy mechanisms and materials as to not discomfort the patient.
- The product should also be developed and assembled in such a way that it can be easily disassembled for maintenance purposes.
- The product should be made of readily available material and maintain a "low cost" type approach without sacrificing any of its functionality or performance.
- The product should be operated without external wires and have an internal battery to run its motors and controller.
- The product is to maintain the safety of the user when using and is to have protection circuits integrated to prevent any electrical hazards and also protect the components.
- The product is to have an embedded micro controller system to allow the control of the different motion patterns precisely and effectively depending on the desired task by the user.

3.2.2. Approach:

In order to create a product that meets the conditions mentioned in the previous section, first we have to Address each point individually.

In each point a brainstorm of solutions has been proposed by team members that fulfill that given point and then we worked on eliminating the solutions that contradict with other objectives.

Also, we had to identify the tools and software we were going to use in order to develop and model this product.

3.3. System Design:

The main elements of the overall system design will be described briefly in the following section and in more details later on:

- *Prosthesis initial visualization:*
  The decision was made so that our prosthesis is to match the human hand as closely as possible. Having the outer look to be that of a palm and normal human fingers while inside each finger will be links that are responsible to transfer motion from the actuated joint to other joints to reduce the DOFs and actuator numbers in the hand. A good inspiration for visualization for that was the bebionic hand model from otto-bock.
- *Manufacturing technique:*
  Since the product consists of many small parts with very specific measurements for the many fixations and connections between members, we decided to move away from traditional manufacturing technologies and utilize 3D Printing technology specifically using the Fused deposition modeling (FDM) 3D printer provided by the faculty.
- *Material used:*
  To fulfill both the conditions of having relatively light weight and being durable and weather resistant, -considering the use of 3D technology- we decided to use ABS (acrylonitrile butadiene styrene) as the core material for the printing process for the various parts.
  Some of its main features are Toughness and durability and Heat and impact resistance.
  Further Technical details about ABS[I] can be found in the appendix (Technical Details and datasheets section 8.6.).
- *Actuators:*
  For accurate Position control and generating proper torque and speed at fingers, the "FAULHABER DC 6V MiniMotor 1524E006S123 GEAR 15/5 141:1" Was chosen. Also, an encoder "HE S164A KW06/99" was used as well for the mentioned position control and feedback for the closed loop control system.
  Further Technical details about the motor[II] and encoder[III] can be found in the appendix.

Figure 26 FAULHABER DC 6V MiniMotor 1524E006S123

- *Thumb Movement:*
  To be able to perform opposition and reposition of thumb, TowerPro SG90 Servomotor[IV] will be used at the bottom of the palm to rotate the thumb. More details about the motor can be found in the appendix.
- *Motor Drivers*
  a motor driver is required to interface between the microcontroller and the motors, a **L298N**[V] IC was chosen, factors that encouraged this decision was availability and low cost and decent performance.
  More details about the driver can be found in the appendix.

- *Software to use for development:*
  Mechanical design and modeling we will use:
  - Inventor CAD for designing parts and assembly and stress analysis.
  - SOLIDWORKS will be used as an alternative for Inventor CAD for some tasks that are difficult to perform such as motion simulation.
  - SAM For the simulation of link systems
  - Idea maker For FDM 3D Printer software control

  Electrical Design and modeling we will use:
  - "Eagle" For electrical schematic simulation and PCB Design layout and assure no design failures.

  Control-related software we will use:
  - Arduino IDE for writing the code to control the STM board, this can be realized by installing the appropriate libraries.
  - Arduino IDE code for PID control
- *Motion transmission:*
  This will be divided into 3 subsections:
  - Motor to Lead screw[VI]:
    The motor shaft will be coupled to a spur gear unit that transmits the motor rotation to the lead screw with a 1:1 ratio.
  - Lead screw to guide nut fixed on member linked to the base joint:
    The lead screw rotations transmit motion to the guide nut vertically, and in turn pushes or pulls the member at the base joint of the finger which translates to either extension or retraction of the finger depending on the rotation direction.
  - Base joint to other joints:
    A link system to make other joints retract when the base joint is actuated to retract and a spring to restore the follower joints to their original position when the extension action is performed.
- *Power Screw supports:*
  4 Bearing[VII] to be used in each finger to support the power screws to allow free rotation independent of cover surface, their types will be ball bearings for radial support.
- *Assembly:*
  All components are to be assembled via positive connections using pins or bolts & nuts[VIII], no permanents fixation is to be used like welding or super glue or any other type of irreversible assembling techniques that would damage the prosthetic parts.
- *Electrical Circuit:*
  A PCB is to be built within the wrist of the prosthetic that contains the main power distribution components & filtering circuits as well as the microcontroller circuit.
- *Power source:*
  The Main power source of the product is to be batteries and no wires are to be connected from any outlet or power source that is external to the prosthetic. 2 9 Volt DC[IX] batteries are to be used, one for the sensor and the other to operate the motors. More details about the battery can be found in the appendix.

- *Microcontroller:*
  The microcontroller is to be an STM32^{X} Development Board with a STM32F401CC (The Black Pill) Model. Some of its primary features that encouraged us for this choice are:
    - 84 MHz max CPU frequency
    - Voltage from 1.7 V to 3.6 V
    - 256 KB Flash
    - 64 KB SRAM

  Also, this decision was made with availability and cost consideration and the model is not mandatory to be used in similar products.
  More technical details about the model can be found in the appendix.

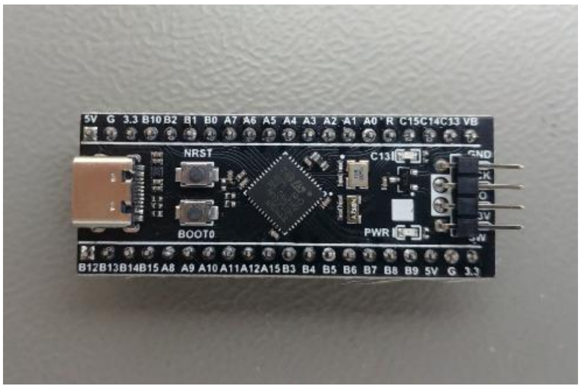


Figure 27 STM32F401CC

4. Chapter 4: Domain specific design

4.1. Mechanical Engineering

4.1.1. Finger Design

A key element in the design of our anthropomorphic prosthetic hand was the development of five human-like fingers. To maintain an anthropomorphic appearance, the fingers had to not only look human, but also move naturally and humanly. After carefully observing the movement of the hand, using everyday object-grabbing methods and anatomical restraints, we highlighted a common curling motion that allowed fingers to tightly close around objects of various sizes and shapes. The challenge, however, was to design a mechanism that replicated this movement and fit into a housing no larger than the average man's finger. We also needed a tough design that could withstand the rigors of everyday use. Before doing any major design work, we explored several options for achieving the desired finger movements. Based on our own considerations and some preliminary research, we have developed two possible methods. The first method is Fixed to finger segments and tips. The cable is routed so that it curls when one of his fingers is pulled. This is similar to how muscles and tendons operate in a natural finger. The second method used a series of inverted four-node linkages embedded in the finger Segment itself to create the same curling method. Below is a table of the pros and cons we have Discovered for each method.

Table 2 Cable Vs Linkage System comparison

Cable system	Linkage system
Pros: • Fewer necessary moving parts • Simpler design • Fewer Materials • Low Cost Cons: • Cable can stretch over time • Routing may be difficult • Possibly more friction	Pros: • Low friction • Rigid bodies will not stretch • More accurate position control • Simple design Cons: •Lots of moving parts allows for more points of failure •Could take a while to find the ideal link length •Link length will differ in every finger

After considering each option, The Decision was made to use a hybrid system using both the linkage system and the cable system.

After settling on what system would be used, The Design of fingers was divided into 3 stages.

- Mechanism Design

  Divided into 2 subsections, 1) Lead Screw Cable Tension Mechanism 2) Linkage System

  1) Lead Screw Cable Tension Mechanism:

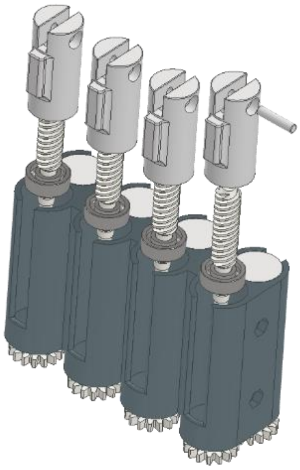


Figure 28 Lead Screw Guide Nut Tension Mechanism

A Cable is passed and rotated around the pin that passes through the guide nut housing from one end and at the proximal phalange of the finger from the other end, When the motor rotates, it transmits motion to the lead screw via gearbox then the lead screw transmits the motion to the guide nut and guide nut housing, pulling the cable down and in turn rotating the proximal phalange downwards

2) Linkage System
   Inspired from four bar mechanisms, when the proximal phalange is rotated, a link that connects the Proximal phalange with the upper phalange is also rotated, that generates a dependent degree of freedom in the upper phalange that follows the motion of the Proximal Phalange

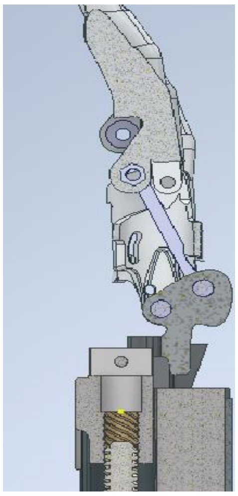


Figure 29 Unrotated link, upper phalange straight

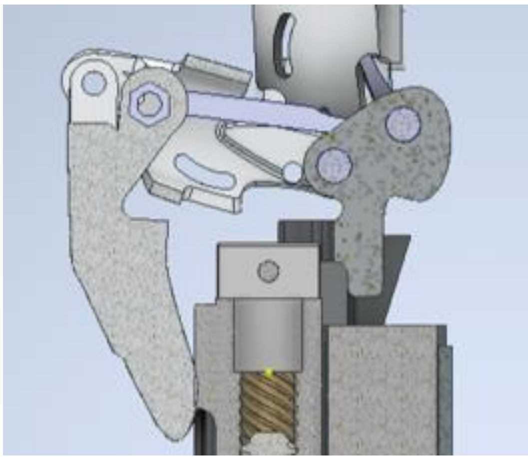


Figure 30 Rotated link, upper phalange rotated

- Finger Design

  Finger is to consist of 3 Components,

  - Proximal Phalange:

    Area that is subject to the tension force and acts as the base of the finger, connected to rotation pins that act as rotation axis.

  - Links:

    Transmit motion from Proximal phalange to upper phalange and creates a dependent degree of freedom.

  - Upper phalange:

    The follower body that rotates when the Proximal Phalange rotates, consists of intermediate and distal phalange designed as one part. Completes the human hand aesthetic design.

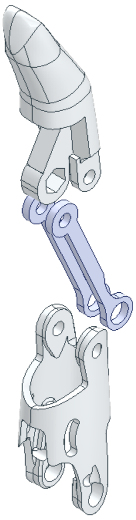


Figure 31 Finger Design (Upper Phalange - Links - Proximal Phalange)

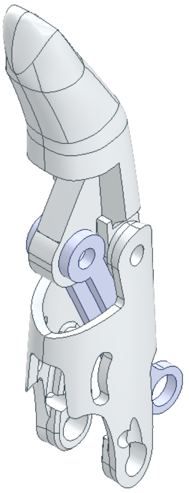


Figure 32 Finger Assembly

- **Simulation and Validation**
  - **<u>4-bar mechanism</u>**

A four-bar mechanism is a mechanical linkage consisting of four rigid bars connected by pivot joints. These mechanisms are widely used in engineering and machinery to convert rotary motion into linear motion or vice versa. The four bars are typically referred to as "cranks" and "rocker arms," and they are connected in such a way that they can transmit motion and force effectively.

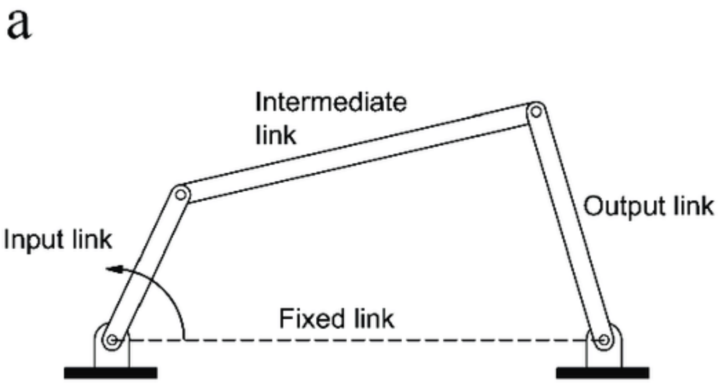


Figure 33 4-Bar mechanism demonstration

Here's a basic explanation of how a four-bar mechanism works:

1) **<u>Components:</u>** A four-bar mechanism consists of four bars or links, each of which is connected to the others through pivot joints or hinges. These bars are often labeled as follows:

- **Input Crank (Link 1):** The bar that receives the initial rotary motion.

- **Coupler Link (Link 2):** The bar connected to both the input crank and the output rocker arm.

- **Output Rocker Arm (Link 3):** The bar that is responsible for the final motion or output.

- **Fixed Ground Link (Link 4):** A stationary bar, often used as a base to which other links are attached.

2) **<u>Pivot Joints:</u>** The pivot joints, also known as revolute joints or hinges, allow the bars to rotate relative to each other. These joints are the key to the mechanism's ability to transmit motion.

The design and analysis of four-bar mechanisms involve mathematical principles, including kinematics, dynamics, and geometry, to determine the desired motion and forces at different points within the mechanism. Engineers use software tools and simulations to optimize these mechanisms for specific applications, ensuring they perform their intended functions efficiently and accurately.

