Design of a Human Hand Prosthesis

A Major Qualifying Project Report submitted to the Faculty of the Worcester Polytechnic Institute

in partial fulfillment of the requirements for the Degree of Bachelor of Arts

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Abstract

Current prosthetic hands have limited functionality and are cost prohibitive. A design of a cost effective anthropomorphic prosthetic hand was created. The novel design incorporates five individually actuated fingers in addition to powered thumb roll articulation, which is unseen in commercial products. Fingertip grip force is displayed via LEDs for feedback control. The hand contains a battery and micro-controller. Multiple options for signal input and control algorithms are presented. A prototype will serve as a platform for future programming efforts.

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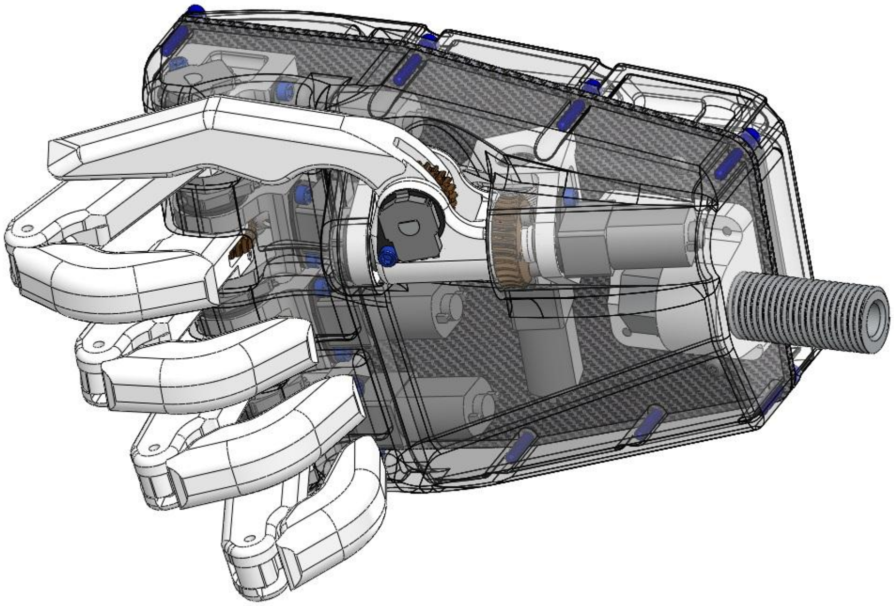
Design of a Human Hand Prosthesis



Acknowledgments

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I would also like to thank Matthew Simpson for helping me work in the machine shops and produce parts for the functional prototype. Finally, I would like to thank Mitchel Wills for spending a great deal of time doing all of the programming for testing the functionality and control aspects of the prototype.

1. Introduction

I have been interested in robotics since I was about 10 years old from seeing movies like Star Wars and Terminator. Designing and building a human robotic arm one day was always a dream of mine. As I grew older, I was surprised to learn that full prosthetic arms were not as common as how the media and news articles portrayed them in laboratory experiments. It turns out that upper extremity prosthetic development is severely behind that of lower extremity prosthetics. This Major Qualifying Project has served as an exploration in researching the current state of prosthetic arms and hands, and ultimately coming up with a new design for a prosthetic hand which is designed to bridge the gap somewhere between simple prosthetic hooks, and expensive uncommonly used robotic prosthetic hands.

There are over an estimated 100,000 upper extremity amputees currently living in the United States alone. (Kulley, 2003) Many of those people could benefit from the psychological gains and physical usefulness of a simple powered prosthesis. It is a sad fact that people who are viewed as "different" in our society stand out, but those people simply want to blend in and be treated normally, and be able to lead normal high functioning lives. Amputees are strong and capable people, who make do with what they have, and are able to overcome adversity. There is room for improvement in all aspects of current prosthetic technology relating to mechanical design, electrical signal processing, and overall system performance. There are not a large number of major companies developing competing products because the market is still quite small and limited from a business perspective. Shown in Figure 1 is an early prosthetic hook and socket created during the Civil War. Modern prosthetic hooks remain very similar aesthetically and it is time to move into the 21st century.

Figure 1 Civil War Prosthetic Hook (Cowan, 2012)

The main goal for this project was to produce a complete mechanical design of a standalone prosthetic hand. The hand would be considered a basis for a future product, but the design would also serve as a mechanical investigation into discovering what should be possible with a different design approach. Ideally, a functional prototype could be produced using the design developed in this project. That prototype could serve as a platform for future MQPs, and academic research both at WPI and other institutions. Therefore, the design had to be thorough enough to enable the final production of a functioning prototype after complete of the project.

2. Background information

At the start of this project, complete upper arm prosthetics as a whole were strongly considered. There is essentially no product on the market today which resembles a complete functional prosthetic arm. There are several companies that produced complete lower arms including retired elbow, but the shoulder has long been overlooked. The marketplace essentially has no room for a complete upper arm prosthetic device because the cost would be so high the third be no available customers. Since 2007, the United States military began expressing interest in revolutionizing prosthetic devices to give wounded soldiers replacement limbs. Many soldiers were injured on the battlefield from improvised explosive devices and landmines. Commonly those soldiers would lose limbs directly or require amputation from shrapnel damage. The military had the budget to help wounded soldiers who had given their limbs fighting for their country. It was clear that lower extremity prosthetics were functional and readily available, but upper extremity prosthetics that essentially not advanced since the Civil War. Most people simply made do with what they had when it came to having an arm amputation. Several soldiers however even loss both of their arms and tragedies and it was clear that something needed to be done for them. (Adee, 2008)

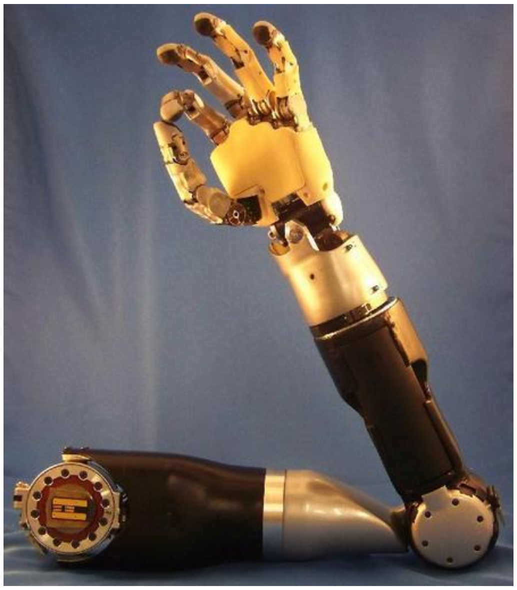

Figure 2 Johns Hopkins APL Arm (New Launches, 2010)

DARPA, or the defense advanced research projects agency, decided to make a huge investment in upper extremity prosthetic limbs. They chose a two-pronged effort by awarding multiyear contracts to Johns Hopkins University Applied Physics Laboratory and DEKA research led by Dean Kamen. Essentially, DARPA has completely solved the problem of building the most advanced robotic humanoid arms possible. Figures 2 and 3 show functional prototypes of the APL and Luke arms ready for testing. The arms can perform almost any task a human can. The only downside to the arms is there cost. The APL arm was a $100 million dollar project, and the DEKA arm was a $20 million dollar project. (Dillow,

2011) Products have not been produced, laboratory prototypes have been produced. These arms were not designed with mass production and market pricing in mind.

Figure 3 DEKA Luke Arm (DEKA Research, 2009)

2.1 Prosthetic hooks

Figure 4 Hosmer 5x Prosthetic Hook (Amputee Supplies, Inc., 2010)

Prosthetic hooks were originally developed in the early 1900's. They have proven to be an effective and reliable tool for amputees to use in their daily lives. Although there are several variations of prosthetic hooks, they all behave in the same general way. There are two hook shaped metal prongs which pivot at the rear section. The prongs are normally held together through spring force. The spring force is supplied by what are known as "tension bands" in the industry, essentially strong rubber bands.

Users can decide how much spring force is required for a given task, and may manually add or remove tension bands as needed with their other hand. The prong hooks are opened by a cable placed under tension. The cable is pulled by a harness being worn by the user consisting of a strap going across the torso and both shoulders. This means that a user must flex their back or shoulders to accomplish the opening action of the terminal hook.

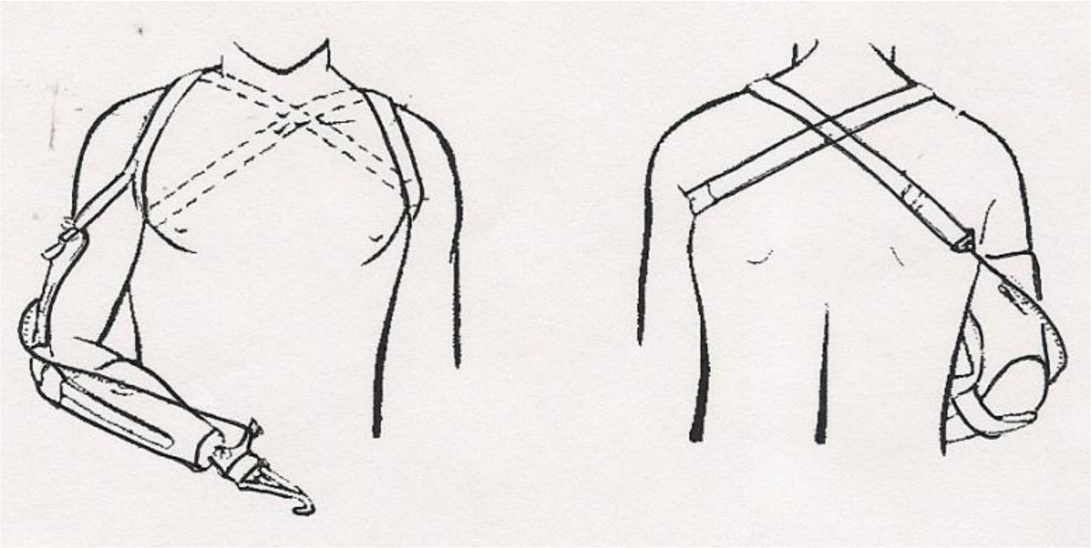

Figure 5 Prosthetic Hook and Harness (Prosthetics, 2010)

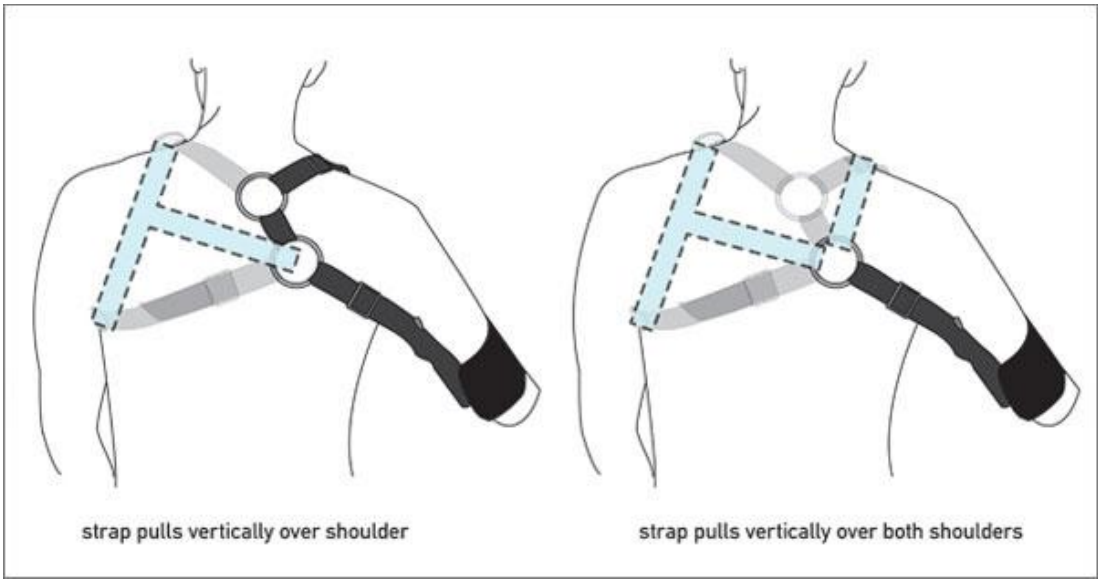

Figure 6 Body Powered Harness Motion (Schweitzer, 2011)

There are several advantages to using prosthetic hooks. Hooks are incredibly reliable; there are only one or two moving parts the entire system. There are no batteries to be charged and there are no electronic components which could possibly fail. In general if something needs to be adjusted with the system common hand tools can be used. The hooks can handle high mechanical loading which is useful for physical labor and strenuous tasks. Users have no fear of damaging components of the hook through rough usage. The inside of the hooks are generally lined with a high grip rubber material. Overall the prosthetic hook systems are very cost effective considering their long lifespan. An entire strap and harness with hook would usually cost less than $9,000 and last many years very easily. Simply put, a user would have no worry about component failure on a day-to-day basis. The bulk of that cost comes from the custom molded socket. The socket is usually made of carbon fiber and molded individually for each user depending on their unique amputation.

Figure 7 Sean Mchugh (Mchugh, 2012)

Prosthetic hooks come with their own limitations. The single greatest limitation stems from the fact that the holding force of the hooks is supplied ready manually adjusted spring tension bands. In order to have a high gripping force, the user would have to strain their muscles to open the hooks which can lead to muscle fatigue or pain. High gripping force is generally desired when handling a large or heavy object. For example, holding onto a broom handle or rake proves to be quite challenging due to the large amount of force required. Related to the limitation of muscle force required to open prosthetic hooks, users often report pain from a strap and harness during activities which require frequent opening and closing of the end effector. One frustration with prosthetic hooks comes from having to change the tension bands manually in order to adjust the gripping force. Multiple tension bands have to be carried at all times and require use of a secondary hand and earth to make changes. The same force desired to securely hold a heavy object is enough to crush a lightweight object such as a thin plastic bottle or some foods. (MIGUELEZ, 2009)

One overarching issue found the prosthetic hooks stems from the social stigma of people who are seen as different in society. Everyone in the world strives to be seen as normal and lead a normal functioning life. Far too often, amputees report discomfort in social situations from being stared at or treated differently. Prosthetic hooks standout easily with their unusual shape and function. Many people still associate prosthetic hooks with pirate hooks sadly. In addition to social issues, wearers of prosthetic hooks report dissatisfaction in their personal lives in and relationships with friends and family. Users find it more challenging to show affection through their prosthetic hook because of its unusual shape and feel. It can be challenging to care the harness with certain styles of clothing.

2.2 Current prosthetic hands

Common Prosthetic Hands

Figure 8 VASI Hand Family (Technologies, Liberating, 2012)

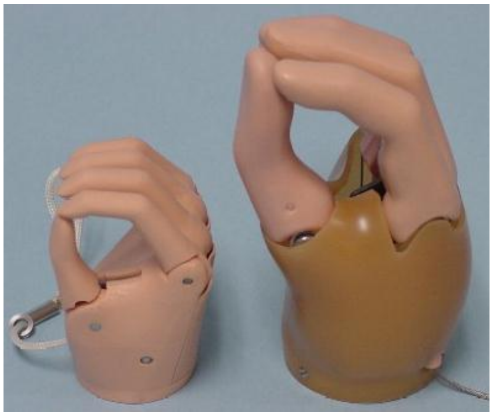

Figure 9 Mech Hands (Technologies, Liberating, 2012)

There are commonly available prosthetic hands which offer very limited and simple functionality. All of these hands offer one action, opening or closing. They generally have a very blocky appearance, and often have 3 fingers instead of 5. The simple hands were easier to design and build, but cannot perform many tasks required of the user.

BeBionic and iLimb Hands

Figure 10 BeBionic Hand (Advanced Arm Dynamics, 2012)

Figure 11 iLimb Hand (Arthur Finnieston Prosthetics + Orthotics, 2012)

Several years ago, robotic prosthetic hands with individually articulated fingers were released onto the market. These hands were completely revolutionary in their look and function compared with other prosthetic options that existed. Touch Bionics was the first company to release one of these hands known as the “iLimb”. The iLimb is based around the design of an individual finger, known as “digits” by

Touch Bionics. Each finger contains its own motor and gearbox which is very helpful when designing a prosthetic hand which must fit inside human proportions. In fact, amputees who are only missing partial fingers may simply use as many Digits as they need in a custom solution from Touch Bionics.

Each finger has a joint at the base and one pivot point at the first knuckle. The fingertip is passively actuated by being pulled on by a cable. One interesting mechanical aspect of the fingers is a spring linkage which allows the fingers to be manually bent inwards to prevent damage if the hand hits into a hard object. Altogether, the iLimb has 5 degrees of freedom. User input is controlled through myoelectric sensors reading the muscle signals remaining on a portion of an amputees arm. The control is designed to be intuitive in this sense that a person should optimally be able to open and close their hand with the same muscle signals they would normally send them to an actual human hand. Touch bionics boasts 14 different grip patterns which are all subtle variations of the most commonly used patterns. (Touch Bionics, 2012)

Overall, the iLimb is a fantastic product which has given a tremendous amount of increased functionality to the lives of many amputees. The iLimb however does not have an actively powered positionable thumb. The user must use their other hand to manually rotate the angle of the thumb. For example, if a user is eating a meal and has their hand in a key grip mode for holding onto a spoon or fork, and then decides to drink from a glass or cup, the user would have to manually rotate the thumb down until it is in position for a cylindrical grip. The iLimb does at least contain a sensor to recognize the current position of the thumb to help ensure the hand is not going to damage itself in certain grip modes. There is also no force feedback provided to the user, so it can be difficult to perform precision tasks. As a result of the lack of force feedback, users may inadvertently drop objects because they are not being gripped firmly enough, but there is no indication before it is too late and the object has fallen.

Figure 12 Darin Sargent (Sargent, 2012)

Several people have posted videos on the Internet demonstrating how they use the iLimb to perform daily tasks. Due to the fact that there are such a low number of prosthetic hands available on the market, these videos serve as a great tool for spreading information about options for the prosthetic community. One such man named Darin Sargent created an entire video diary explaining the process of him obtaining the iLimb from initially hearing about it, all the way through months of use. He documented his journey clearly and excitedly including the emotional highs and lows along the way. The most viewed video of his diary is an extremely touching moment which candidly captured his younger daughter reaching for his prosthetic hand to hold onto it, as if it was his real hand. The young girl accepted the prosthetic limb as his actual hand in that moment.

One surprising moment from Sargent's video diary was the explanation of his initial discussions with Hanger Prosthetics. Hanger Prosthetics was a local distributor recommended by Touch Bionics who specializes in custom prosthetic and orthotic devices. Hanger Prosthetics is a large national chain well known in the prosthetic community and industry. The sales specialist described that the full the cost of the prosthetic hand should be covered completely by insurance. They disclosed that the cost of the hand would be a staggering $60,000. Sargent, as well as most people, had a very small budget, so paying for the hand out right was not remotely an option. It was several weeks of back-and-forth phone calls from the insurance company and Hanger prosthetics before it was concluded that the insurance company would be willing to cover most of the cost of the prosthetic hand. This would normally sound like good news, but that they would only be able to cover 75% of the cost, which would leave $15,000 still to be paid for. This was simply too much money for Sargent, but the people at Hanger prosthetics were persistent enough with the insurance company to reduce the cost until only $1000 remained. This side story helps explain just how expensive robotic prosthetic hands actually are.

The BeBionic hand is incredibly similar in construction to the iLimb. The BeBionic hand was produced by RSL Steeper with the intention of offering similar functionality to the iLimb at a slightly reduced cost. Some people speculate that the hand is a direct spinoff based on identical mechanical components. There are little to no functional differences between the two hands, so they are considered the same for the sake of discussion.

Michelangelo Hand

The Michelangelo Hand built by Advanced Arm Dynamics is simply the most advanced hand on the market today in prosthetics. It actually has the powered opposable thumb, the first one released as an actual product. Sadly, the arm costs $100,000, so it is unable to be purchased, and difficult for even insurance companies to pay for. (Pittman, 2012) The hand is incredibly well refined and streamlined in execution.

Figure 13 Michelangelo Hand (Schweitzer, 2011)

Interview with Art Shae

I was fortunate enough to find a local Prosthetist named Art Shea who works at New England Orthotics and Prosthetics. They are a local branch right in Worcester, about 1 mile from WPI campus. Art was incredibly nice and honest, willing to answer all of my questions. Our discussion was very helpful in narrowing down the scope of my project early on in the design phase. At the time, I was still considering investigating a complete human arm as opposed to focusing on the hand, but when he described the low level of amputees who are missing a complete arm it lead me towards the hand.

Art was very frank in explaining why prosthetic devices can cost so much, they are all custom and most of the cost comes from the frequent visits with the prosthetist as opposed to the actual cost of the device. Each amputee has a unique situation. Not everyone can accept a socket or prosthesis at all because of problems with nerve damage and pain levels, or bone fragmentation. He also offered me several older prosthetic part catalogs which lead to my inspiration of designing a hand that would be able to bolt in directly where a hook used to be. If an amputee has already gone through the time consuming and difficult process of getting a custom socket, then they are more willing to experiment with new and different terminal devices.

2.3 Design methodology

The overall design for this prosthetic hand was treated as an investigation of feasibility. After performing the necessary background research and studying the available products on the market, it was determined that constructing an entire prosthetic arm was not necessary. A prosthetic hand would be much more realistic to design any limited timeframe of this project. Additionally, the market for a prosthetic hand is substantially larger than that of complete prosthetic arms. (Bradford) The process for designing this new product focused first on what needs of the user would be. Those needs were assessed through research and confirmed with a professional prosthetist. Next, products on the market are carefully evaluated for their function and key attributes.

In order to build upon current ideas, areas of potential innovation were discussed. Mechanical ideas included novel actuation methods such as hydraulics and pneumatics or linear motors, central transmissions with variable clutches, then spring storage techniques. Mechanical linkage concepts ranged from cables and pulleys to gears and four bar mechanisms. Ultimately, it was decided that the main unique novelty of this design would be the actively articulated thumb roll motion. None of the current prosthetic hands on the market included a powered thumb roll. Additionally, on the controls side, it was determined that including a visual force feedback to the user through variable brightness LEDs would be innovative. Finally, an overall theme of cost reduction would put this prosthetic hand into a much broader market.

A set of design requirements was formulated and adhered to for the remainder of the project. The design process began with brainstorming followed by rough pencil sketches and finally detailed computer aided design work using Solidworks CAD software. As the mechanical design progressed, both electrical and mechanical components were sourced and integrated into the design. The design was continually updated with new iterations each day until it was optimized enough for manufacturing purposes. When doing detailed design work, a "product" mindset was adhered to. This meant that the quality of the finished product, in addition to the manufacturability, would be of equal importance. For example, when possible, multiple of the same components should be used as opposed to individual separate components. Similarly, reducing the overall number of parts and components would be hugely beneficial. Understanding and thinking about how each custom component would be manufactured was accounted for during the detailed design process.

2.4 Design requirements

User Interface-

-Hand will be safe to use and handle during operation

-There will be covers or a shell over all components for protection from common impacts

-Attachment locations will include currently used standard universal socket methods

-(½-20 stud interface)

-Batteries will be easily swappable or rechargeable with 1 hand and no additional tools

Human Form Factor/Appearance-

-Will resemble the general form of an adult human hand

-Entire hand will weigh 450g including self-contained power and control

-Hand will consist of 6 DOF, 5 individually actuated fingers, plus thumb roll

Mechanical Power/Speed-

-Hand will have 15 lbs cylindrical grip force

-Finger tips will have 1.5 lbs force while extended

-Fingers will be able to travel from fully opened to fully closed in 1 second or less

-System will last at least 2 hours under continual use, and idle operation of at least 12 hours

Control and Sensor Integration-

-Fingers will contain at a minimum 1 analog force sensor per finger

-Each joint will have analog position feedback throughout the range of motion (rotary potentiometer or encoder)

-Each joint will utilize commercial off the shelf electronic speed controllers

-There will be a commonly available standard microprocessor able to handle sensor inputs and motor outputs, for example an Arduino Mega or equivalent.

Manufacturability-

-Design will utilize COTS parts as much as possible

-Entire cost to manufacture and assemble one complete hand will be less than $3,000 at quantity (1x) and less than $2,000 at quantity (100x)

Safety/Failsafe Conditions-

-If input control signal is lost, all actuators and motion will stop.

-If the battery is running low, the LEDs will signal the user for recharging.

-The hand will not be able to destroy itself, all actuators will have software and mechanical limits to prevent unwanted motion at joint limits.