- **<u>Implementation in design</u>**

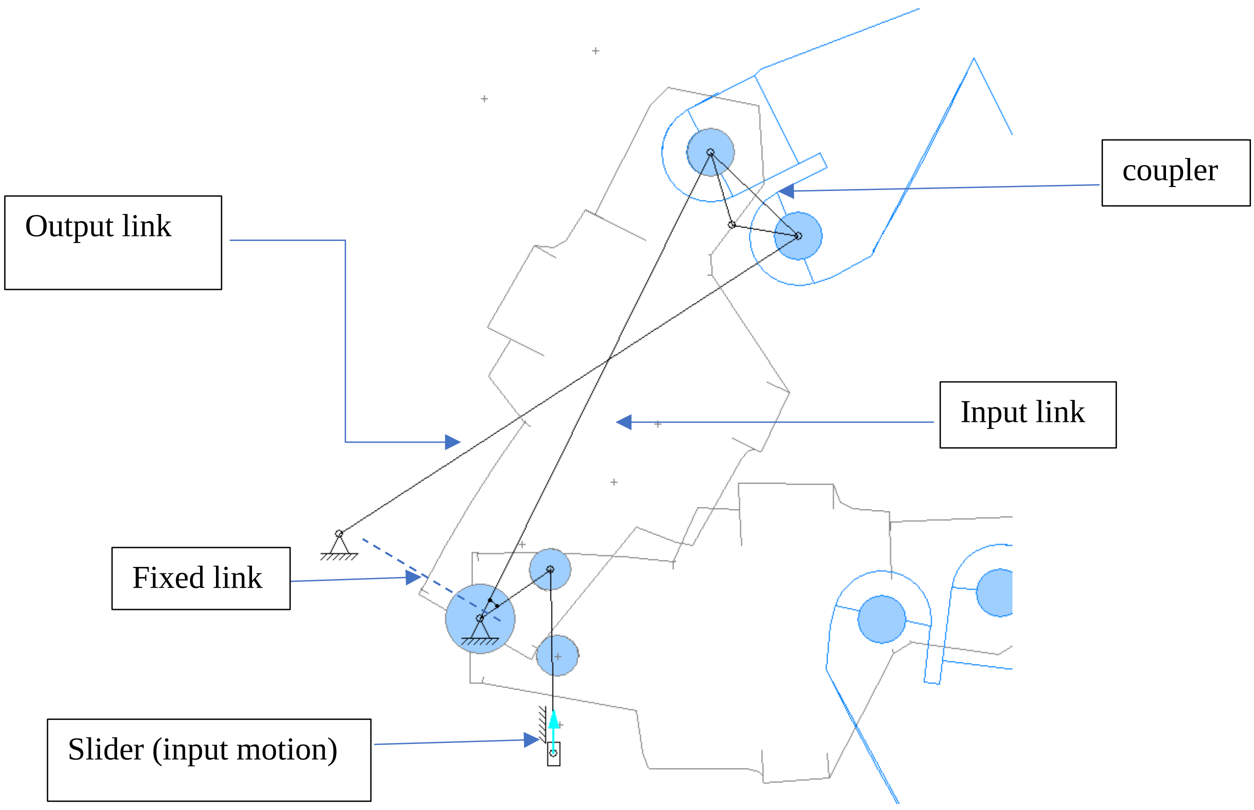


Figure 34 SAM Simulation Components

The four elements of the 4-bar mechanism are presented in the above figure as well as the input motion which is the motion of the guide nut in the power screw mechanism this motion is represented here by the slider as the guide nut moves only in y-direction this motion control the whole mechanism as it transfer the motion on the motor to the mechanism input link.

To imagine how this mechanism is going to work a simulation software program (SAM the ultimate mechanism designer) is used to simulate the motion of the finger and will help us to determine the required input motion we need in the y-axis for the finger to be fully closed.

- **<u>Software Simulation</u>**

What is Sam?

SAM (Simulation and Analysis of Mechanisms) is an interactive PC-software package for the motion and force analysis of arbitrary planar mechanisms, which can be assembled from basic components including beams, sliders, gears, belts, springs, dampers and friction elements.

How is the simulation built?

- draw Initial design of the finger segments on inventor.

- Export a 2D sketch in the format of DXF of the finger side face marking the point of the joints from inventor.

- Importing these DXF files in SAM software.

- Aligning and joining the finger segments to draw the start and the required end position of the finger.

- Start building the 4-bar mechanism relative to the start position.

- Attach the joints and links of the mechanism with its corresponding segments and joints of the DXF drawings.

- Drawing and attaching a slider that represents the motion of the guide nut to the mechanism.

- Defining the input motion to the mechanism in our case is the slider.

- Define the output data to be presented on a graph in our case (the motion of the slider in y direction, the angel rotated by the proximal phalange)

- Run the simulation.

- Observing the output and changing the slider and fixed nodes position till we reach the optimal position (the least distance travelled by the slider that gives us the largest angle the proximal phalange rotates)

To validate and verify the finger design, the following simulation was built on SAM Software and the following results were obtained and is to be further validated in control phase:

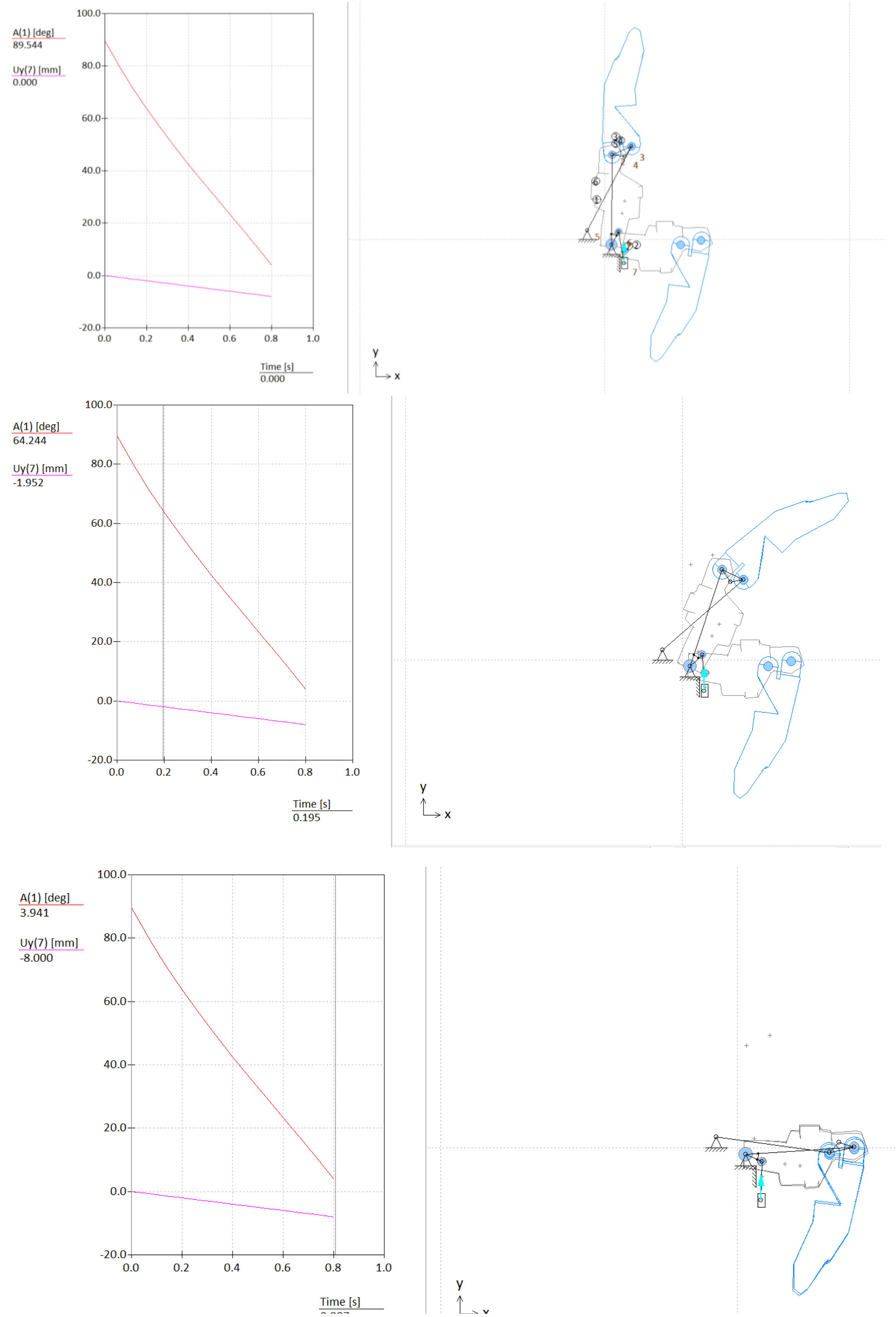


Figure 35 SAM Finger Simulation (From Rest to Curl)

The previous figures show the motion of the finger in steps from its upper extreme position to its lower extreme position. We can say that this motion checks the box where the motion of the finger looks natural like a human hand movement.

On the left side of the photo, we will notice a graph that represents the relation between two lines.

First the purple line: it represents how long the slider have to move down the y-axis for the finger to be fully closed and it moved down throw the range by a distance nearly equal to 8 mm which is accepted for us as 8 mm is a small distance for the guide nut to move along the power screw as it won't be necessary to build a long lead screw that might take a large space inside the hand palm thus making the overall dimensions of the hand bigger and inconvenient.

Second the red line: the red curve represents the motion of the first segment of the finger (proximal phalange) in degrees which we can see here that the finger rotates by an angle of nearly 90 degree which what a normal human hand proximal phalange will rotate for the hand to be fully closed.

We can also export this relation from the SAM software as a numerical value in the form of a table for better illustration and to ease the design process.

Table 3 SAM Simulation Results

Nr	Time	A(1)	Uy(7)
[-]	[s]	[deg]	[mm]
0	0.000	89.544	0.000
1	0.067	80.143	-0.667
2	0.133	71.587	-1.333
3	0.200	63.679	-2.000
4	0.267	56.276	-2.667
5	0.333	49.263	-3.333
6	0.400	42.546	-4.000
7	0.467	36.044	-4.667
8	0.533	29.678	-5.333
9	0.600	23.376	-6.000
10	0.667	17.054	-6.667
11	0.733	10.618	-7.333
12	0.800	3.941	-8.000
13	0.800	3.941	-8.000
14	0.800	3.941	-8.000
15	0.800	3.941	-8.000

To wrap it all up

Simulation helped us to imagine how the four-bar mechanism will operate and move the finger naturally and helped us to achieve the minimum required distance the guide nut has to move for the finger to be fully closed thus helped us to decrease the overall dimensions of the lead screw that helped us to decrease the overall dimensions of the hand.

❖ Spring Calculations

Spring Calculations were performed with the Aid of inventor Design accelerator environment

The minimum and maximum force affecting spring was assumed to be 150 Newton (Generated by the motor) and 208 N (External carried load), The following results came back with no errors.

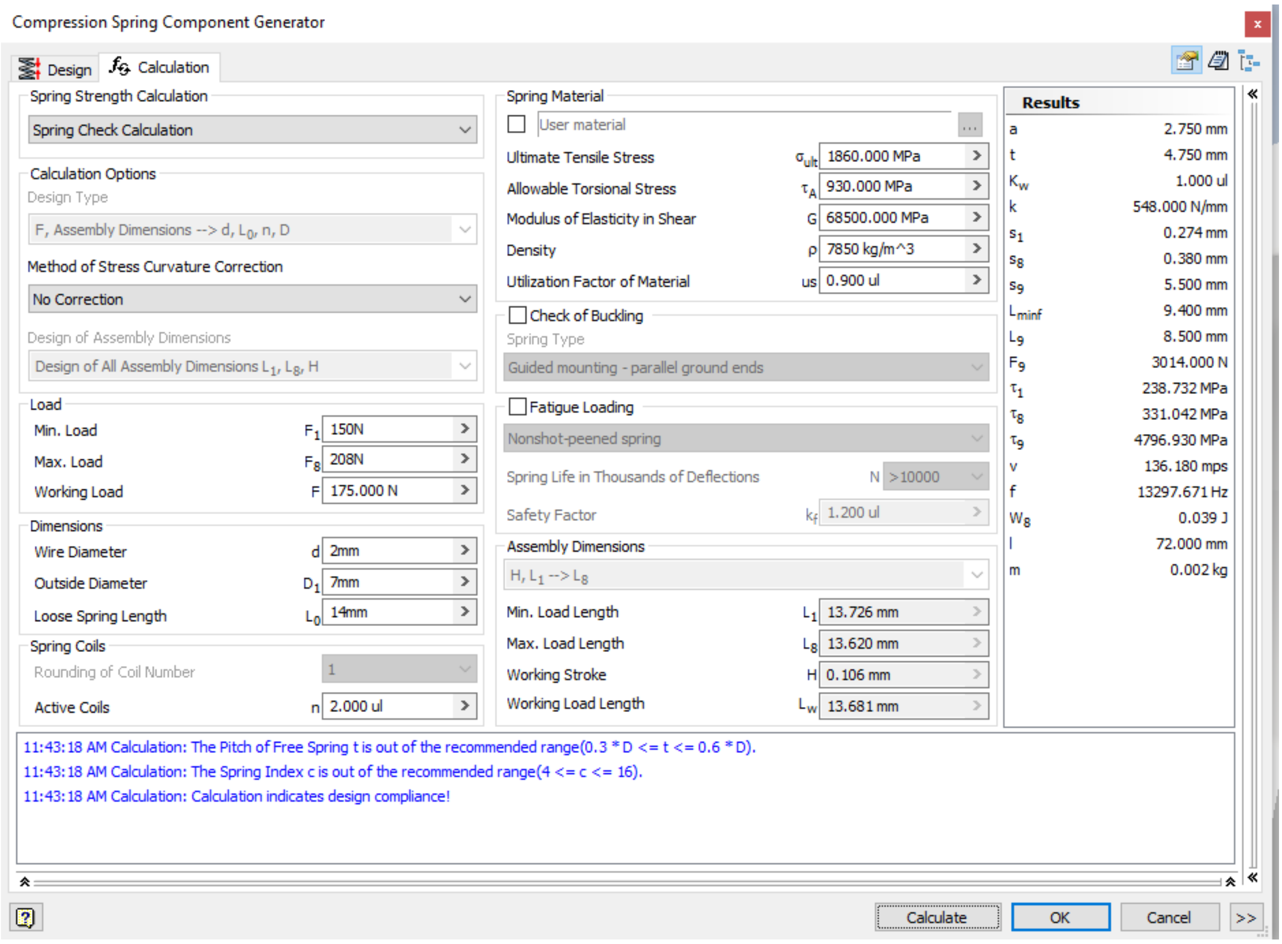


Figure 36 Spring Calculations

❖ Bearings Calculations

Bearing selection was based on and checked by the results from the simulation from Inventor CAD, Force and speed were input into the design calculator and the validation of design was assured by software.

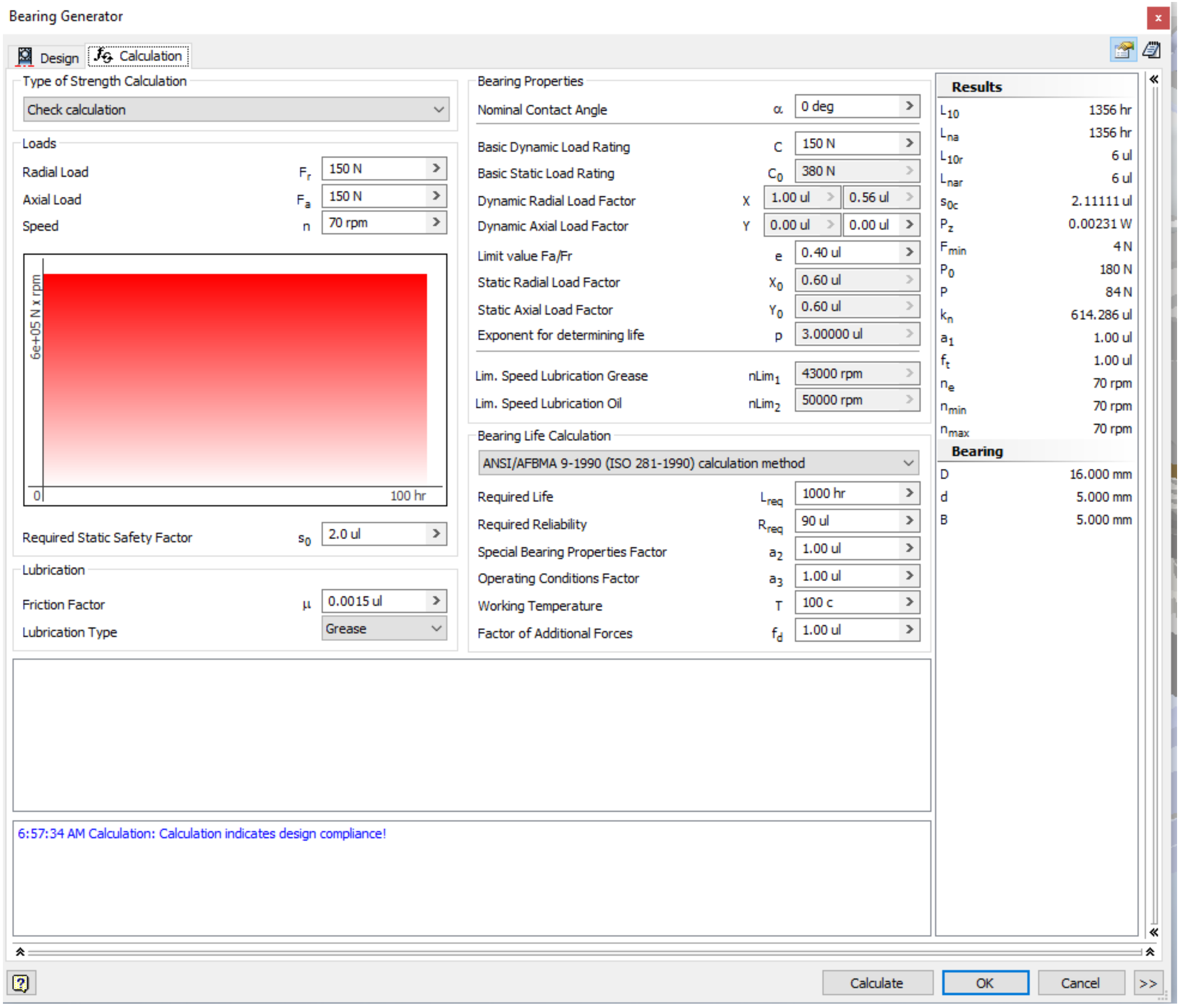


Figure 37 Bearing selection and validation of design.

❖ Lead Screws

➢ Gear Power / Torque calculation:

Assuming 100% efficiency of motor and gear transmission

$T_{Lead\ Screw} = T_{Driven\ Gear} = T_{Driver\ Gear} = T_{motor} = 0.150NM$ as stated in the motor datasheet

➢ Lead screw axial force generated:

From the following formula we can calculate the axial force generated by the lead screw which in turns is the pull force on the string

$$T = T_1 + T_2 = F_i \frac{d_m}{2}\left[\frac{\tan\alpha + \mu'}{1 - \mu' \tan\alpha}\right] + F_i \cdot r_{ms} \cdot \mu_s$$

Where T1 is the lead screw torque, Fi is the axial force we want to calculate, d_m is the mean diameter of the lead screw, α is the helix angle, μ is the coefficient of friction between bolt and nut and μ′ = μ/cos β where β is the thread included angle, 30 degrees for Metric and μ is the friction coefficient & rms=0

With the previous info, we can calculate the axial force by substituting:

$$0.150 = F_{axial} * \frac{8+6}{4}\left[\frac{\frac{2}{\pi d_m}+\frac{0.2}{\cos(30)}}{1-\frac{0.2}{\cos(30)}*\frac{2}{\pi d_m}}\right]$$

$\therefore F_{axial} = 0.13$ kN, This will be the tension force in the string.

- Lead screw guide nut design:
  - Nut Thickness:

    From Formula: $N = \frac{H}{p}$

    Where N is number of teeth, H is Guide Nut Height and P is Pitch.

    We can calculate N $= \frac{15}{2} \cong 7\ teeth$
  - σ Due to bending:

    From Formula $\sigma = \frac{F*\frac{P}{4}*\frac{P}{4}}{N\,\pi\, d_m*\frac{\left(\frac{P}{3}\right)^3}{12}}$

    Where F is Axial Force, P is Pitch, N is number of teeth, dm is Nut mean diameter = 9 mm

    We can calculate $\sigma = \frac{130*\frac{2}{4}*\frac{2}{4}}{7*\pi*9*\frac{\left(\frac{2}{3}\right)^3}{12}} = 6.7\ MPa < \ \sigma_{br} \therefore Safe\ Design$
  - τ_s Sheer stress on guide nut:

    From Formula $\tau_s = \frac{F}{\pi d t}$

    Where "d" is diameter inside the cover and "t" is the thickness outside the cover.

    we can calculate $\tau_s = \frac{130}{\pi*10*3.5} = 1.18\ MPa\ < \tau_{s\ br}\ \therefore Safe\ Design$
  - Guide Nut Bearing Strength:

    from Formula $\sigma_{bearing} = \frac{F}{\left(\frac{P}{2}\right)(N*\pi\ d_m)}$

    We can calculate $\sigma_{bearing} = 0.76\ MPa < \sigma_{bearing\ br}\ (17\ MPa) \therefore Safe\ Design$

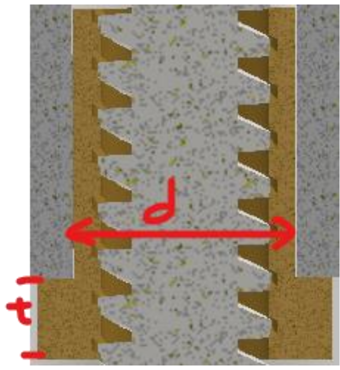


Figure 38 Guide nut sheer stress parameters demonstration

❖ Gears:

The gear design was modeled on Inventor CAD with the following specifications before manufacturing

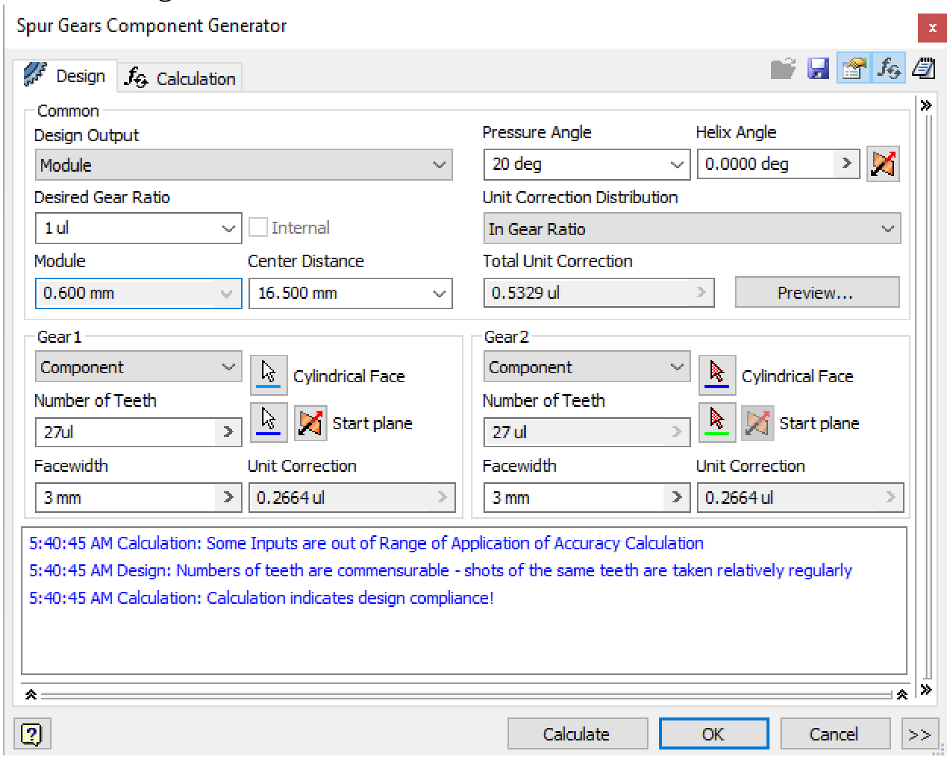
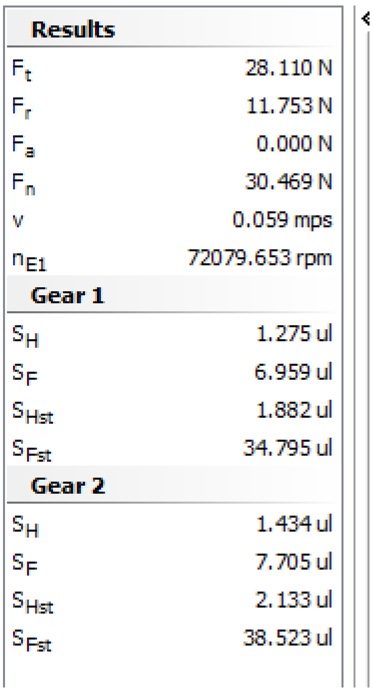


Figure 39 Gear Design



Results	
F_t	28.110 N
F_r	11.753 N
F_a	0.000 N
F_n	30.469 N
v	0.059 mps
n_{E1}	72079.653 rpm
Gear 1	
S_H	1.275 ul
S_F	6.959 ul
S_{Hst}	1.882 ul
S_{Fst}	34.795 ul
Gear 2	
S_H	1.434 ul
S_F	7.705 ul
S_{Hst}	2.133 ul
S_{Fst}	38.523 ul

Figure 40 Gearbox Factors and parameters

4.1.2. Palm Design

The Palm Was Designed to consist of 3 main components.

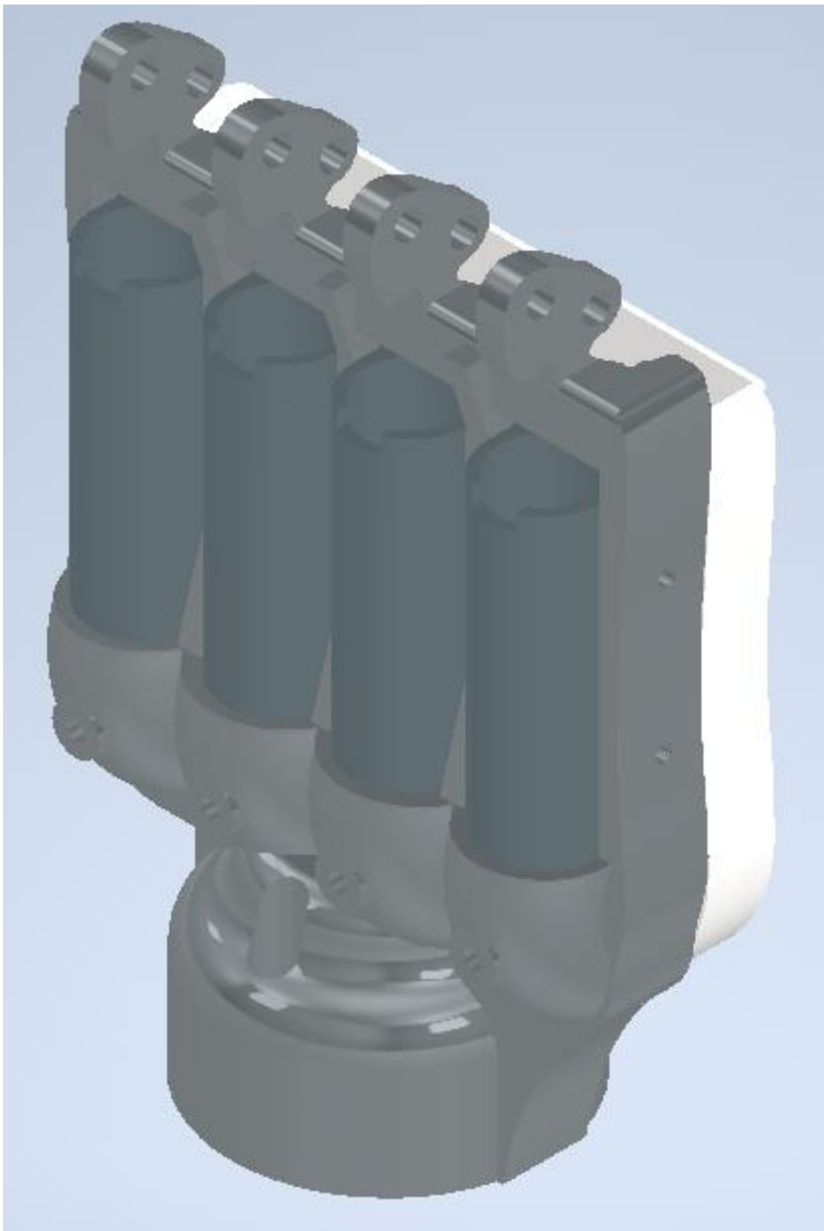


Figure 41 Palm Assembly (Back View)

1. Hand Core:
   It is designed to:
   - be the base frame for the prosthesis, carrying all motor holders and lead screws and gears.
   - being the frame on which the covers will be fixed on.
   - Having hinges for each finger mimicking the knuckles aesthetic
   - acting as support for rotation pins of fingers.
   - Its base was designed with consideration for the wrist/forearm assembly to connect to it.