3. Mechanical design

Detailed mechanical design was accomplished through the use of rough hand drawn sketches and Solidworks CAD software provided by WPI. Backup data and part files were kept throughout the design process and can be made available upon request. Individual parts were carefully modeled with as much detailed information and accurate dimensions as possible. When working with such limited space and small components, accuracy was a priority.

3.1 Finger Linkage Design

One single finger was the starting point for the entire design process. The human hand was studied visually while grasping and handling many different objects. Being that the hand consists of four similar fingers and one thumb, it was logical to conclude that the finger design could potentially be replicated four times. This meant that if the size and space requirements to actuate one individual finger proved too large, then another method would be needed. The finger design process began with determining what motion was required for each finger. The human hand was simply viewed gripping various household objects such as a cup and marker commonly found in a person's daily routine. The location of the various joints were measured and translated to drawings. The human finger is an amazing piece of engineering consisting of three individual pivot joints which can almost be individually actuated through muscular tendons. The four main fingers can also be spread apart sideways and rolled slightly culminating in an impressively large amount of total degrees of freedom. Fortunately, to perform the majority of common gripping tasks, only a small amount of motion should actually be required. The human finger achieves a conformal adaptive grip by bending the knuckles as an object is grasped.

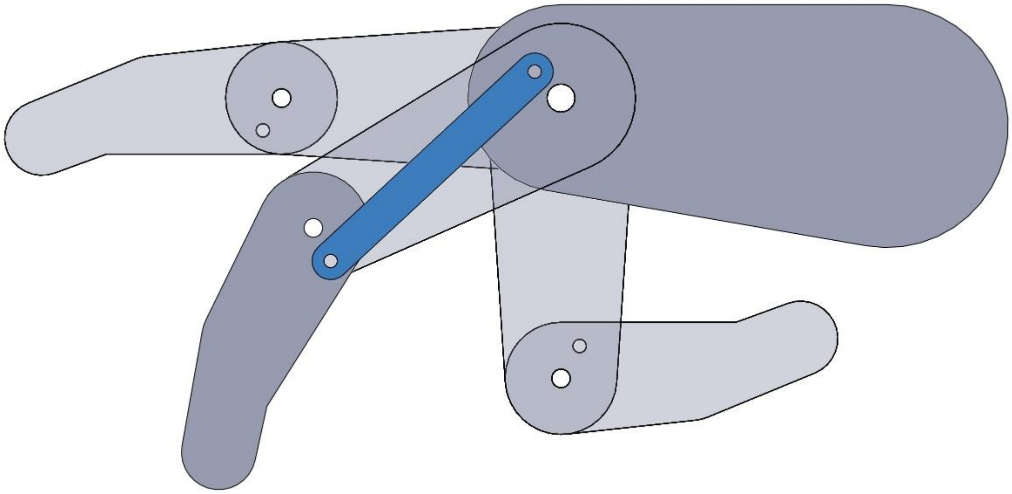

Figure 14 Initial Finger 4-Bar Motion Study

By carefully studying your fingertip, it can be viewed that the final knuckle joint only rotates a small amount. Therefore the first opportunity for simplification comes from treating the fingertip as one fixed link as opposed to two separate links joined by a knuckle. The parts of my index finger were carefully measured and a rough CAD model was produced consisting of a side view of one finger in the profile of a palm. As previously described, the fingertip was treated as one link with the final knuckle fixed slightly bent. An assembly was created in Solidworks which allowed for the motion of the two joints to be studied. The human finger when viewed from the side is convenient in that it rotates approximately 90° from full extension to full closure. Similarly, the second knuckle joint also rotates approximately 90° at this time. As one slowly flexes their hand from fully opened to fully closed, it becomes clear that the two joints move at approximately the same rate in a 1:1 ratio. That realization opened up many mechanical possibilities for simple linkages which would allow for the base finger to be rotated actively while at the same time passively linked to the first joint.

Previous robotic hands have demonstrated a linked finger motion including the ilimb. Robotic hands built in research labs have a commonly used tiny cables and pulleys linked in a figure-8 layout which consumes very little space and achieves a nice constant pulling force. Miniature cables are able to handle very high loads considering their small size and weight, but they are difficult to design in a robust and simple system that does not require constant maintenance. Usually, the termination of the cable ends proves to be very difficult to accomplish and leads to many problems. Tensioning high strength cables in small spaces is another constant problem. On the other hand, simple mechanical linkages are incredibly robust and reliable if they can be designed into the system. One link can act under both tension and compression, allowing for active force to be applied during both the closing and opening of a joint. There is no complicated procedure for installing or maintaining a linkage system.

When looking at the finger motion in the Solidworks assembly, a link was added joining the palm or base of the hand to the final fingertip. As the first joint of the finger was rotated, linked motion of the fingertip was achieved. The location of the linkage pin holes was kept at a constant radius of ¼” from the points of rotation. By maximizing this distance, the link would be under the least possible amount of stress and help reduce backlash in the final product. The angle of the linkage pin holes was a variable, as well as the length of the link itself. All of those variables were constantly adjusted until the desired visual motion was achieved. By moving the first finger joint through a 90 degree arc, the fingertip was also moved in a 90 degree arc relative to the first joint. The motion appeared smooth and relatively constant throughout the range of motion. When designing 4 bar mechanisms, it is important to make sure that an over center, or toggling situation is not going to occur. Due to the fact that only 90 degrees of total motion was required, toggling was not really an issue; the link was stable even at the extreme positions. The motion was verified by holding a real human finger next to the computer screen and moving the Solidworks assembly at the same time as a real finger joint.

3.2 Finger Joint/Drivetrain design

Once the finger motion assembly was chosen, the next step was to choose how to power that finger joint. Electric DC motors are by far the simplest and best option for this application. Hydraulic and pneumatic components would introduce tremendous packaging and safety issues, as well as unusual control problems. DC motors are widely available in multiple sizes and power options, with a variety of COTS electronic speed controllers. The first thing to be evaluated in this system was to look at the approximate size consumed by a simple transmission and motor setup to see if it would roughly fit into the form factor of a human hand or not.

At this time, some other control and usage aspects began to drive the finger drivetrain design. In the ideal world, a user would be able to command a finger to go to a location and the finger would be able to stay there without constantly applying power. For example, if a heavy tool is to be grasped, the hand would close its fingers around that object until it is held securely. Once the sufficient gripping force is achieved, the motors would stop. In a traditional electric motor situation, a constant voltage would have to be applied to a stalled motor in order to produce a constant output force. This would be very bad for the system because it would be inefficient and constantly wasting available power. Additionally, almost no electric motors can handle being stalled for even short periods of time, even at low power; motors are not designed to be heaters. Therefore, the proper mechanical drivetrain would include some type of active braking or force holding aspect which would somehow allow the motor to be turned off without having the fingers move when force is applied. If the fingertip was flexible enough to act as a spring, then once the finger was closed and held at a certain position, the tip would be able to constantly apply a spring force to a grasped object without the use of constant power.

Worm gears stood out as a clear option for a system of this nature. Work gears provide very high reductions in small spaces, and they also have non-back driving tendencies. In some mechanical systems that can be a problem, but in this system it would be a desired trait. Additionally, a worm gear transmission isolates mechanical shock to the input gear only, and nothing before the input gear, so a motor would be protected from system shocks. Worm gears however have one major drawback, they are very inefficient. Common worm gears have 1 screw start, or “lead”, and rely on sliding friction between the input worm and the driven worm gear. Efficiencies of 50% are considered common even with low friction brass gears, compared to 95-98% efficiencies common in spur gear transmissions. A middle ground however is to use 2 start worm gears which are not as inefficient as traditional worm gears, but still provide anti-back driving tendencies. Worm gears were shopped for from common industrial suppliers to make sure that standard off the shelf gears would be used. Stock Drive Products, or SDP-SI, demonstrated and interesting phenomenon were the pitch of a worm gear is not always related to how small it is. Finer pitches than 48DP resulted in worms which were actually larger in diameter, which was surprising. Therefore, 48DP was chosen as the desired worm pitch, with an abundant selection on input worms and worm gears of all different tooth counts and bore configurations. A 24 tooth brass gear, 1/8” face width was selected for its ½” pitch diameter. If that gear was any smaller, then the load on the gear teeth would be unnecessarily high, and if it was larger, the gearbox design would grow too large to fit in the proportions of a human hand.

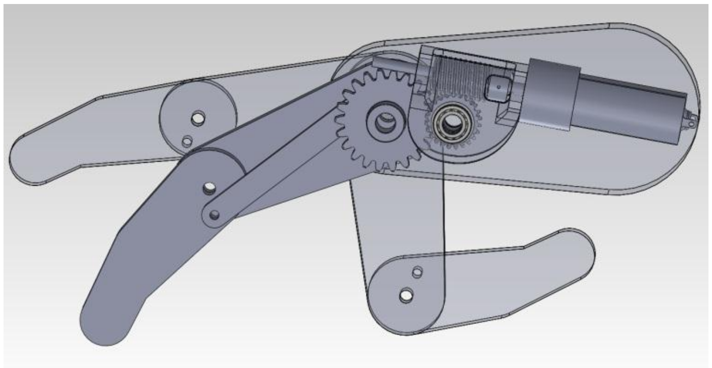

Figure 15 Initial Finger 2-Stage Reduction Design

A simple one piece worm gear gearbox was designed in CAD which would have a notional small DC gear motor attached to one face, and the output shaft perpendicular to the input shaft. On the first attempt at packaging, a second stage of gearing consisting of 24 pitch spur gears was added to attempt to keep the entire transmission inside the profile of a human hand. Although the packaging accomplished that task, it introduced a large number of components and added complexity that was not optimal. Next, as can be seen in Figure 16, a simpler gearbox was designed which directly linked the worm gear to the first joint of the finger.

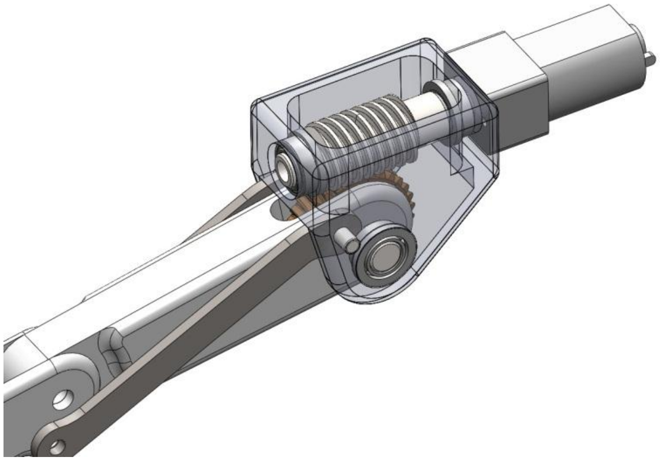

Figure 16 Early Refined Finger Gearbox

This design aspect allowed for a low number of parts, especially gears and transmission componenets which can be expensive. Overall, a one stage reduction would also be more compact overall than a two stage reduction, even though it would appear larger by slightly violating the physical dimensions of a human hand. A design of this nature would give the prosthetic hand the appearance of having tall knuckles with an abrupt ledge. This design style was selected for its overall simplicity with the size violation tradeoff taken under consideration to be kept as minimal as possible.