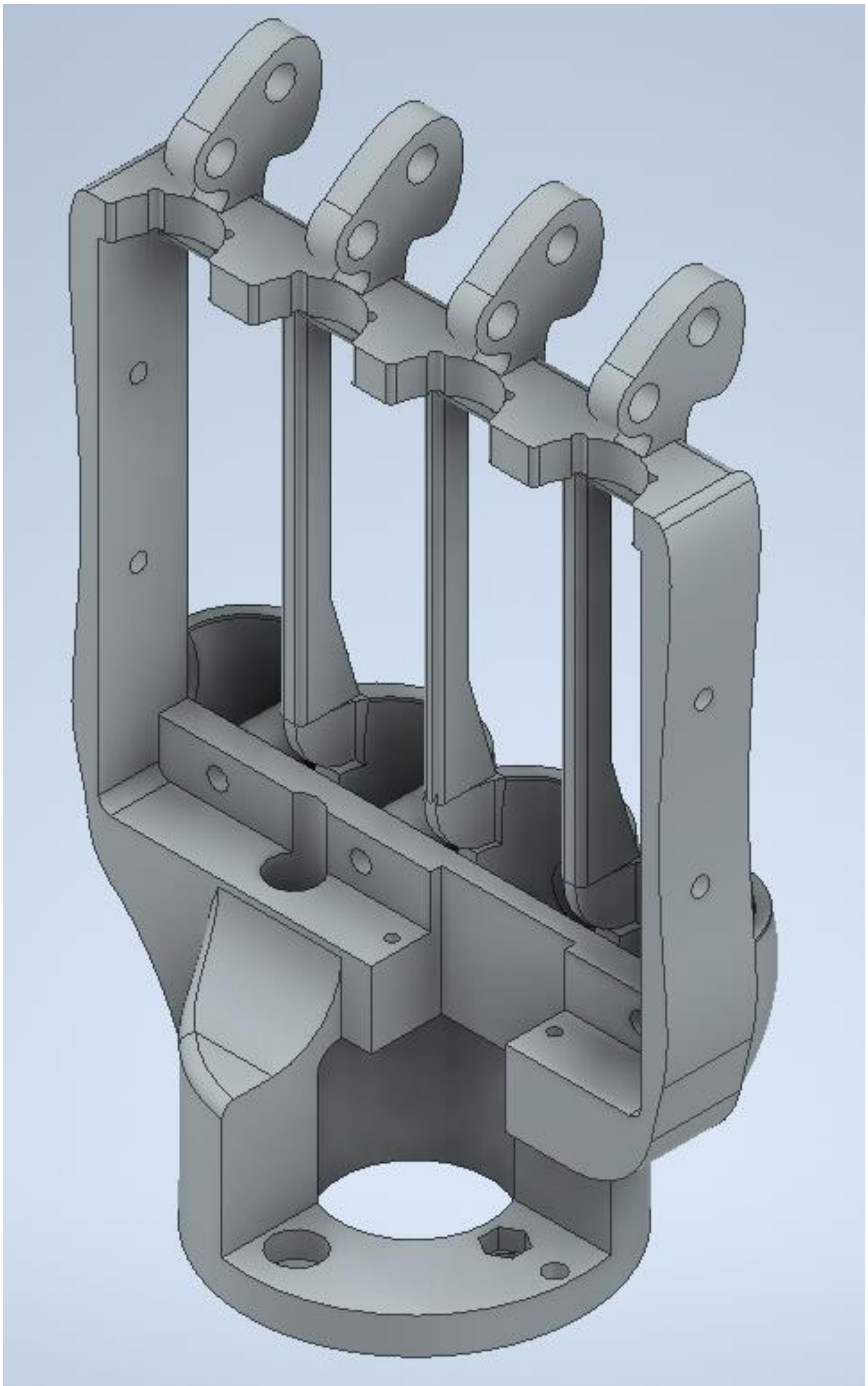


Figure 42 Core Hand Design

2. Motor Housing
   Responsible for locating and fixating the actuators for the palm and also provide support for lead screws and locate the bearings that were used for it.

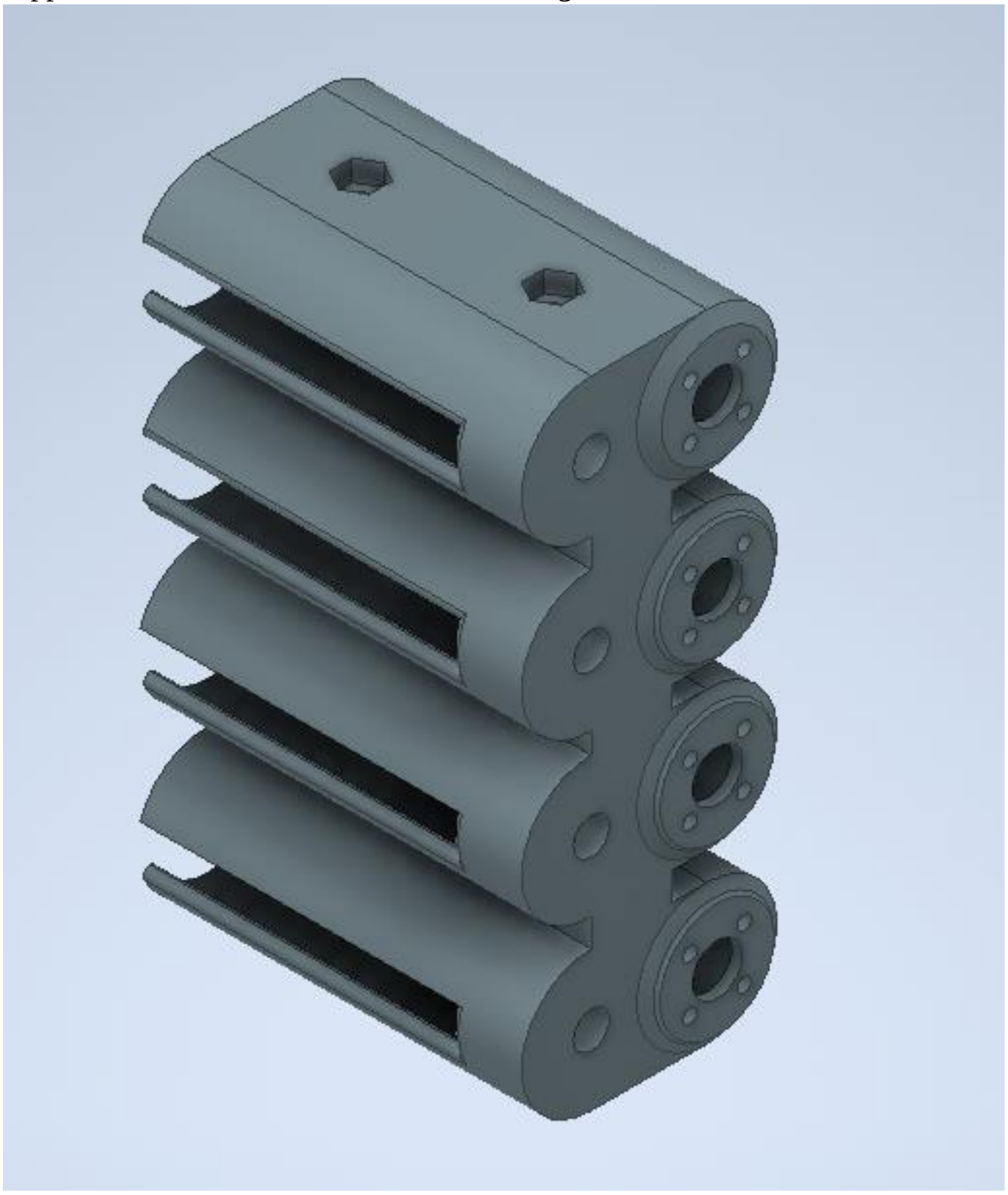


Figure 43 Motor Housing Design

(Lead Screw – Left Side, Motors – Right Side)

3. Front Hand Palm Cover
   Acts as cover for the motor holder and hand core, preventing any weight from directly impacting these components.
   It was also designed with consideration to where the thumb assembly is to be connected to the hand.

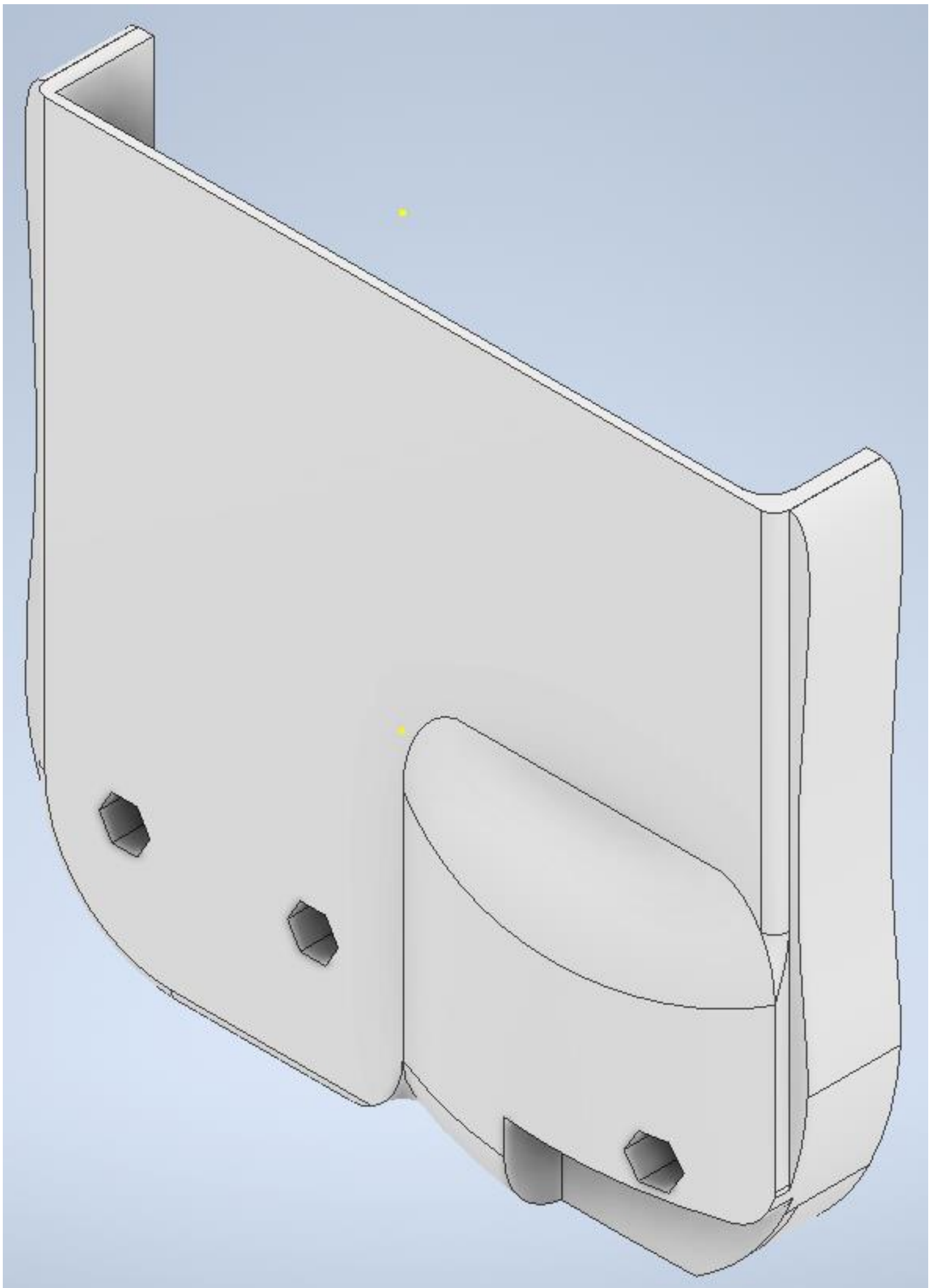


Figure 44 Palm Design

4.1.3. Thumb Design

Figure 45 Thumb Assembly

The Thumb Was Also Designed to Consist of 3 Main components.

1. Thumb Housing:
   This part is to be rotatable by a servo motor to mimic the opposition and reposition motions of the real human thumb, and it is also to contain the motor and motor cover and any other parts that contribute to thumb motion.

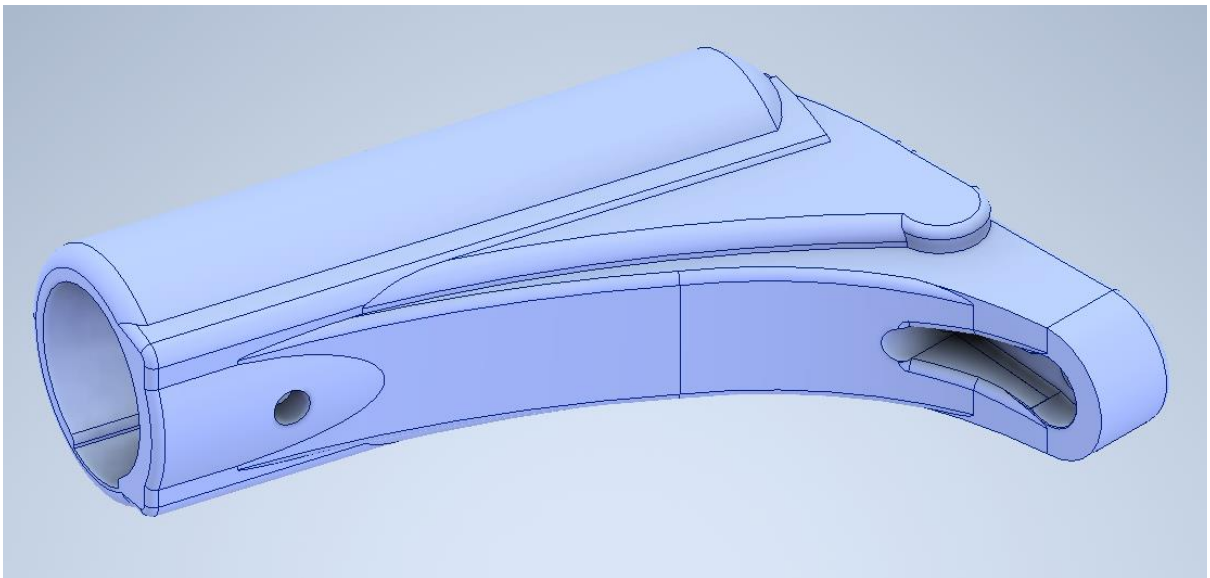


Figure 46 Thumb Housing

2. Thumb Motor Cover:
   Consists of 2 main parts
   a) Motor Cover (Lower Half):
      locates and fixes the motor in position that is responsible for thumb motion.
   b) Thumb Hinge (Upper Half):
      Where Thumb Tip will be fixed on and rotates about

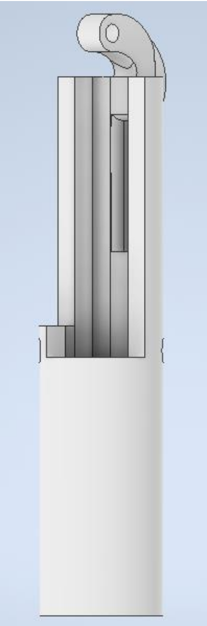


Figure 47 Thumb motor Cover

3. Thumb tip:

   The Part which will be actuated by the motor via lead screw guide nut tension mechanism.

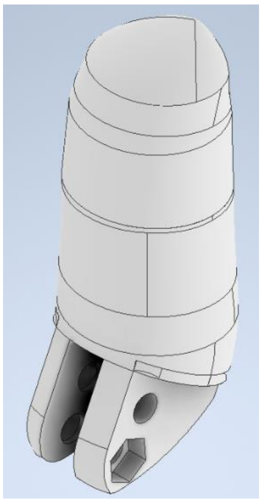


Figure 48 Thumb Tip

4.1.4. Forearm Design

This is the part that will hold most of the control components alongside the batteries. It holds the PCB, the battery and connected to the part which is attached to the socket of the hand.

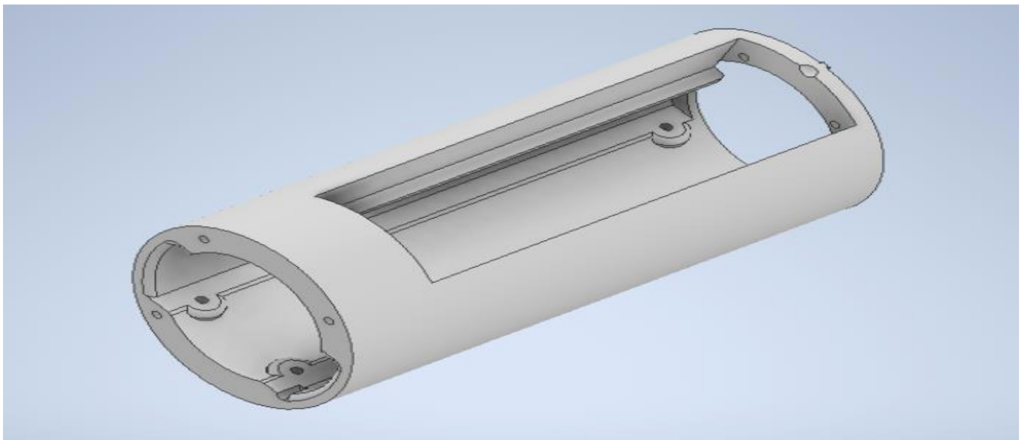


Figure 49 The main container

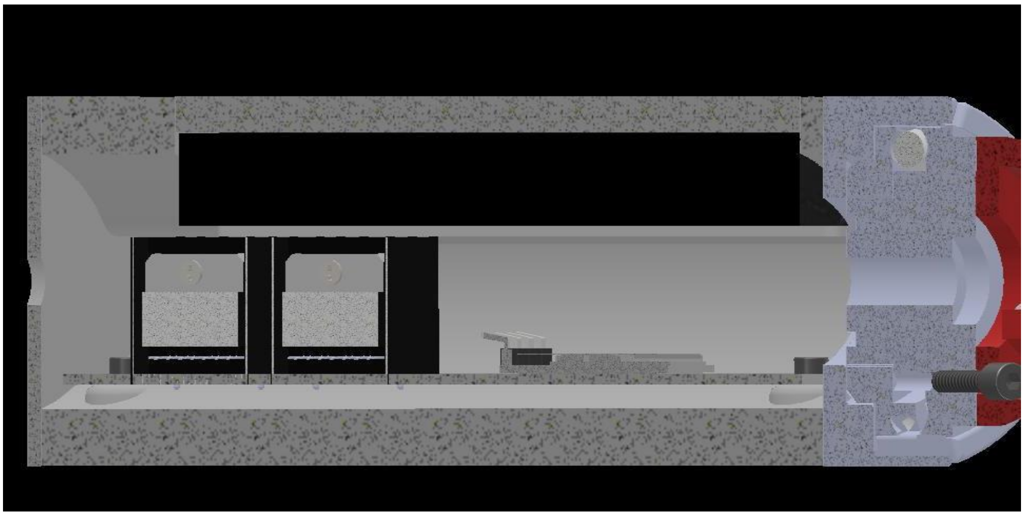


Figure 50 Forearm Section

The forearm connector

This part is what we used to connect the forearm with the main hand and palm.

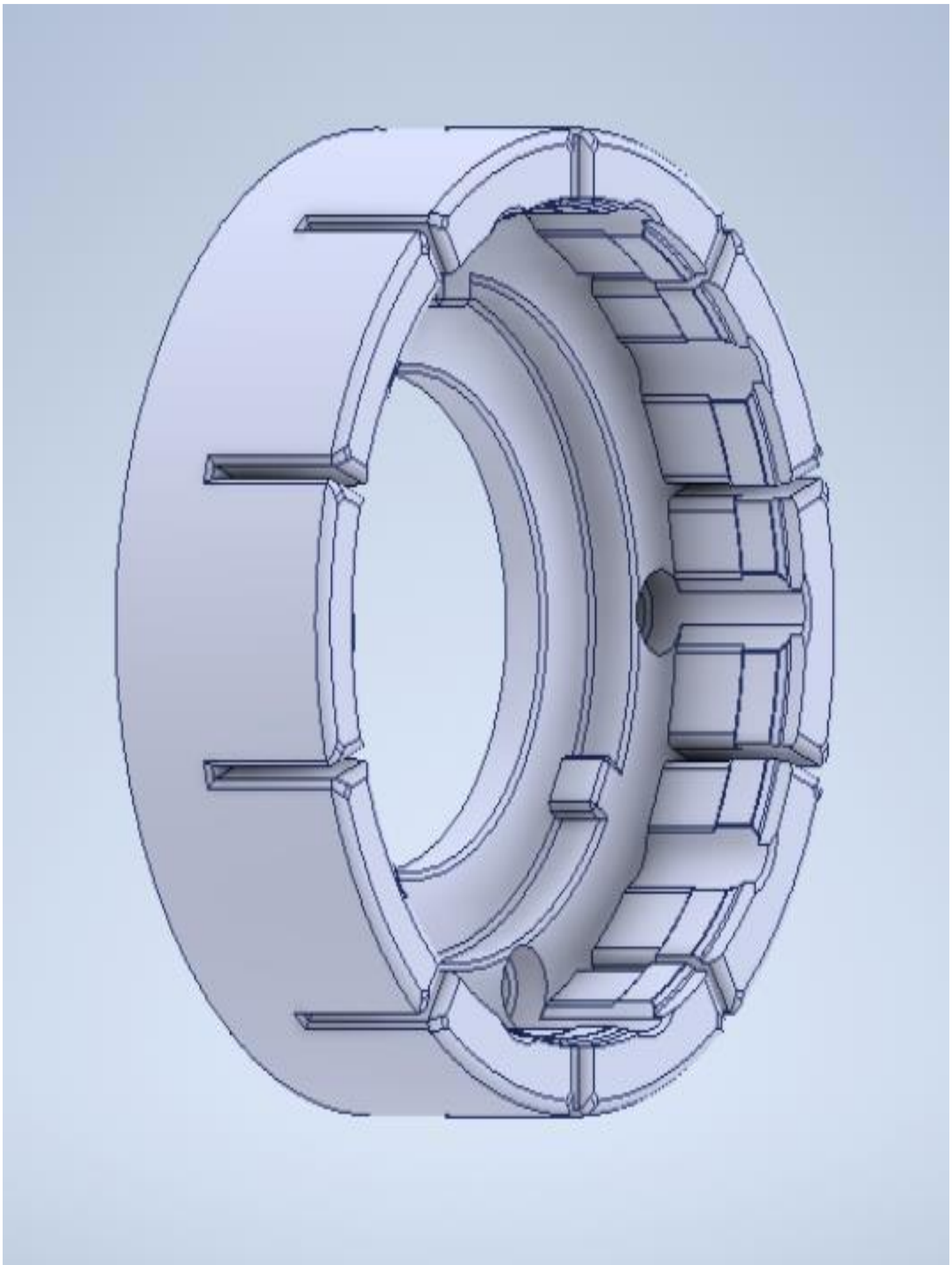


Figure 51 Forearm Connector 1

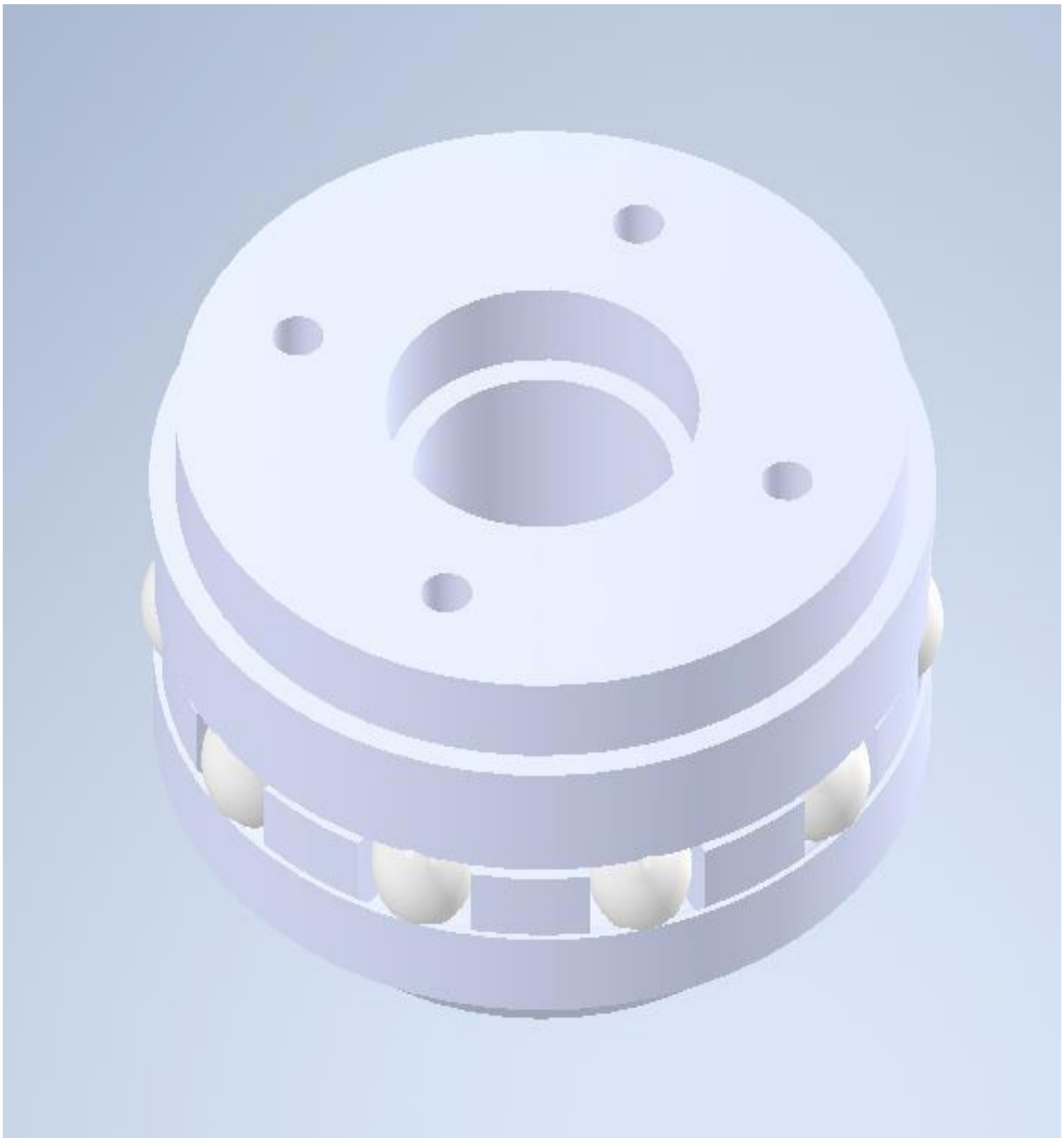


Figure 52 Forearm Connector 2

The part in Fig.51 and the part in Fig.52 are the main parts that connect the hand to the forearm, where the bearings shown in Fig.52 sinks in the groves in Fig.51 till the forearm connector 2 is fully housed inside the forearm connector 1, then the hand is rotated to the right meshing the forearm and hand completely without any clearances, the wires is then pulled through the hole in the middle of the forearm connector 1 and 2 to the main container of the forearm where all the electrical components and the PCB will be present and covered in an eye pleasing manor making the whole design compact, elegant and very easy to dismantle it for repairs, making it a very efficient design

4.1.5. Final Assembled Design:

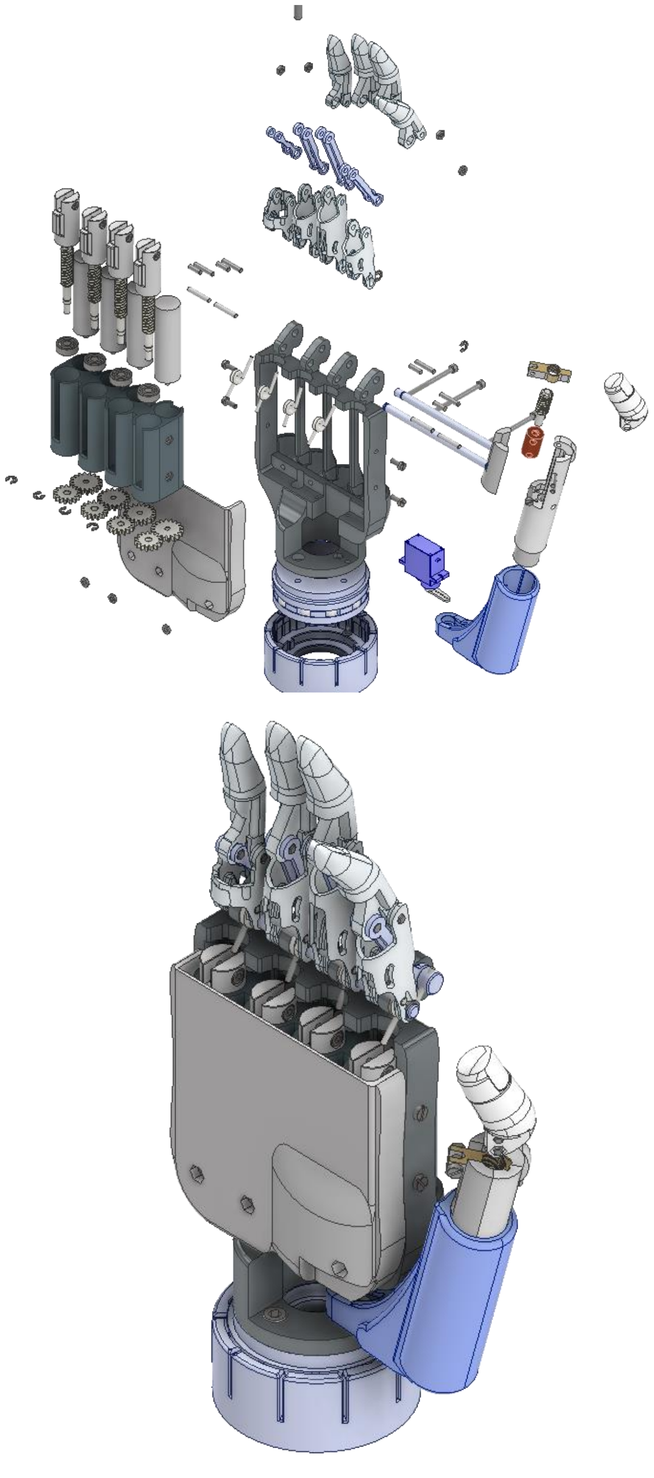


Figure 53 Assembled Model Design

4.2. Electric Engineering

Electric design and implementation for the project was performed with respect to 3 vital stages:

1) Electric circuit design
2) Fingers Actuation
3) Wire planning and labeling

4.2.1. Electric Circuit & PCB Design

This was done by simulating the electric circuit on Eagle software and calculating required voltages to operate all the motors as well as the microcontroller and to check for any design failures or short circuits in the design and also design the PCB.