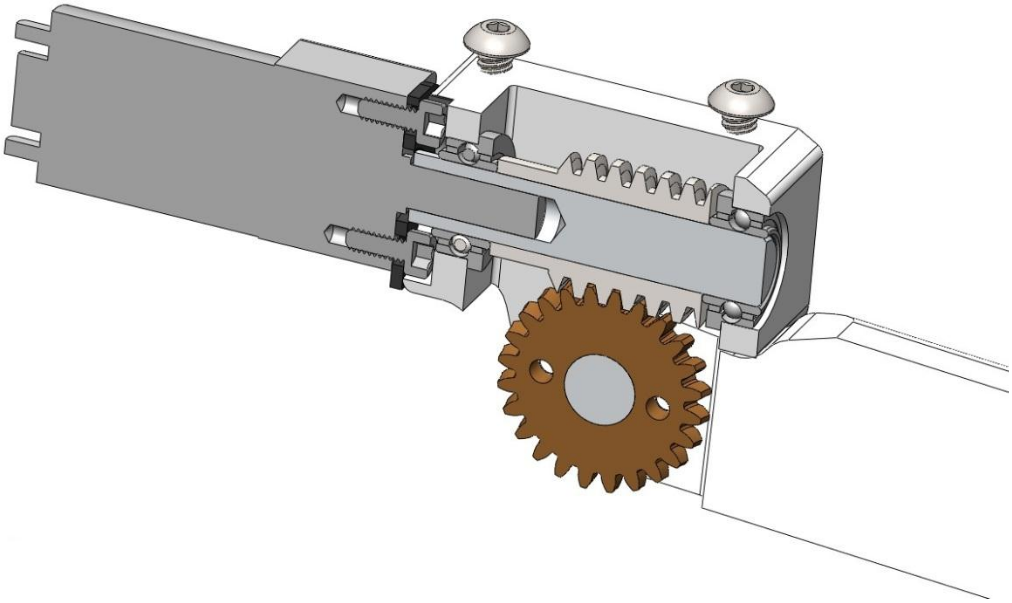

Figure 17 Final Finger Gearbox Section View

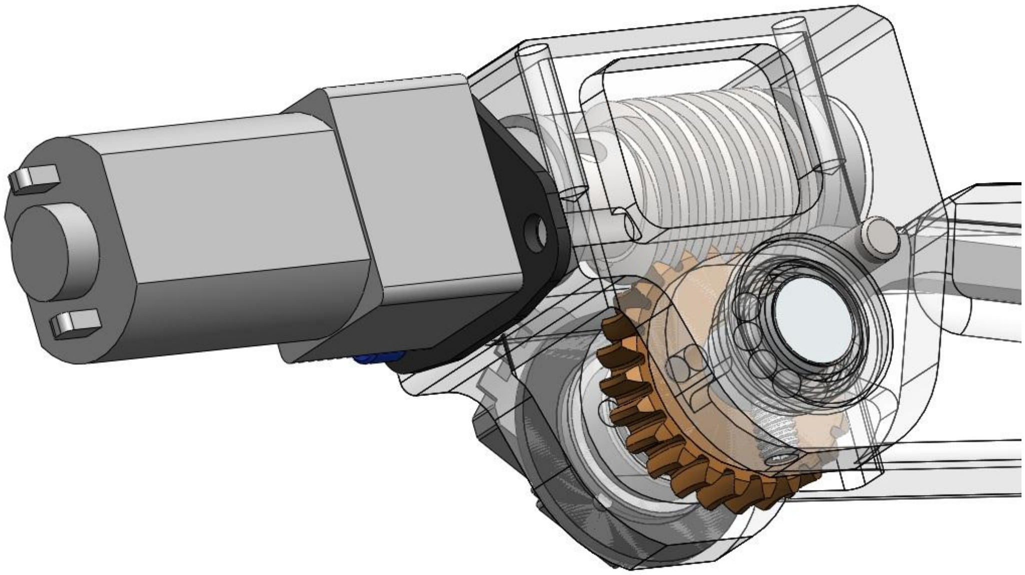

Figure 18 Final Finger Gearbox Solution

These images show the results of detailed CAD work and design iteration and refinement. The final finger gearbox is able to rotate the finger joints through 110 degrees of motion. The one piece gearbox body is designed to be CNC milled out of plastic, ideally Delrin selected for its high strength and ability to be easily machined and hold threads well. Being one single piece makes it easier to manufacture and ensures that the two intersecting shafts will line up accurately. The gearbox has 6 flat perpendicular faces to also aid in manufacturability. Ball bearings were selected for all rotating shafts because it is difficult to source small precision bushings with small wall thickness and short lengths. Ball bearings do add increased cost and parts compared to just using the plastic body of the gearbox as a plain bearing, but it was a good choice for reducing additional friction as much as possible considering the fact that worm gears were already being used. The ball bearings were flanged also so the thrust loads from the worm gears would be handled by the bearings. High strength 7075 aluminum alloy was chosen for highly loaded components such as the main joint pivoting shaft. The shaft would have to handle the force from any objects held by the fingers, which could potentially be heavy and introduce dynamic forces. Precision ground 7075 aluminum rod from an industrial supplier was perfectly suited for this application. That same aluminum rod could also be used for the input worm shaft because the 48 pitch worm gear came pre-furnished with a 3/16” bore. 3/16” bore ABEC 5 flanged ball bearings with a 5/16” outer diameter were commonly available from multiple sources including McMaster. The 24 tooth brass worm gear was also available with a 3/16” finished bore from an industrial supplier.

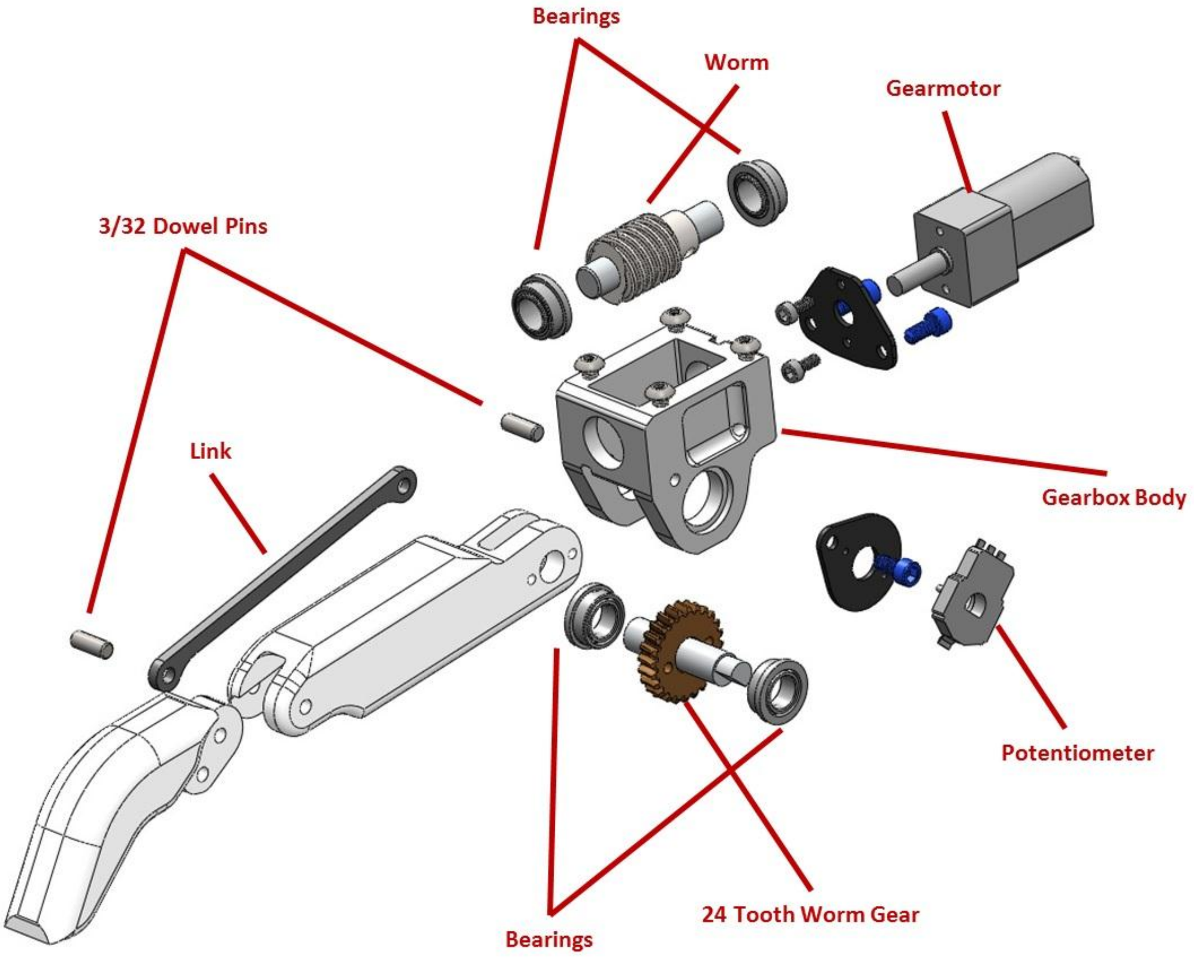

Figure 19 Finger Gearbox Assembly Exploded View

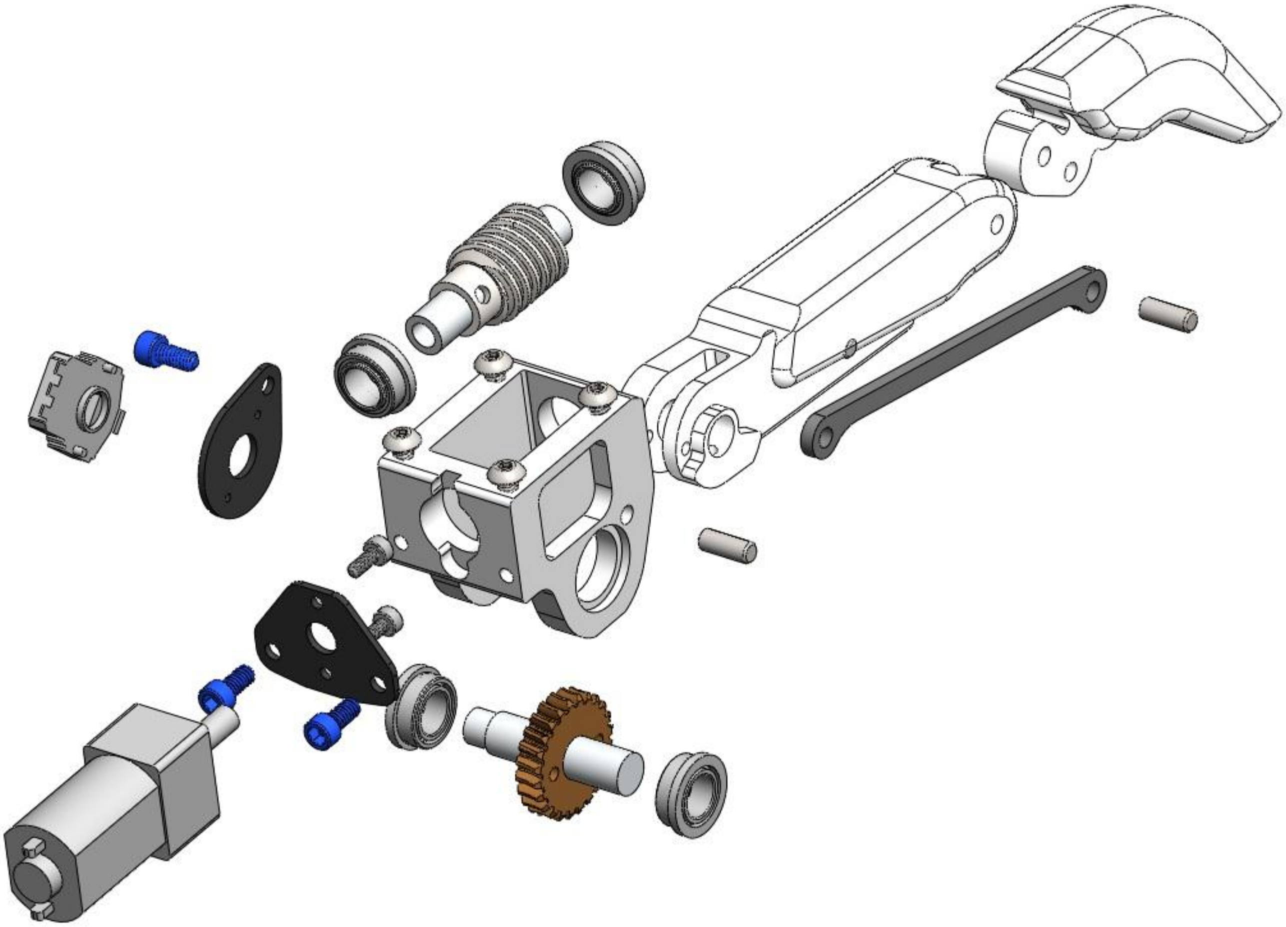

Figure 20 Finger Gearbox Assembly Exploded View 2

The linkage joints and finger knuckle joints were very simply designed as COTS alloy steel dowel pins. 3/32 dowel pins are rated to break at 1,400 lbs in this double shear configuration, and would be very easy to press into plastic parts with bores undersized by .001”. The remaining mating parts would simply rotate on the dowel pin without a bearing because of the low speed and limited rotation of the components. The linkage was also designed from 7075 aluminum, and was made larger than it needed to be for strength purposes in order to make it easier to machine. If the link was made very thin, and with small diameter holes, then it would have to be cut from sheet stock with a laser cutter or wire EDM, which would add manufacturing cost. By being made 1/16” thick, and having 3/32” holes, the link was able to be easily CNC milled. The motor mount and the potentiometer mount are made out of the same material, thin Delrin sheet 1/32” thick. These parts can be laser cut very easily or injection molded if quantities were high enough. As an added bonus, if the motors or potentiometers are desired to be changed, then a new mount can be designed to simply accept those components, and the rest of the finger gearbox could remain intact.