3 Main circuits were implemented in the PCB.

- Microcontroller Circuit
  Responsible for power and logic distribution across the PCB plus voltage regulation when needed.

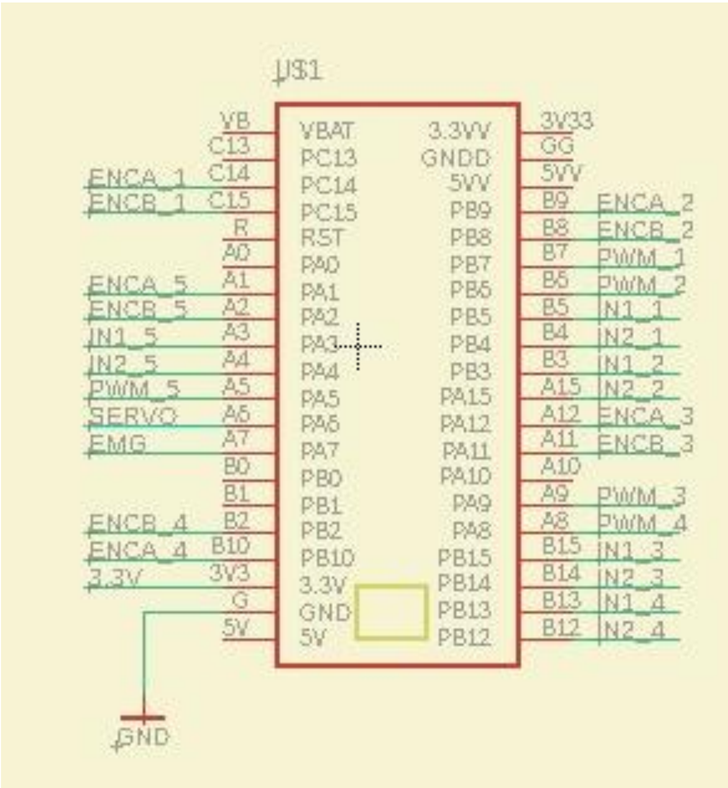


Figure 54 Microcontroller Connections Schematic

- L289N IC Motor Driver Circuit
  Responsible for Actuator-Controller interface and allows for more than 1 actuator to be connected to the same Driver which reduces the number of drivers needed and simplifies the circuit.

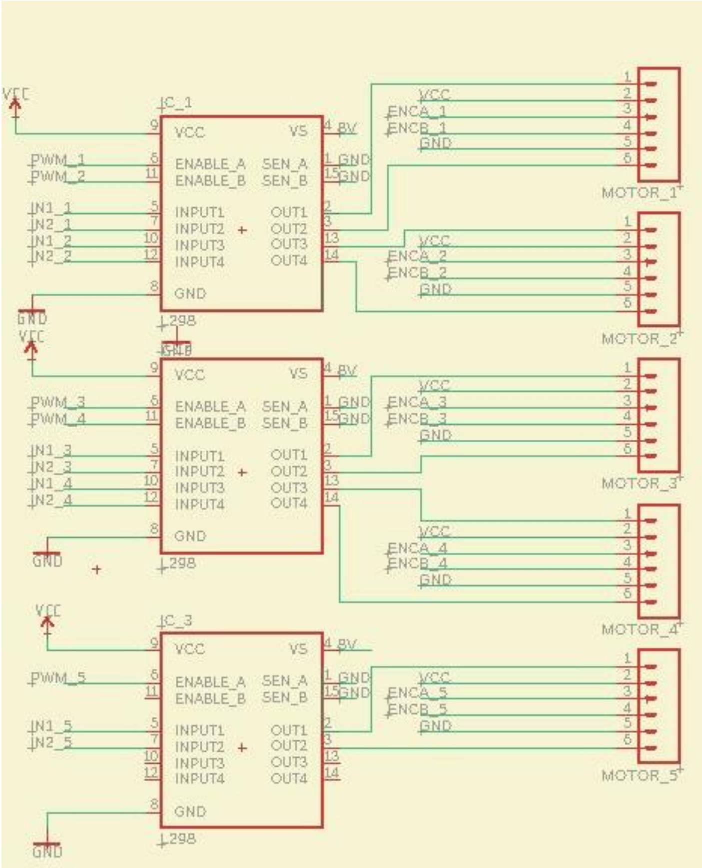


Figure 55 Motor Drivers Circuit

- Protection circuit

  Connected to the power source, consists of 2 circuits:

  - Reverse Voltage circuit: responsible for controlling unity of current flow direction. Allows current to flow in only 1 direction.
  - Voltage surge protection: Responsible for managing voltage to be within a specific threshold and prevents any sudden Spike in voltage.

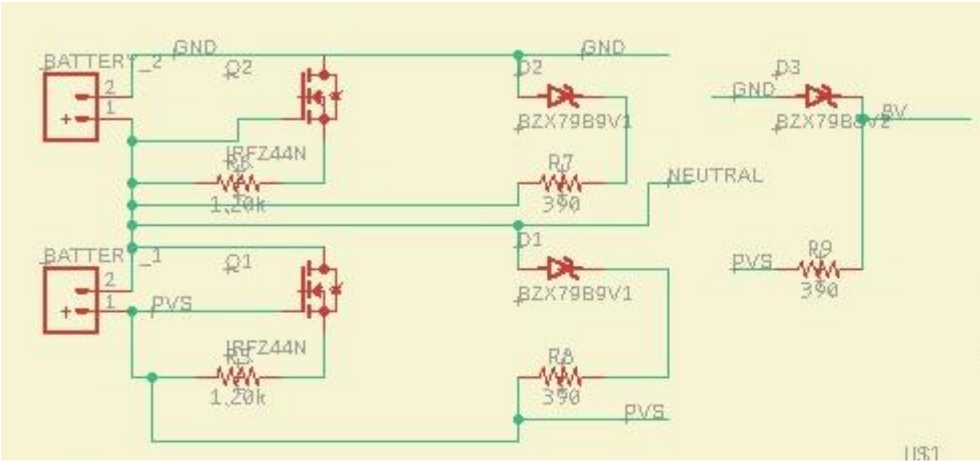


Figure 56 Protection Circuits Schematic (Reverse Voltage & Voltage Surge)

Final Circuit Schematic:

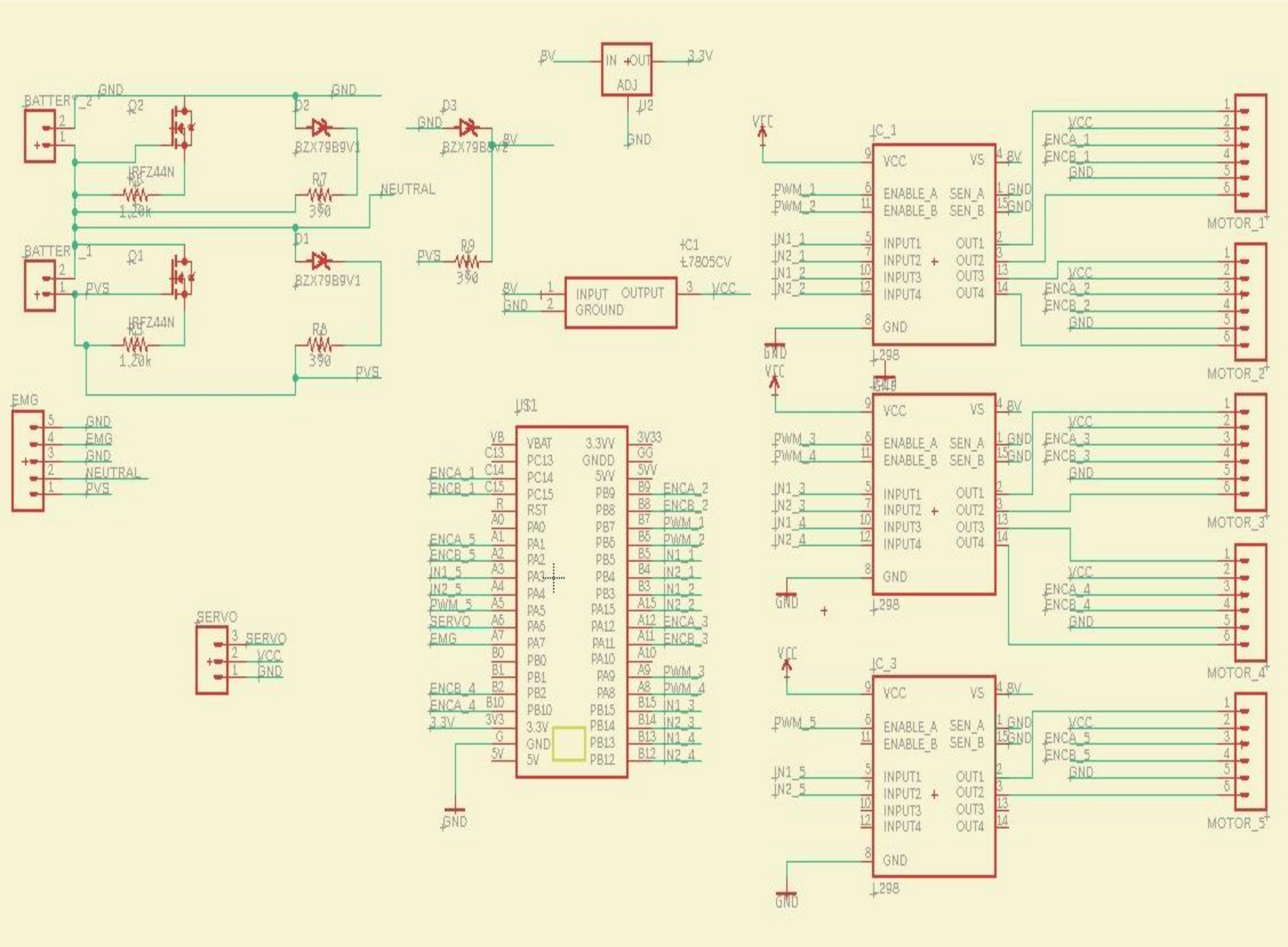


Figure 57 Electric Circuit Schematic on Eagle Software

Final PCB Layout:

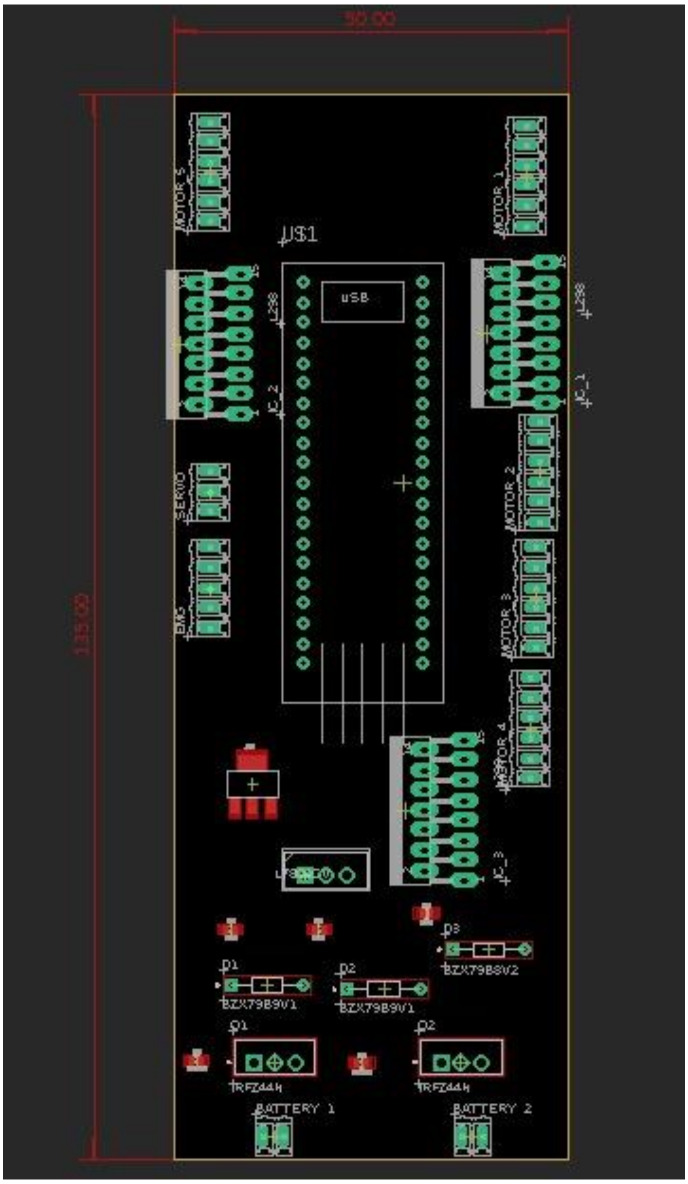


Figure 58 PCB Design

Comments:

- PCB Size was under constraint since the forearm design inner diameter is 60mm, PCB dimensions had to be less than that value with a margin. The Decision was made for the PCB To have 50 mm Width and 135 mm Length.
- Due to that constraint, components were placed relatively close (in a compact method) to the microcontroller and the connections were relatively close, this does not cause design failure, however, it is not ideal design and could be improved for safety purposes.

After verifying the design was okay and no faults were found with the aid of the software, we implemented the previously shown designs into a PCB to be placed inside the forearm later on in the system integration stage.

4.2.2. Actuation of fingers:

After calculating the required torque and speed for the finger, we compared some of the commercially available motors for the final selection. The main goal was to find a motor that didn't require a gear box design. Which would accommodate smaller motors but require additional hand space Provides the torque and speed you need. Additional factors were cost, voltage requirements and lead time and weight.

The FAULHABER Mini Motor: SA Gearhead: 15/5 ratio 141:1 K832 was chosen as the fingers motor because it is powerful enough to meet the requirements even though the motor is very small.

Figure 59 The FAULHABER Mini Motor size demonstration

Where The motor, gearhead, and encoder have a 16 mm diameter and a combined length of 57.65 mm not counting the 4 mm long shaft The total length is about 72 mm. The total mass is approximately 55 grams .so the size of the motor played a huge role in the selection procedure as a fairly larger motor would’ve made a bulkier unnatural looking hand, The FAULHABER mini motor gives a huge advantage due to its size to torque ratio. Additionally, the availability of these motors in our university lab made it an amazing and inexpensive choice.

Figure 60 l289n IC

The next step was to power the motor. The currents and voltages required to run these motors are much higher than a typical microcontroller can supply, so a motor driver is required to interface between the microcontroller and the motors.
After Comparing drivers available commercially we’ve found drivers that have many options for industrial applications such as: For example, serial communication options, various packaging options, low power options, sleep modes, etc. However, the main priority is given to the output voltage and current levels as they are the requirements for driving the motor. There was also a driver with a low pin count Considered to simplify wiring in the system.

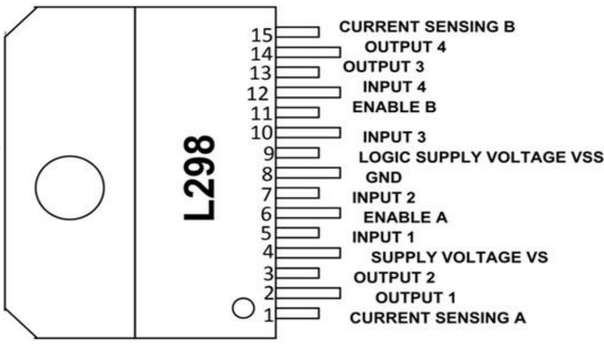


Figure 61 L289n schematic

Based on the mentioned points the driver selected was the L298N chip from STMICRONTROLLERS With a fairly small but enough number of pins, availability to supply the required current and voltage the l298n IC was enough to derive and control the motors.

4.2.3. Color coding and labeling:

- Color Coding:

According to the National Electrical Code (NEC) Standard, the color coding that we implemented is:

Positive	
Negative	
Encoder B	
Encoder Positive	
Encoder A	
Encoder Negative	
Micro controller	

- Labeling:
  - Every Actuator was labeled with its assigned finger name.

4.3. Control system:

After finishing the previous 2 stages and assembling the product together, it was time to test and evaluate the system performance, this stage is essential for validating the design and implementation and highlights any mechanical or electrical defects that went unnoticed in the validation stage of their individual fields.

As mentioned before, the control is to be done by an STM32F401CC in an Arduino IDE.

STM32F401CC Brief:

The STM32F401CC is an advanced microcontroller unit (MCU) designed by STMicroelectronics as part of their STM32F4 series. It is built around the ARM Cortex-M4 core, which provides high-performance computing capabilities. This MCU offers a comprehensive set of features and peripherals, making it suitable for a wide range of applications in the industrial, consumer electronics, and IoT sectors. With its low power consumption and efficient CPU, the STM32F401CC is capable of delivering robust performance while minimizing energy consumption. Furthermore, this MCU incorporates a variety of hardware interfaces, enabling seamless connectivity and communication with external devices. Overall, the STM32F401CC is a versatile and powerful microcontroller unit that can meet the demands of complex and resource-intensive applications.

After setting up the environment the following conditions were considered in order to achieve the desired product performance

- The product should have different modes of operation for various tasks.
- Accurate position control of the motors must be achieved for proper product performance evaluation.

4.3.1. Modes of operation:

The product comes with 10 preinstalled modes for various tasks that is capable of passing the AHAP Test mentioned in Section (2.2.3.3.), these modes are:

- Mode 1: Hook grip
- Mode 2: Spherical grip
- Mode 3: Tripod pinch
- Mode 4: Extension grip
- Mode 5: Cylindrical grip
- Mode 6: Diagonal volar grip
- Mode 7: Lateral pinch
- Mode 8: Pulp pinch

Alongside the 2 other non-grip modes:

- Mode 9: Index pointing/pressing.
- Mode 10: Platform

For visual clarity about how these modes should look like, refer to the (2.2.3.3) Section.

4.3.2. Accurate position control:

For the finger to reach its desired position for a specific pattern precisely without overshooting in any of the 5 motors, a closed loop feedback system was integrated within the software for accurate position control… the closed loop feedback system uses PID control because it is the most accurate and stable controller in the mechatronics field.

4.3.2.1. Brief about PID control and closed loop feedback system:

PID control, also known as Proportional-Integral-Derivative control, is a commonly used feedback control algorithm in engineering and industrial automation. It is employed to regulate and stabilize systems by continuously adjusting the control inputs based on the error between the desired setpoint and the actual process variable.

The control input is typically a signal that affects the system's behavior, such as a voltage, current, or valve position, in our case it is rotation angle or motor position.

Motor encoder PID position control is a specific application of the PID control algorithm used to control the position of a motor based on feedback from an encoder. The encoder provides precise information about the motor's current position, allowing the PID controller to make adjustments and maintain the desired position accurately.

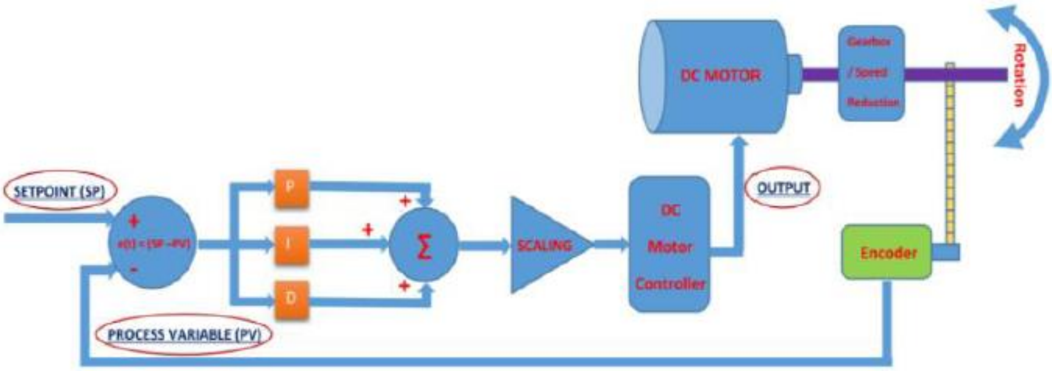


Figure 62 PID Closed loop Feedback control system.

Here's how motor encoder PID position control typically works:

- Setpoint and Feedback: The control system defines a desired position, known as the setpoint, where the motor should be. The motor encoder continuously provides feedback on the motor's actual position, which is compared to the setpoint (this set point will vary depending on the desired mode of operation for the prosthesis).
- Error Calculation: The error is calculated as the difference between the setpoint, and the actual position obtained from the motor encoder. The error represents the positional deviation that needs to be corrected.
- Proportional (P) Control: The P component of the PID controller determines the control output based on the current error. It multiplies the error by a proportional gain (Kp) to produce a correction signal. The larger the error, the larger the correction applied. The P control provides immediate response to deviations from the setpoint.
- Integral (I) Control: The I component of the PID controller considers the cumulative error over time. It integrates the error and multiplies it by an integral gain (Ki) to produce an additional correction signal. The I control helps eliminate steady-state error by gradually reducing the accumulated error over time. It ensures accurate positioning over extended periods.
- Derivative (D) Control: The D component of the PID controller takes into account the rate of change of the error. It calculates the derivative of the error and multiplies it by a derivative gain (Kd) to generate a corrective signal. The D control anticipates future behavior based on how fast the error is changing. It helps dampen overshoot and improve stability.
- Control Output: The control output is computed as the sum of the proportional, integral, and derivative components:

  Control Output = (Kp * P) + (Ki * I) + (Kd * D)

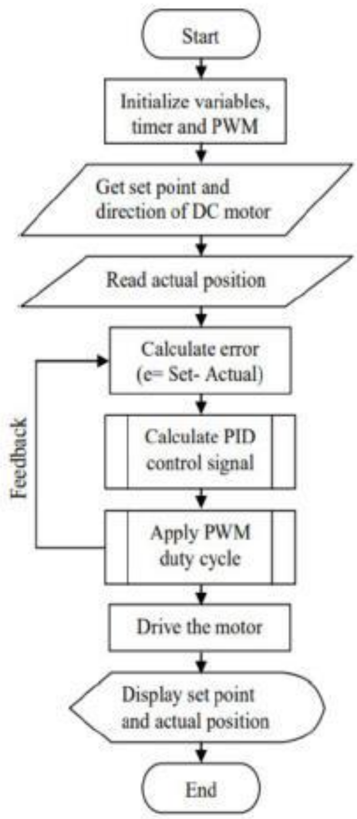


Figure 63 PID Closed Loop visualization

The control output represents the adjustment signal sent to the motor to correct its position. It could be a voltage, current, or PWM signal depending on the motor control system.

- Motor Adjustment: The control output is applied to the motor, which adjusts its position accordingly. The motor encoder continuously provides feedback on the new position, repeating the control loop.
- Tuning: The PID controller gains (Kp, Ki, Kd) need to be appropriately tuned to achieve desired control performance. Tuning involves adjusting the gains to optimize stability, responsiveness, and accuracy based on the motor's characteristics and the control system requirements.

4.3.2.2. Encoder Handling:

Using the “Encoder” library, 4x Encoding was utilized which gives higher accuracy.

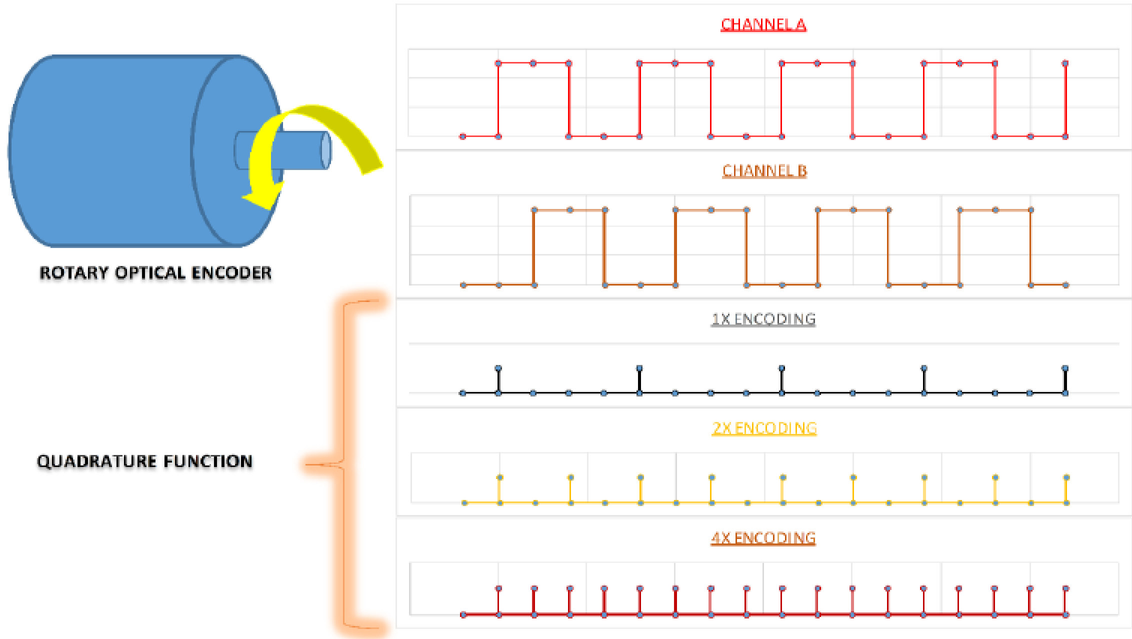


Figure 64 4X Encoding

How it works:

- ➢ Encoder myEnc(pin1, pin2);

  Create an Encoder object, using 2 pins. You can create multiple Encoder objects, where each uses its own 2 pins. The first pin should be capable of interrupts. If both pins have interrupt capability, both will be used for best performance. Encoder will also work in low performance polling mode if neither pin has interrupts.

- ➢ myEnc.read();
  Returns the accumulated position. This number can be positive or negative.
- ➢ myEnc.write(newPosition);
  Set the accumulated position to a new number.

4.3.2.3. *PID Parameter tuning:*

There are many techniques to perform PID parameters tuning to acquire the values for (Kp, Ki, Kd) to optimize the performance of the control system, here is a brief on the most common methods and how to perform them:

1. Manual Tuning:
    - Start by setting all gains (Kp, Ki, Kd) to zero.
    - Increase the proportional gain (Kp) until the system starts to oscillate.
    - Adjust the integral gain (Ki) to reduce the steady-state error.
    - Fine-tune the derivative gain (Kd) to dampen oscillations and improve stability.
    - Iterate and repeat the process until the desired control performance is achieved.
2. Ziegler-Nichols Method:
    - Set all gains (Kp, Ki, Kd) to zero.
    - Increase the proportional gain (Kp) until the system starts to oscillate with a sustained amplitude.
    - Measure the oscillation period (P) and use it to calculate the critical gain (Ku).
    - Set the proportional gain (Kp) to 0.6 times the critical gain (Ku).
    - Set the integral gain (Ki) to 2 times the inverse of the oscillation period (1 / (2P)).
    - Set the derivative gain (Kd) to 0.125 times the inverse of the oscillation period (0.125 / P).
    - Fine-tune the gains as needed based on the system's response.
3. Trial and Error:
    - Start with conservative initial values for gains (Kp, Ki, Kd).
    - Observe the system's response and make adjustments to the gains iteratively.
    - Increase the proportional gain (Kp) for a faster response but watch for oscillations.
    - Increase the integral gain (Ki) to reduce steady-state error but be cautious about overshoot.
    - Increase the derivative gain (Kd) to dampen oscillations and improve stability.

It's important to note that PID tuning is often an iterative process, and the specific method and approach may vary depending on the system, its dynamics, and the desired control objectives. It's recommended to perform tuning in a controlled environment and thoroughly test the system's response to ensure stability and desired performance before deploying it in real-world applications.

4.3.2.4. PID implementation in project:

The End goal of implementing PID Control is to achieve accurate positioning for the fingers by tuning the parameters of gains in the closed loop feedback system for the PID controller., The output Graph should look something like the following:

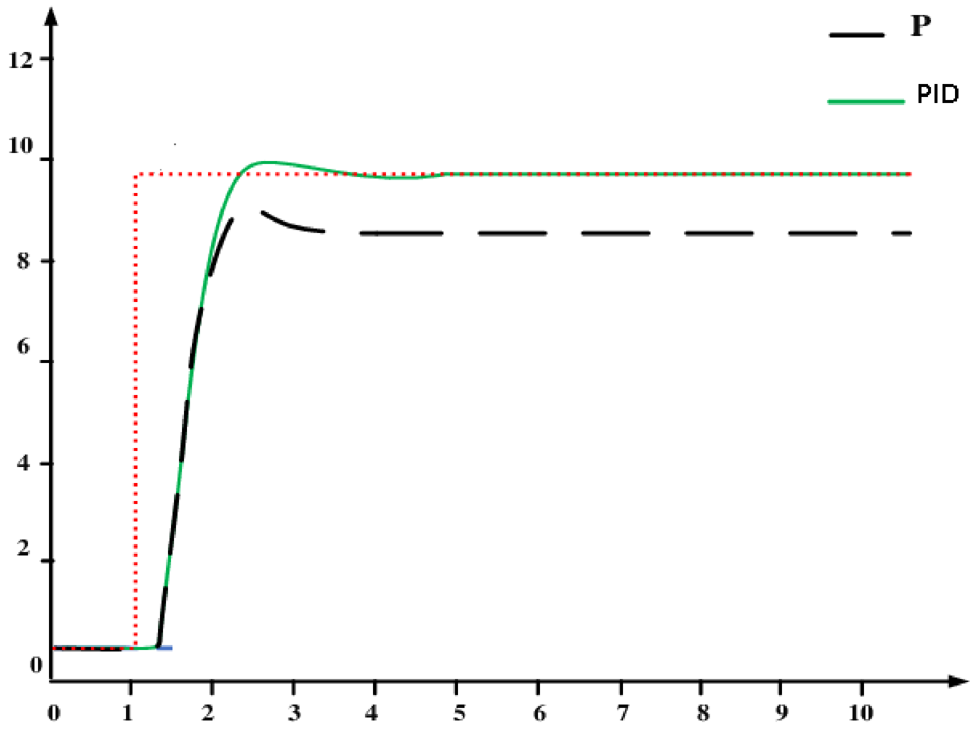


Figure 65 PID Output Graph Example

While the previous graph could be optimized for better results and less overshoot, it still generates satisfactory results depending on the application.