The fingers are designed to be made out of polycarbonate for its high strength and durability. As an added bonus, the transparent polycarbonate has a beautiful aesthetic quality to it. Additionally, adhesives stick well to polycarbonate which is needed for attaching the rubber grip liner to the fingers. Polycarbonate machines very well and has the strength needed to handle some abuse from user impacts and potential damage. The width of the first finger joint matches the slot opening of the gearbox body, so lateral forces are directly transferred to the gearbox walls without any additional parts. The driving worm gear transfers torque to the finger through two COTS 1/16” alloy steel dowel pins. The holes are easily machined into both components and reamed .0005 to .001” undersize for a light press fit. One elegant aspect of the finger design is the fact that the linkage is contained within the finger so there are no additional external moving parts. This did complicate the design of the first finger piece, but it made for a nicer final product by reducing the number of additional components. The finger parts were designed to be CNC milled or molded if desired in large enough quantities.

Once the components for one complete finger were selected and all of the parts were designed, the finger assembly was put into a temporary model of a complete hand. Four 2-56 tapped holes in the top surface of the gearboxes were used to mount them to the main carbon fiber chassis plate with alloy steel COTS button head fasteners. It was determined that the individual fingers fit inside the general anthropomorphic shape of the human hand, so that was acceptable. Additionally, it became evident that it should be possible to simply duplicate 4 identical fingers to comprise the index, middle, ring, and pinky fingers for this prosthetic hand. Although the real human hand has fingers which vary in length and shape, the general form of identical fingers should achieve similar gripping performance while still maintaining the psychological aspects of keeping a general human hand shape. To aid in the human effect, the fingers were positioned angled out slightly similar to the positions of a real human hand. If it is felt that the final fingers should be closer in shape to real human fingers, then the only pats which would need to be changed would be the polycarbonate finger pieces and the length of the aluminum link; all other components would remain identical.

3.3 Motor Selection

Proper motor selection was an important aspect of this design because all 6 degrees of freedom could be powered by the same type of motor. A range of different motors were compared based on their speed and torque in addition to their size and cost/availability. Teble 1 illustrates data gathered while searching for a suitable motor option.

Table 1 Motor Specifications

Name	Reduction	Voltage	RPM (no load)	Stall Torque (in-lbs)	Stall Torque for 15 RPM	Weight (oz)	Comments	Lead Time	Cost
B62	62:1	14.4	360	13.75	330	2.47	Easy to work with	none	$30
A-max 16 352856	1:1	13	11800	.042	33	.74	No GB	4-8 weeks	$58+GB
RE 16mm 118731	1:1	11.5	14000	.312	290	1.4	No GB	4-8 weeks	$128+GB
Pololu 250:1 HP	250:1	6	120	3.75	30	.35	Open GB	none	$16
Escap 16N78-212P	1:1	6	9300	.108	67	.85	No GB	none	$60
Escap	1:1	6	8700	.584	338	1.87	No GB	none	$75
SRV Drive	100:1	7.4	330	1.50	1.5	.31	Tiny, fragile	none	$15

Figure 21 Pololu 250:1 Gear Motor HP (Pololu, 2012)

The Pololu DC brushed gear motors are a perfect fit for this application. They are very tiny, yet still quite powerful. They are convenient to work with by have 2 face mount screws, and a flatted output shaft. The best feature of these motors though is the fact that Pololu offers dozens of different gear reductions all in the same motor package size. This means that even after the entire hand has been built and tested, if it is discovered that there is too much friction in the system and more torque is needed, a new motor can simply be swapped in and nothing else on the design would have to change. The motor selection is a perfect example of a situation where a large industrial company would simply look at the absolute highest power to weight ratio precision industrial motors. In this case, the most weight you could save would be about .1 oz per motor, and a very tiny amount of space. That change would come with a very hefty price tag however. Motors which cost $5-$15 are very different than $100 motors when your application has 6 of them, and a desired final budget of $2,500.

3.4 Compound Thumb Design

The compound thumb gearbox with integrated roll is the heart of this prosthetic hand design. It is the single most novel aspect, and what sets the design apart from the other current products on the market. Figures 22 and 23 show very early design planning of the hand with thumb added.

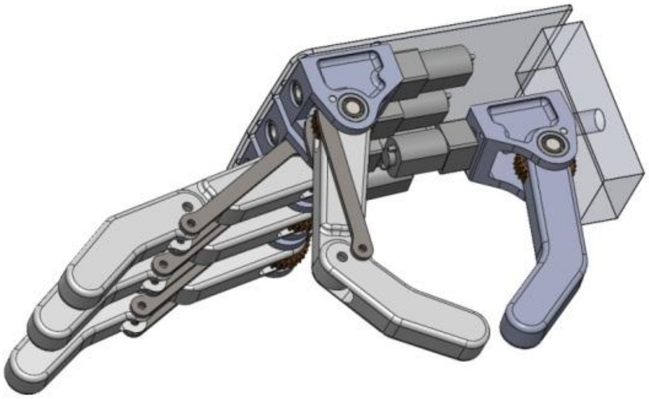

Figure 22 Preliminary Design Demonstrating the Pinch Grip

Once the main finger gearboxes and components had been designed, the most challenging aspect of the novel prosthetic hand was evaluated. The process of designing the thumb joint began in CAD by placing a duplicate finger gearbox into the rough hand assembly, but replacing the finger which has two links with a single jointed thumb shape. The initial placement highlighted the difficulty of packaging so many motors and moving parts into such a confined area. Several thumb positions had to be examined: a pinching position aligned with the index finger, a fist with fingers overlapping, and the thumb rotated up into a key grip position.

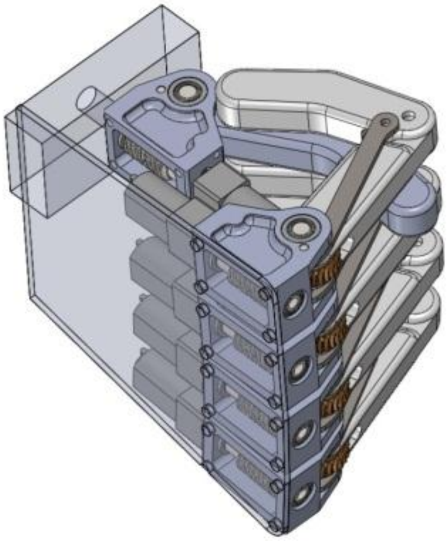

Figure 23 Preliminary Design Demonstrating the Power Grip

From the preliminary CAD positioning shown in Figures 22 and 23, it was clear that the thumb roll axis would need to be angled away from the main chassis plate close to 15 degrees in order to achieve the proper thumb location during a key grip. It was also evident that the thumb would not need to be jointed to achieve desired functions, similar to the one piece finger tips of the rest of the fingers. One purpose of the thumb is to oppose the index finger during a precision pinching grip, in that example it simply needs to remain at a known location, and not even be actuated. During a cylindrical grip, the thumb should close in-between the index and middle fingers to provide additional clamping force and support on the grasped object. This is different from current prosthetic hands which do not allow for thumb and other fingers to overlap each other. The thumb should also be made of polycarbonate and be flexible enough to act as a spring in order to apply a constant holding force without active power application. The other primary thumb position would be when the thumb is rotated up to perform a key grip. The thumb would be very useful for holding onto a spoon or fork when it pushes down onto the side of a partially closed index finger. Therefore, the thumb needed to be able to satisfy those three main conditions.

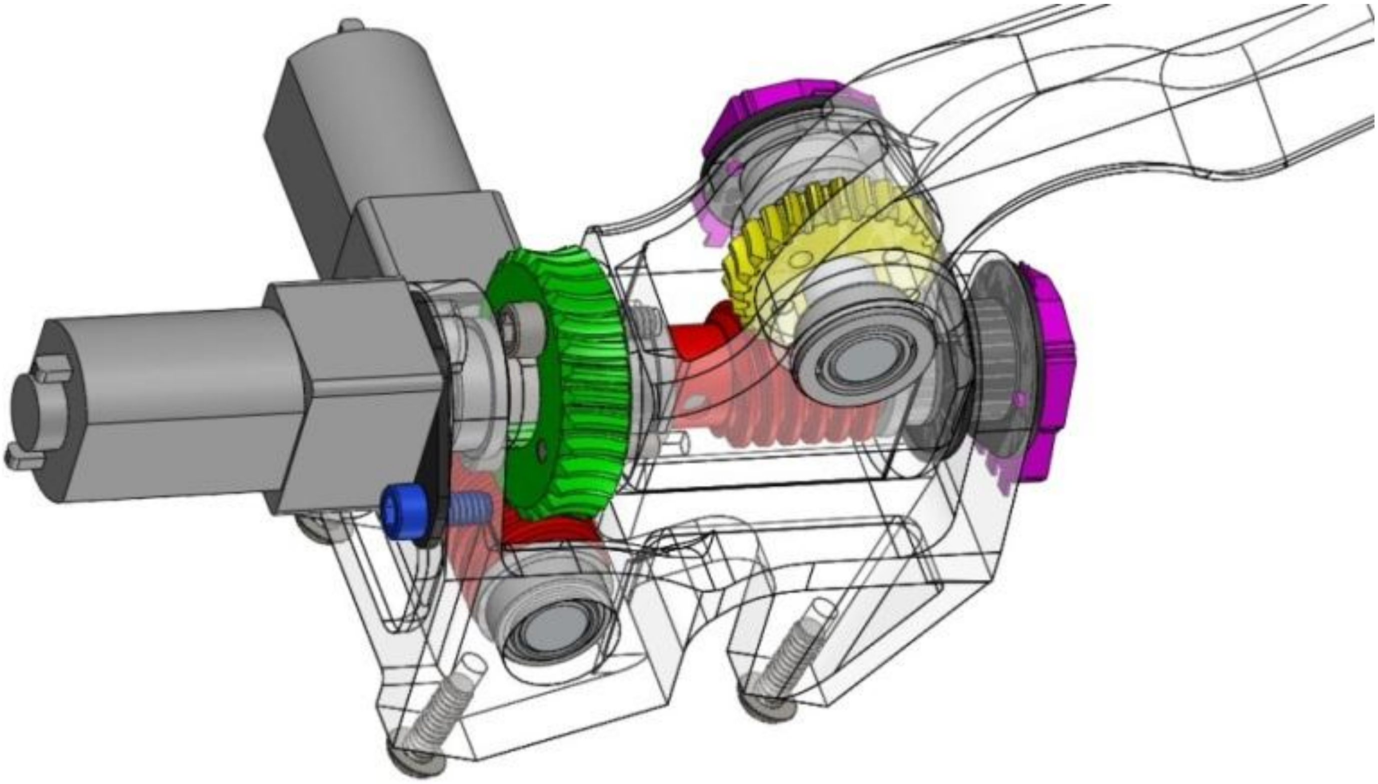

Figure 24 Final Compound Thumb Gearbox Solution

After careful design iterations in Solidworks, solutions for the locations of the thumb pivot and roll axes were discovered. Then, a complex gearbox was developed, described as a “compound worm gearbox”. The basic principle used to design this was to use the input shaft from the thumb flexing joint as the structural pivot for allowing the thumb to roll. The same components were used once again from the main finger gearboxes to keep the design as simple as possible. The design is explained more clearly by the colors of the individual components in these figures. The thumb itself is pinned directly to the reused (yellow) 24 tooth brass worm gear in the exact same way as the main fingers with the again reused 1/16” COTS alloy dowel pins. The simple Delrin gearbox has the same ball bearings pressed into it used in the rest of the fingers, with another 7075 aluminum shaft. The same potentiometer (purple) reads the position of the thumb flex, although the 1/32” thin Delrin potentiometer mount has been slightly modified for wire routing purposes seen in Figure 25.

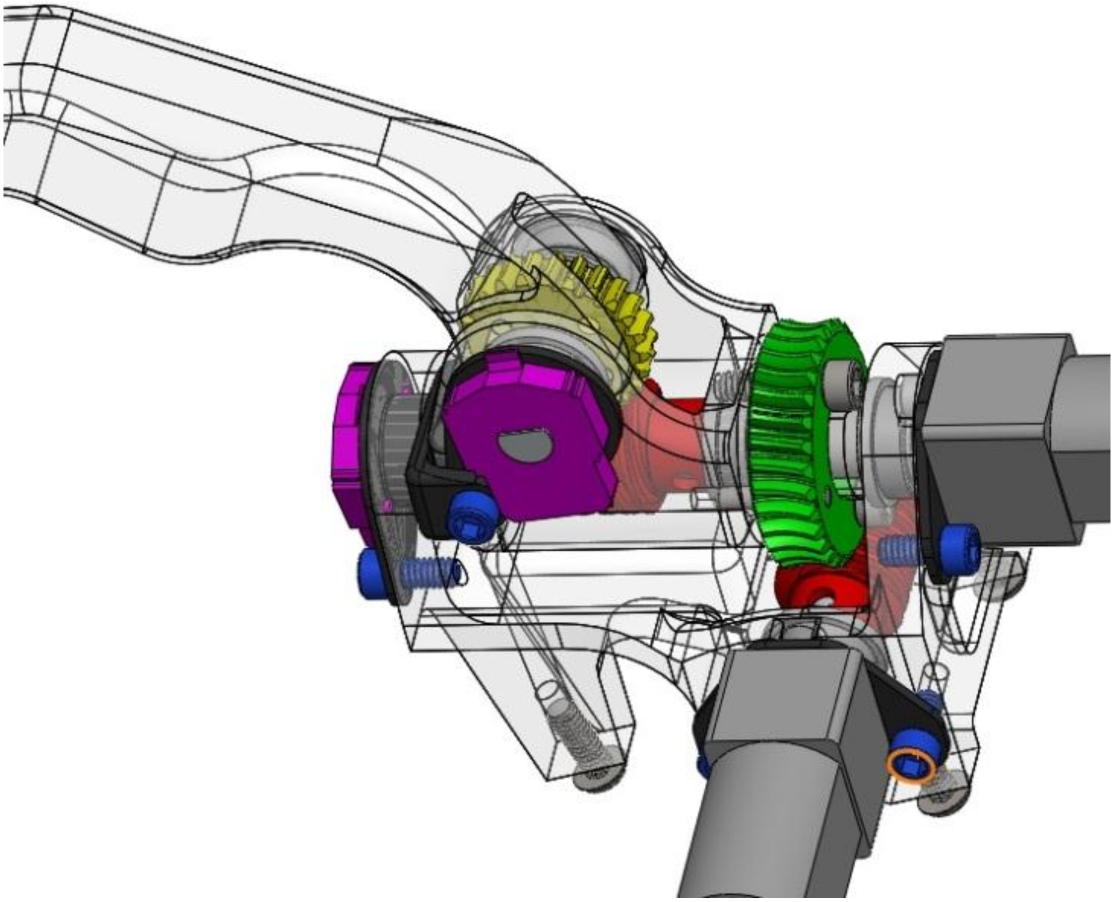

Figure 25 Final Compound Thumb Gearbox Solution 2

The (green) 30 tooth brass worm gear is used to provide the novel thumb roll rotation. The gear is pinned with alloy steel dowel pins to transfer torque to the thumb flex gearbox body, and it is attached to that body with two 2-56 cap screws. The gear is pressed over a boss of the gearbox to ensure concentricity and not put additional loading on the dowel pins. The (green) gear is not attached in any way to the aluminum shaft which passes through its bore. The gear is co-axial with the (red) input worm which drives the flex motion, but the gearbox rotates on more of the same ball bearings used throughout the design. In order to read the rotation angle of the thumb roll, a unique Delrin pot shaft adaptor was designed which serves as both a plain bearing for the end of the aluminum shaft, and also has an ear with bolt hole for mounting on the side of the thumb flex gearbox. The pot adaptor has the necessary D-shaft profile for the potentiometer design in. This piece is separate from the thumb flex gearbox in order to make the entire system able to be assembled.

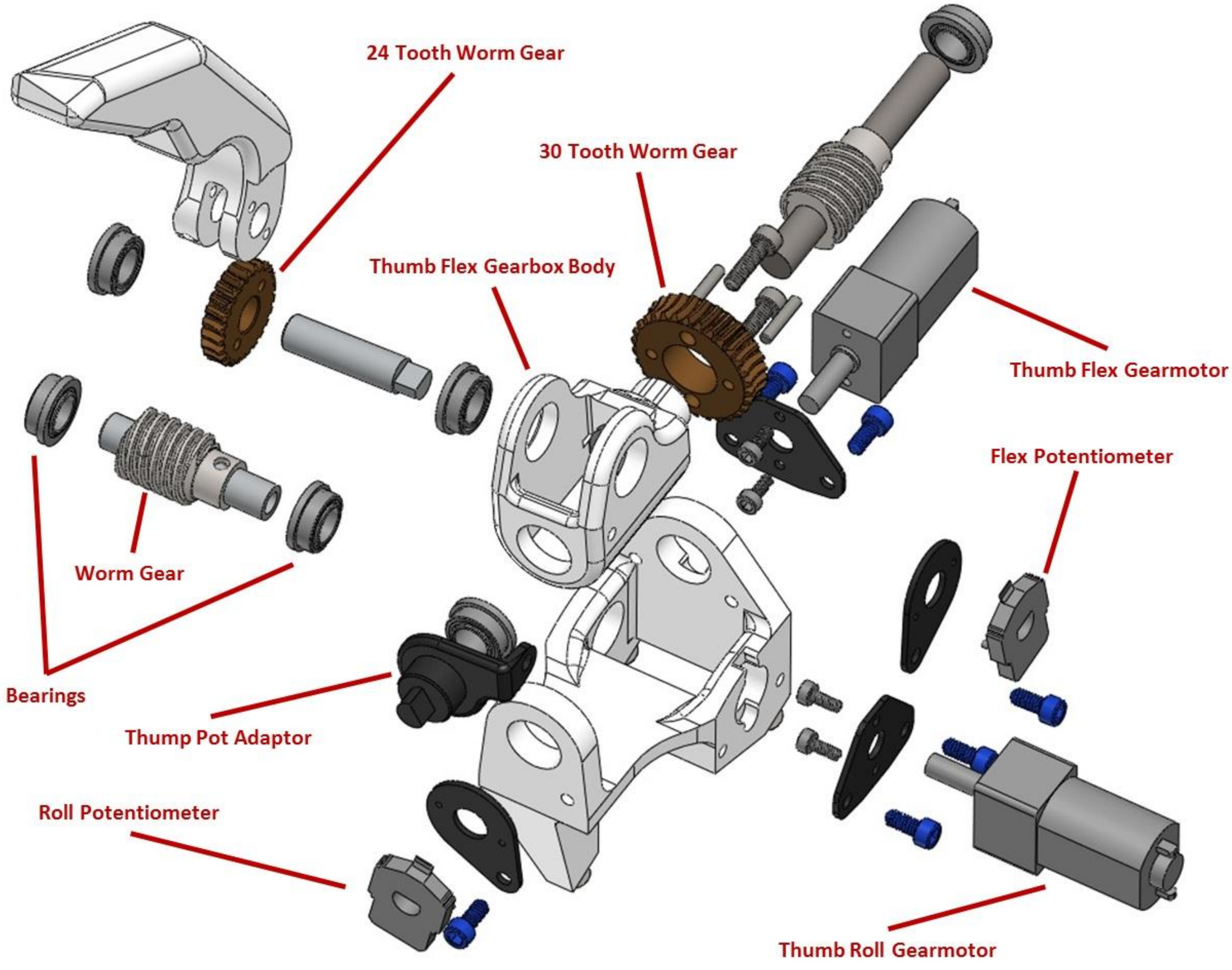

Figure 26 Labeled Thumb Assembly Exploded View

Once again, the same motors and gearboxes are used, with the identical motor mount plate and mounting screws. The motors for the thumb were positioned in such a way as to not interfere with any other components inside the palm area of the hand. The larger thumb gearbox required an angle mounting surface in order to achieve the optimal thumb positioning angle. This gearbox bolts to the main carbon fiber chassis plate with the same fasteners as the other finger gearboxes.

3.5 Hand Chassis Design

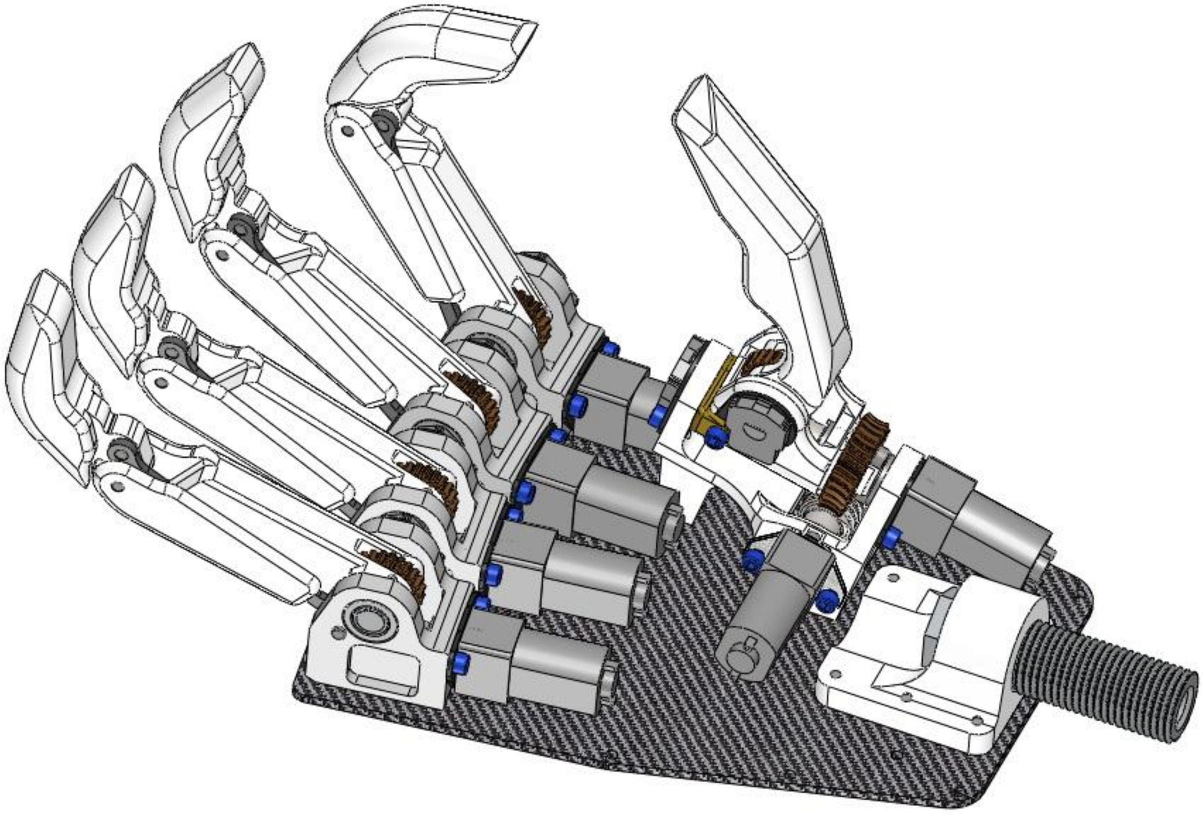

Figure 27 Main Hand Components Attached to Chassis Plate

The main structure of the hand is shown in Figure 26. All components bolt to a single strong main chassis plate. Carbon fiber epoxy laminate sheet 1/16” thick was selected for its incredible strength to weight ratio and stiffness at that thickness. The entire sheet simply has clearance holes for the #2 fasteners which attach all components. There is one 5/8” hole where the stud mount attaches to help take the shear load off of the mounting fasteners. It is assumed that the fingers will often be sharing a load and distributing the force on the mounting screws over many fasteners.

The stud mount is one more additional CNC milled Delrin component whose purpose is to provide the universal ½-20 threaded stud found across most prosthetic terminal devices. The mounting stud is a modified COTS aluminum threaded turnbuckle with the hex portion already included. The fastener is simply cut to length and has a hole drilled through for weight reduction. Six 2-56 button head fasteners, identical to the ones used throughout the design, attach the stud mount to the carbon fiber plate.