A Trial-and-error approach was taken to get the needed gain values for a stable system performance.

Comments:

The result acquired were acceptable and able to perform the required position and speed control with no errors, however these results could be further improved by using a more sophisticated approach to calculate the gain values (Like using the Ziegler-Nichols method)

5. Chapter 5: Prothesis Evaluation and comments:

5.1. Product Evaluation:

- Specs:
  - Maximum Reach (Distance from Wrist to Tip of tallest Finger): 25 cm
  - Approximate Model Weight: 900 g.
  - Recommended Carrying Weight: Below 10 KGs
  - Required Operating Voltage: 9 Volts
  - Disassembly:
    No permanent joints were used. The product can be disassembled and reassembled with no problems.
- Task fulfillment:
  - Mechanically:
    Mechanism and Design were able to achieve their respective objectives
    1. The Prosthesis maintained the human hand aesthetic with natural curling motion and satisfactory position control
    2. The Prothesis maintained Lightweight Design and Durability
    3. The Prothesis is manufactured with relatively low cost and readily available materials
    4. The Prothesis is easily disassembled for maintenance purposes.
  - Electrically:
    The Electrical engineering of the prothesis was able to fulfill the objectives under the constraint of prioritizing user safety
    1. No External wires or connection to external outlets or power sources to operate the prothesis
    2. Protection Circuits are integrated within the PCB to prevent any electrical hazards.
    3. Clear and understandable color coding and labeling for wires used.
  - Control System:
    1. Position - Speed control was performed with satisfactory results
    2. Implemented Modes of operation were able to perform and fulfill their required task to achieve the user's needs.

5.2. Comments:

1- The Gears are preferred to be steel with better Fixation on the motor shaft.
2- The Linkage System should be made of steel for safety purposes and guarantee no Failures.
3- Recommended Carrying weight Is to be maintained under 10 KGs. 10-20 KGs will cause no failures initially, but it will jeopardize the safety of mechanisms under fatigue load. 20+ KGs will cause links failure then Proximal phalange failure depending on the overload.
4- For Handling of heavier weights, Prothesis to be manufactured with steel instead of ABS is highly recommended.
5- The PCB is to be Double Layered For appropriate routing and manufacturing.

6. Cost:

Products cost

Product	No. of	Price	Description	Supplier
STM32F401CC	1	260	Microcontroller	Fututre Electronics
Bearings	4	60	Lead Screw Supports	Ampere Electronics
Lead Screw 8*300 mm	1	150	Motion Transmission	Ram Electronics
Guide Nuts	5	250	Motion	Ram Electronics
Bolts & Nuts	~	35	Fixation	-
Wires	~	25	Connectors	-
FaulHaber Motor	5	-	Actuator	Provided by Faculty
Servo Motor	1	100	Actuator	Future Electronics
L289N Motor Driver	3	105	Motor Driver	Ampere Electronics
HE S164A KW06/99 Encoder	5	-	Encoder	Provided by Faculty
ABS	1 KG	450	3D Printing Raw Material	Ampere Electronics
Lithium Battery	2	90	Power Source	Future Electronics
PCB	1	300	Electric Circuit	-
Springs	5	100	Fingers spring	-

Operation and manufacturing costs

Process	Cost	Duration
3D Printing	Provided by Faculty	92 H 43 Min
Center Lathe	400	4 H 13 Min
PCB Printing	300	48 H

Total Cost Estimate: 2325 EGP

Cost Per Member: 465 EGP

7. Summary in Arabic:

تشهد التقدمات في العلوم والتكنولوجيا تقدمً واعدًا في مجال الأطراف الصناعية، ولا سيما في مجال تصميم الأيدي الصناعية. إن هذا المجال متعدد التخصصات يتطلب معرفة في علم الفسيولوجيا وعلم التشريح والأنظمة الكهربائية والإلكترونية والتصميم الميكانيكي والبرمجيات، وغير ذلك، وذلك حسب نوع التحكم المستخدم. ومع ذلك، فإن معظم الأبحاث في هذا المجال لا تزال تقتصر على المختبرات بسبب تحديات طبيعتها متعددة التخصصات والتمويل المحدود .

وتعتمد الاختيارات المتاحة للأطراف الصناعية على متطلبات المستخدم الفردية. في هذا المشروع، يتم التركيز على الأذرع الكهروميكانيكية، وهي الأكثر شيوعًا بين الأجهزة الكهربائية. تحتوي هذه الأذرع على محركات وبطاريات لتشغيل حركتها، وتتحكم فيها إشارات كهربائية تولدها عضلات الجزء المتبقي من الجسم.

يتم توفير التدريب على الأذرع الكهروميكانيكية عادةً من قبل أخصائي العلاج الوظيفي وفنيي العظام. عندما يتقلص عضلة ما، فإنها تنتج إشارة كهربائية يتم التقاطها بواسطة الكابلات المرتبطة بالجلد في الجيب الصناعي. تنتقل هذه الإشارات إلى جهاز تحكم يبدأ الحركات وفقًا لنوايا المستخدم. على سبيل المثال، عندما يرغب المستخدم في إغلاق اليد الصناعية، يقوم بتقلص العضلات المقابلة، وسوف تغلق اليد على النحو لمطلوب. توفر التكنولوجيا الحديثة الآن إمكانية التحكم بوظائف متعددة باستخدام يد واحدة، مثل نمط قبضة واحدة، ودوران المعصم، وثني الكوع، وحتى حركة الكتف.

تتمتع الأذرع الكهروميكانيكية بعدة مزايا مقارنةً بالأجهزة المستندة إلى الحركة الجسدية. فهي تقلل من الحاجة إلى استخدام الأشرطة والمشابك، وتوفر قوة بدون مجهود، وتوفر أنماط قبضة متعددة، وتمكن من حركات يد أكثر طبيعية. بالإضافة إلى ذلك، يستمتع الكثيرون بالمظهر الروبوتي الذي يمكن أن تقدمه الأذرع الكهروميكانيكية عندما لا تكون مغطاة بقفاز تجميلي. على الرغم من أن هناك قيودًا ا تشير إليها كثير من الأبحاث حول الأذرع الكهروميكانيكية، مثل عدم قدرتها على الماء، إلا أن التقدمات الحديثة في تقنيات تصنيع المقابض والمفاصل تعمل على حل هذه المشكلة لبعض الأجهزة الطرفية والمفاصل.

تعتبر التقدمات العلمية والتكنولوجية في مجال الأطراف الصناعية من الجوانب الرئيسية التي تدفع نحو تطبيقها العملي في البحوث. تركز تصميم الأيدي الصناعية على الجوانب المتعددة والأساسية مثل الفيزيولوجيا وعلم التشريح، والأنظمة الكهربائية، والميكانيكية، والبرمجيات. ومع ذلك، يتم إجراء معظم الأبحاث في المختبرات ويواجه العديد من التحديات بسبب طبيعته المتعددة التخصصات ونقص التمويل.

تتوفر أنواع مختلفة من الأيدي الصناعية، بما في ذلك تلك التي تعتمد على واجهات عصبية وقد تم اختبارها. يعتمد اختيار اليد الصناعية على متطلبات المستخدم. في هذا المشروع، يتم التركيز على الأذرع الكهروميكانيكية، والتي هي الأكثر شيوعًا. تعمل هذه الأذرع بواسطة محركات وبطاريات لتحريك الجهاز، ويتم التحكم فيها عن طريق إشارات كهربائية تنشأ من عضلات جذع الجسم. .

عبر التاريخ، شهدت الأذرع البيونية تطورًا متسارعًا. في السابق، تم استخدام الأذرع البسيطة التي تعتمد على الحركة الميكانيكية لنقل الحركة، ولكنها كانت غير قابلة للتحكم بشكل كامل. مع التقدم التكنولوجي، تم تطوير الأذرع البيونية المزودة بأنظمة كهروميكانيكية تتحكم بالحركة باستجابة للإشارات الكهربائية المنبعثة من عضلات الجسم.

8. Appendix:

8.1. Construction Drawings:
8.2. Assembly Drawings:
8.3. Stress Analysis:
8.4. Code used:

All These Information can be found on the following Link

https://engasuedu-my.sharepoint.com/personal/1803833_eng_asu_edu_eg/_layouts/15/onedrive.aspx?id=%2Fpersonal%2F1803833%5Feng%5Fasu%5Fedu%5Feg%2FDocuments%2Fprosthetic%20hand%2Fprosthetic%20hand&ga=1

8.5. References:

Books:

[1] Hollerbach JM. The Human Hand as an Inspiration for Robot Hand Development
[2] Naik, G. (2019). Biomedical Signal Processing
[3] Frank, R. G., & Elliott, T. R. (2000). Handbook of Rehabilitation Psychology
[4] Boubaker, O. (2020). Control Theory in Biomedical Engineering: Applications in Physiology and Medical Robotics.
[5] P. Maduri and H. Akhondi, "Upper Limb amputation," 2022. https://www.ncbi.nlm.nih.gov/books/NBK540962/
[6] Handbook of PI and PID controller tuning rules. by Aidan O'Dwyer

Articles:

[1] Raichle K.A., Hanley M.A., Molton I., Kadel N.J., Campbell K., Phelps E., Ehde D., Smith D.G. Prosthesis use in persons with lower- and upper-limb amputation.
[2] Bethge M., Von Groote P., Giustini A., Gutenbrunner C. The world report on disability: A challenge for rehabilitation medicine. Am. J. Phys. Med. Rehabil.
[3] Mechanical design and performance specifications of anthropomorphic prosthetic hands: A review Joseph T. Belter, MS, BS;1* Jacob L. Segil;2 Aaron M. Dollar, PhD, SM, BS;1 Richard F. Weir, PhD3 https://www.rehab.research.va.gov/jour/2013/505/page599.html
[4] Wang Y, Tian Y, She H, Jiang Y, Yokoi H, Liu Y. Design of an Effective Prosthetic Hand System for Adaptive Grasping with the Control of Myoelectric Pattern Recognition Approach. https://doi.org/10.3390/mi13020219
[5] Johansson RS, Flanagan JR. Coding and use of tactile signals from the fingertips in object manipulation tasks.
[6] Sanes JN, Donoghue JP. Plasticity and primary motor cortex. Annu Rev Neurosci.
[7] Scott SH. The computational and neural basis of voluntary motor control and planning.
[8] Vincent JFV, Bogatyreva OA. Biomimetics: its practice and theory
[9] Human Hand Anatomy-Based Prosthetic Hand https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7795667/#B1-sensors-21-00137
[10] Introduction to Myoelectric Prostheses https://www.armdynamics.com/upper-limb-library/introduction-to-myoelectric-prostheses

Technical Reports:

[7] Joaquín Ibáñez Borreda DESIGN OF A MECHANICAL SYSTEM FOR UNDERACTUATION OF HAND PROSTHESES https://repositori.uji.es/xmlui/bitstream/handle/10234/200975/TFG_Ib%C3%A1%C3%B1ez_Borreda_J.pdf?sequence=1

Electronic sources:

[1] Feix T, Pawlik R, Schmiedmayer HB, Romero J, Kragic D. A comprehensive grasp taxonomy. In: 2016 IEEE International Conference on Robotics and Automation (ICRA). 2016. p. 536–43.
[2] 8E70=*, 8E71=*, 8E72=* Bebionic models: https://shop.ottobock.us/store/medias/647G1774-0-en-INT-03-2209w-4911370-en.pdf?context=bWFzdGVyfHJvb3R8MjI5MDQxNXxhcHBsaWNhdGlvbi9wZGZ8aDQ5L2gxMC85MTI2MTgyODEzNzI2LnBkZnwwNDdlOTVkZmUzZGQzY2FkOTk5MDZhMzA0NTBlMzRkZGViZTYxNWRkNTg4NDBkMmQ5ZDVmNDk4YzE4NzkzODNh
[3] BeBalance Otto-bock: https://shop.ottobock.us/store/medias/bebalancePlusIFU.pdf?context=bWFzdGVyfHJvb3R8MjEwNzA0MHxhcHBsaWNhdGlvbi9wZGZ8aDc1L2g3MC84ODkyNjYyNDgwOTI2LnBkZnw1NjFiYzEzZjJmOTUwM2JlNDIxMjlhYzdiNzE4YjM0ZTcwMTBlZDE1MmNlMDBhNzVlNjg1YjMzYmNhN2M5ODAx

8.6. Technical Details for components and datasheets:

[I] ABS (acrylonitrile butadiene styrene): https://vexmatech.com/assets/datasheets/fdm/ABS.pdf
[II] FAULHABER DC 6V MiniMotor 1524E006S123 GEAR 15/5 141:1: https://hades.mech.northwestern.edu/images/8/8f/Faulhaber-datasheet.pdf
[III] HE S164A KW06/99 Encoder: https://hades.mech.northwestern.edu/images/8/8f/Faulhaber-datasheet.pdf
[IV] SG90 Servomotor https://www.datasheet-pdf.com/PDF/SG90-Datasheet-TowerPro-791970
[V] L289N Datasheet: https://www.tech.dmu.ac.uk/~mgongora/Resources/L298N.pdf
[VI] Lead Screw Trapezoidal screw type, Lead Screw Diameter Ø 8 (mm), Pitch 2 (mm), Lead 2 (mm), Length: 800 (mm) Stainless Steel https://www.handsontec.com/dataspecs/linear%20motion/T8-Copper-Nut.pdf
[VII] Bearing 625ZZ Shielded Miniature Ball Bearing 5x16x5mm https://www.smbbearings.com/firebrick/ckeditor/plugins/upload/Uploads/Documents/bearingpdfs/625ZZ-miniature-bearing-5x16x5mm.pdf
[VIII] Common bolt nut fasteners https://www.thefastenerfactory.com.au/pub/media/catalog/category/bolts_nuts_washers_product_guide.pdf
[IX] Lithium Ion Battery https://www.ineltro.ch/media/downloads/SAAItem/45/45958/36e3e7f3-2049-4adb-a2a7-79c654d92915.pdf
[X] STM32F401CC Specifications: https://www.st.com/resource/en/datasheet/stm32f401cc.pdf