3.6 Cosmetic Covers and Grip

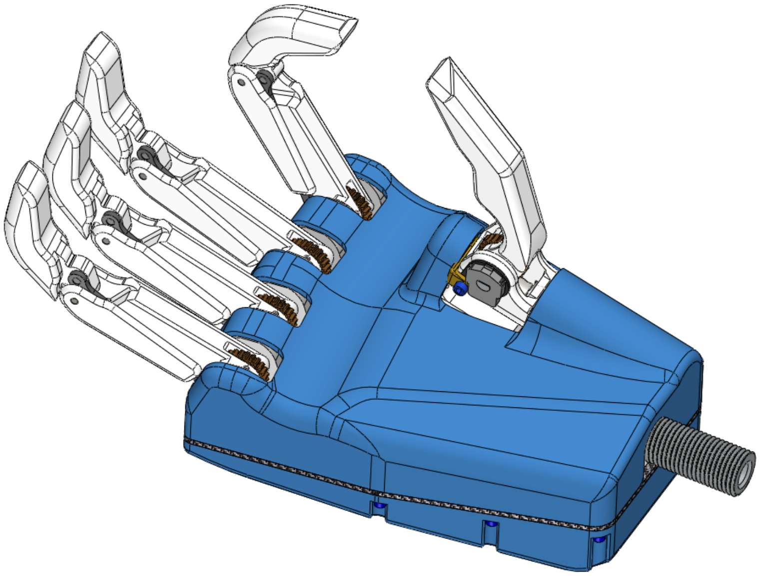

Figure 28 Hand Cosmetic Covers Highlighted

The final mechanical components for the prosthetic hand were the covers for the palm area and back of the hand. The covers are highlighted (blue) in the image. Although the compound thumb gearbox was very challenging to initially think of and conceptualize, the palm cover was by far the most challenging single component to design. It took 3-4 days of continual work and is still not perfectly optimal. The palm cover serves several purposes: to provide an opposable gripping surface for objects grasped by the fingers, to protect all of the internal workings of the hand, and to provide threaded mounting holes for the mating back cover. The part was so challenging to draw because it is highly shaped in unusual ways in order to carefully hug the finger gearboxes, yet clear the thumb gearbox and other internal components. The entire piece was modeled using the “shell” feature in Solidworks, along with the “rib” feature. The main piece is 1/16” thick designed to ultimately be molded from or milled out of polycarbonate. Strengthening ribs were added to the areas where the finger tips would push an object directly into the hand. There are ten 2-56 tapped holes for attaching to the back cover in a clam shell style assembly.

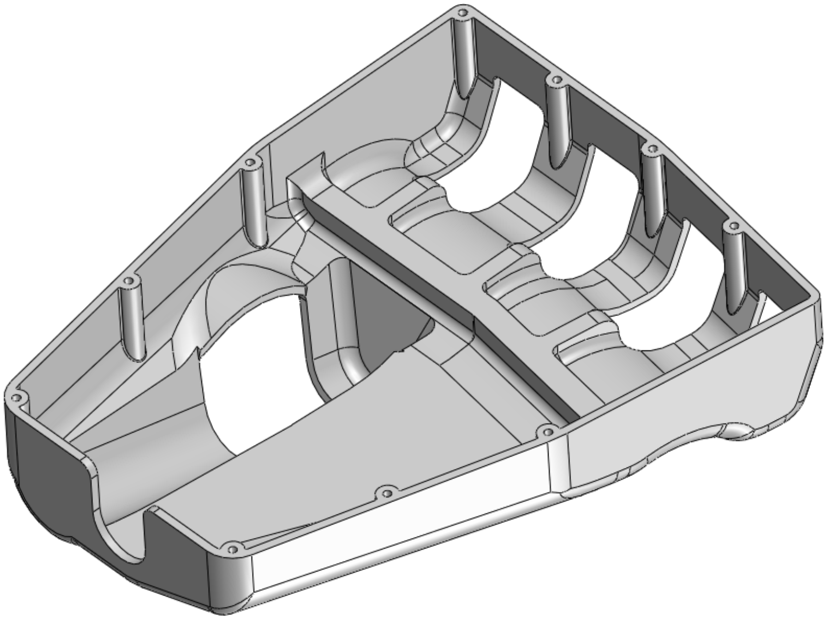

Figure 29 Final Palm Cover Inside View

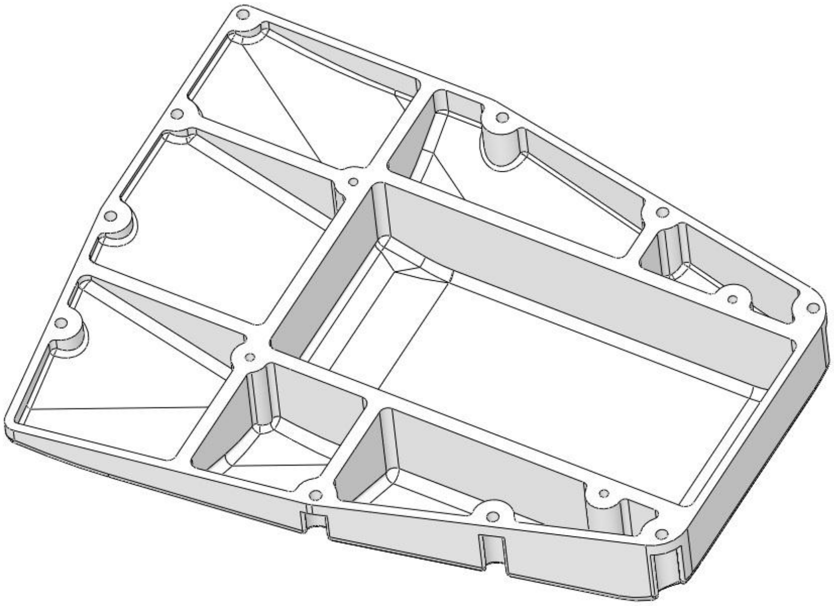

Figure 30 Final Back of Hand Cover Inside View

The back cover was designed in a similar style, except it was slightly simpler because there were not as many unusual 3D surfaces. The main purpose of the back cover is simply to hold the on board battery for powering the hand. Around the battery compartment there are full height strengthening ribs with 4 additional threaded holes. This back cover can be bolted to the carbon fiber plate and provide additional rigidity to prevent any unwanted flex in the main structure. Normally, the button head mounting screws pass through the back cover, through the carbon fiber plate, and thread into the palm cover, thus sealing the entire hand shut and forming a very rigid complete shell assembly. An alternative approach would be to not have the battery on board the hand at all, similar to how the iLimb works, and the entire back cover could be left off, thus reducing the thickness of the hand by a significant full ¾”. That option would allow a user to reduce weight toward their end effector, and have a slimmer overall prosthetic device. They would then mount the battery somewhere inside their prosthetic socket in the forearm area. Clearly that is not an option in all situations, so the normal hand configuration would include the back cover with battery contained inside.

The outer surface of the palm is covered in 1/16” thick transparent 60 shore A durometer silicone rubber adhesive backed sheet from Mcmaster. This rubber surface is also lining the inside of the fingers. This grippy surface is what makes holding onto objects firmly possible. The rubber compresses easily to add a small amount of cushioning in addition to its high coefficient of friction with most materials. The transparent look matches well with the polycarbonate fingers to give a finished product look to the fingers.

4. Control considerations

4.1 Electronic Speed Controller Selection

Electronic speed controllers or “ESC’s” take power from a battery, and input from an electronic signal, and convert that signal into a controllable desired output voltage to control a motor’s direction and power level. By approximately the year 2005, there were only a few options for small reversible ESC’s, but since then the hobby robotics industry has gained tremendous momentum and now there are dozens of options. When selecting the proper speed controller for your application, you must look at your required voltage, maximum current draw, average current draw and features. In this case, the features required are full forward and reverse (some small speed controllers are 1 direction only designed for remote control airplanes), good low speed control, and PWM input, the remote control and hobby signal input standard.

Table 2 Electronic Speed Controller Specifications

Name	Channels	V range	A (cont)	Weight (oz)	Cost	Communication
RoboClaw 2x5	2	6-30	5	1.24	$70	RC or Serial
Sabertooth 5	2	6-18	5	.6	$60	RC
Pololu Jrk 21v3	1	5-28	3	.23	$50	RC, Serial, USB (current sensing, limiting, all adjustable, PID built in)
SyRen 10	1	6-24	10	.9	$50	RC or Serial
BaneBots 3-9	1	6-24	3	.33	$29	RC
TinyESC	1	6.5-36	1	.16	$35	RC

For the DC motors selected for the finger joints, the motors will be run a 7.4v nominal from a lithium polymer battery pack, and can potentially draw 1.6 amps when stalled. The no load free current of the motor and gearbox is 70 milliamps. In this situation, the motor can never be allowed to be stalled at full power because the motor and gearbox would have enough torque to simply destroy the teeth on the brass worm gear. Instead, software control limits will have to be in place to limit the maximum power to be approximately half of stall, when a DC brushed motor happens to also produce its maximum power output. That means that the maximum peak current should be around 1 amp, and a more realistic draw would be around .2 amps under normal loads. After seeing which speed controllers can handle that, choosing the physically smallest controller would be the best choice, as long as it is not super expensive or with an unusual other feature.

Figure 31 Fingertech TinyESC (Fingertech Robotics, 2012)

In this case, the FingerTech Robotics “TinyESC” stands out as simply the best controller for this application. The designer of this controller wanted to make the device as small and light as possible so it could fit into miniature robots. These controllers have been used reliably for years in combat robots such as 1 and 3 lb Battlebots with much success and a proven track record. At a tiny .16oz including long wires, and $35, the TinyESC’s are a perfect match for the prosthetic hand.

4.2 Microcontroller Selection

The prosthetic hand requires an on board processor capable of handling all movements of the hand in addition to all sensor inputs and user feedback. A project of this nature does not require a large amount of processing power, but considering the extreme space limitations, there are many analog to digital inputs and general digital I/Os necessary. Each degree of freedom requires one digital channel as an output to generate the PWM signal for the speed controllers, and one ADC analog input to read the potentiometer which measures the current position of that degree of freedom. Additionally, it is necessary to have one more analog input used to measure a current or force sensor for at least the index finger which is the only one absolutely needing actual force measurement. When using the hand as a standalone prototype and not a finished product, it would be good to have one additional analog input used to measure a variable user input control such as a one axis joystick. Several digital output pins are needed to control which LEDs are on for user feedback, and they also need to have the ability to be pulsed quickly for dimming or blinked to show variation. That comes to a total of 8 analog inputs, and ~11 digital outputs. Additionally, the controller needs to have serial input through USB or similar standard to make sure it is able to be communicated with future control input third party devices or as a research platform connected to a computer.

The Arduino family of microcontrollers has recently become the standard hobbyist and robot controller for its low cost, large amount of features, and ease of use. The single greatest reason why it is so popular though is because there are thousands of code libraries and examples from various people's projects. There is a tremendous network of community support and online forums where troubleshooting and examples are discussed. For these reasons, it seemed obvious to design the hand around one of the Arduino microcontrollers. The $19 Pro Mini is essentially perfect for this application of limited space. There are no connectors attached, so wires can be hard soldered to the board for the absolute smallest size possible. It is difficult to find another controller with the same amount of analog inputs in anything close to this size or cost.

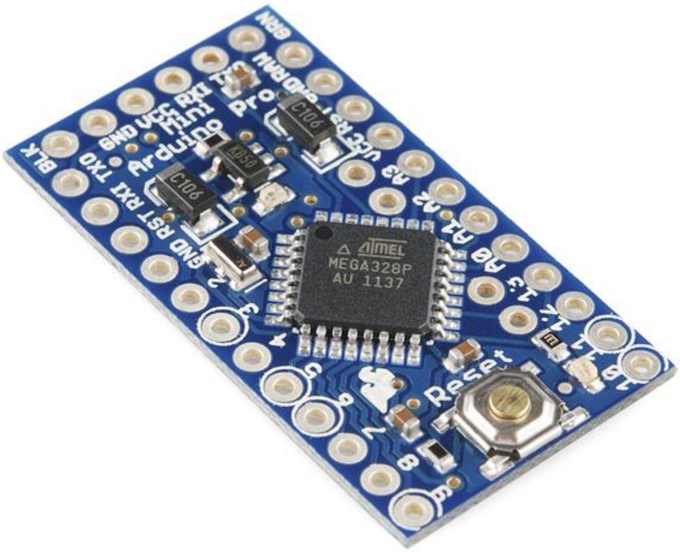

Figure 32 Arduino Pro Mini (Sparkfun Electronics, 2012)

Features:

- Dimensions: 0.7x1.3" (18x33mm)
- Atmega328 running at 16MHz with external resonator (0.5% tolerance)
- USB connection off board
- Supports auto-reset
- 5V regulator
- Max 150mA output
- Over current protected
- Weighs less than 2 grams!
- Reverse polarity protected
- DC input 5V up to 12V
- On board Power and Status LEDs
- Analog Pins: 8
- Digital I/Os: 14 (Sparkfun Electronics, 2012)

4.3 Fingertip Force Sensing

One important component of prosthetic hand design is grip force sensing. Having the ability to measure actual grip force within a finger, and then be able to react to that force, opens up many possibilities for advanced control algorithms, and a potentially better user experience. Users of body harness powered prosthetic hooks already use a sort of built in force sensing by feeling the tension in their harness; they also learn from experience how much force is required for a given task. The problem is more challenging for robotic prosthetic hands. Some of the advanced products such as the iLimb describe that they have active force sensing and automatic object slip detection/prevention, but user experiences do not seem to describe that functionality. Additionally, a user has no actual feedback to know how much force is being applied at a given time.

Through intuition, it seems reasonable that you should only need to ever measure the grip force of one finger, the index finger. During a precision pinching operation, the thumb is left in a fixed known position, and only the index finger is actuated. In that situation, one could perform sensitive tasks, such as picking up a grape and not crushing it, simply by having the force feedback from only that finger. During a power grip, or cylindrical grip, all of the fingers are actuated at the same time, but they would essentially share the load, so force feedback from the index finger should provide enough information to have practicality in theory. An example would be gripping a plastic water bottle. The hand would have more than enough strength to completely crush the water bottle if too much force is applied, but if not enough force is applied the water bottle could be dropped. In that case, as the grip is tightened, force would increase on the index finger, as well as on the other fingers, but there should be enough information to know when enough grip has been applied from practice.

Due to the nature of this project being focused on a design, and not a product actualization, these ideas are notional. If the force could be sensed, it could be quickly and easily relayed back to the user through the use of variable brightness LEDs located right on the hand itself. With real human hands of course there are times when you are gripping an object while not looking at it, but with a prosthetic hand it would be impractical without hundreds of touch sensors, so the users is presumed to almost always be looking directly at the object they are manipulating. This means that with no extra mechanical components, or wires for a traditional vibratory haptic feedback system, LEDs would instantly let the user know how much force the sensor is picking up in the fingertip. Testing would need to be done to determine what thresholds of brightness are useful, as well as how sensitive the force sensing would need to be. One assumption would be that only smaller forces in the 1 lb and less range would need to be measured, because more force than that usually would mean that a sturdy object is being gripped, and not something that is fragile. The force sensor could also be used as a functional limit in certain modes, so if a user was in a “soft” precision pinch, it would be impossible for them to apply more force than some arbitrary limit, which would remove a level of concern from the user. Other modes could allow for more or even maximum force to be applied.

Analog Current Sensors

The simplest and easiest way to obtain a force measurement without adding any additional mechanical force sensor is to directly measure the motor current. A motor's current is directly proportional to the load applied, so as force increases, the current draw increases. Analog current sensors are very common. One example available from Sparkfun is the "Allegro ACS712 Fully Integrated, Hall Effect-Based Linear Current Sensor". This board takes the tiny necessary IC from Allegro, and adds a breakout board making it easier to connect wires to for prototyping, and includes adjustable gain inputs for changing the level of sensitivity which is useful for measuring smaller ranges of current. In theory, current sensors work very well. In practice, current sensors have many drawbacks and require extensive system tuning and adjustment to become useful. For example, every time a motor starts up, it will momentarily draw a very large amount of current, even if the finger is still under no load. Additionally, one would generally gear down a motor to provide enough torque that the motor should not experience a very dramatic increase in load when the finger would come into contact lightly with an object. This means that it would be challenging to accurately measure forces that are small. The benefit of this system is that it can be tested inline without any physical changes to the hand prototype.

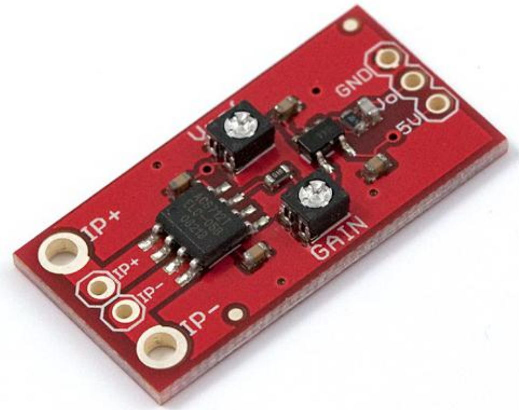

Figure 33 Analog Current Sensor on Breakout Board (Sparkfun Electronics, 2012)

Force Sensitive Resistors or Strain Gauges

Another more direct option for measuring the grip force would be to use literal force sensors which would mechanically be mounted and integrated into the fingertip. These sensors are analog and provide varying force information, and come in a variety of shapes/sizes and sensitivities. One advantage of these sensors is a very direct linear relationship; measured force would be right at the source and easy to understand. However, one would be very limited by the size of and location of the sensor. It would ideally be placed right in the finger tip, but it would be then unable to measure the force of certain objects which would not come into contact with the tip of the finger during grasping. Another complication would be the space required for routing the wires of the sensor through the two parts of the finger, and into the main body of the hand. Having tiny wires which have to bend 90 degrees at multiple points is an undesirable design challenge which would not have a clean and simple solution.

Figure 34 Force Sensitive Resistor (Sparkfun Electronics, 2012)

Similar to force sensitive resistors, a strain gauge sensor could be mounted on a part of the finger tip, or finger base, and measure the deflection of the part. The deflection of the part would be chosen as a highly stressed hinge point, such as the hinge point already designed into the fingertip. As more force is applied, anywhere along the fingertip, the strain gauge would report an analog signal relating to the force. One major drawback of that system would be the change in force depending on how far away the load is applied relative to the hinge point. The fingertip would act as a long lever in that situation, so it would most likely be difficult for a user to get practice with recognizing how much force is being applied unless they were constantly gripping objects the same way most of the time, for example through pinching primarily. Another drawback would be the same problem as the force sensor, the wires and mounting for the strain gauge pose a difficult design challenge.

4.4 Grip Mode Selections

Examples of common notional grip patterns are illustrated and briefly described below. Ultimately, a large number of additional grip modes could be programmed in the future. Having a functional Solidworks assembly made previewing and visualizing various grip patters a quick process.

Precision Pinch

- All fingers are pre-set to the positions shown in Figure 34
- Index Finger is the only powered joint
- Great for picking up small objects, fine manipulation

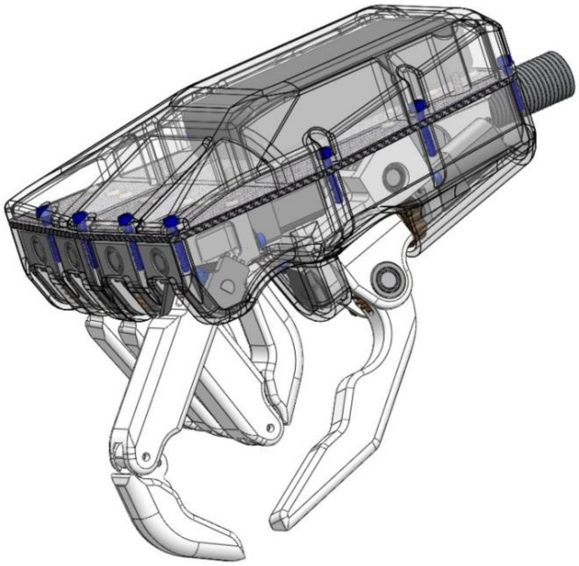

Figure 35 Pinch Grip 1

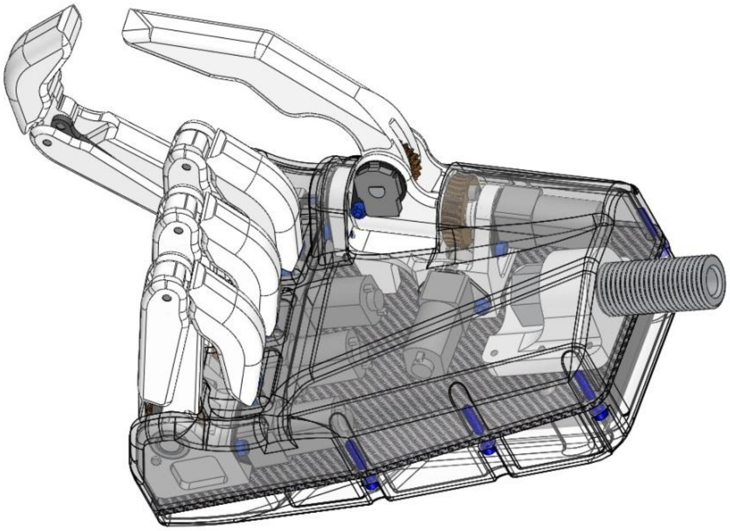

Figure 36 Pinch Grip 2

Power Grip (Cylindrical Grasp)

- All fingers are pre-set to the fully open positions, the thumb is rolled down
- All fingers are powered simultaneously
- Provides maximum gripping strength on large and small objects
- Good for holding onto anything with a handle, tools, broom, rake, etc

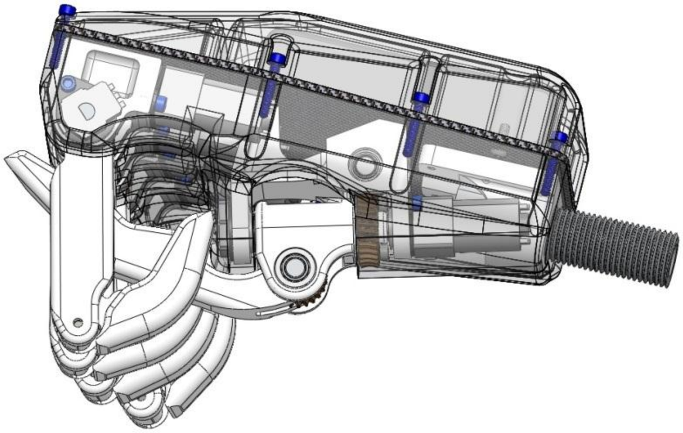

Figure 37 Power Grip Closed Fist 1

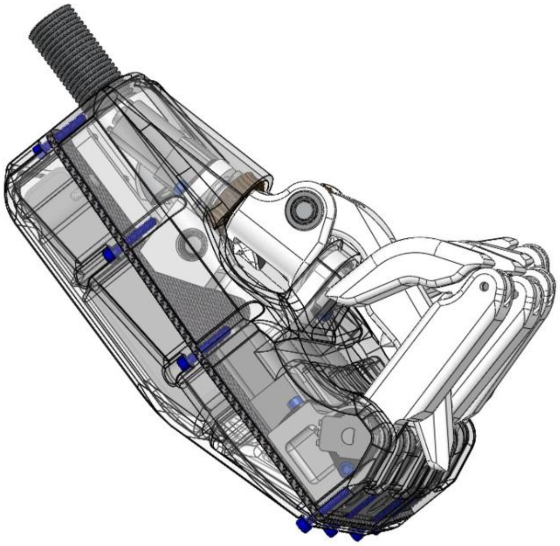

Figure 38 Power Grip Closed Fist 2

Key Grip (Lateral Pinch)

- All fingers are pre-set to the positions shown in Figure 38
- Thumb Flex is the only powered joint
- Great for holding onto spoons and forks, handling flat objects, money/paper

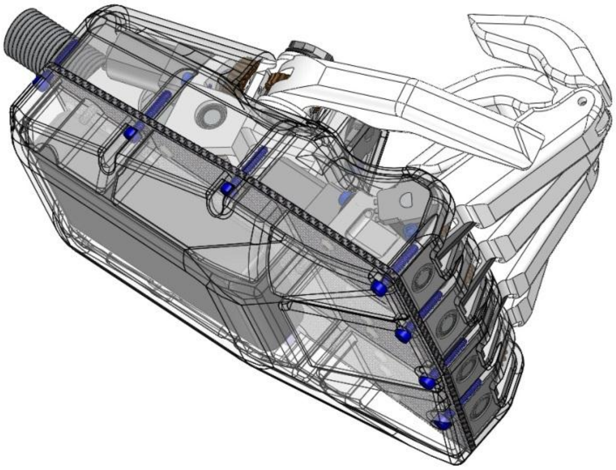

Figure 39 Key Grip 1

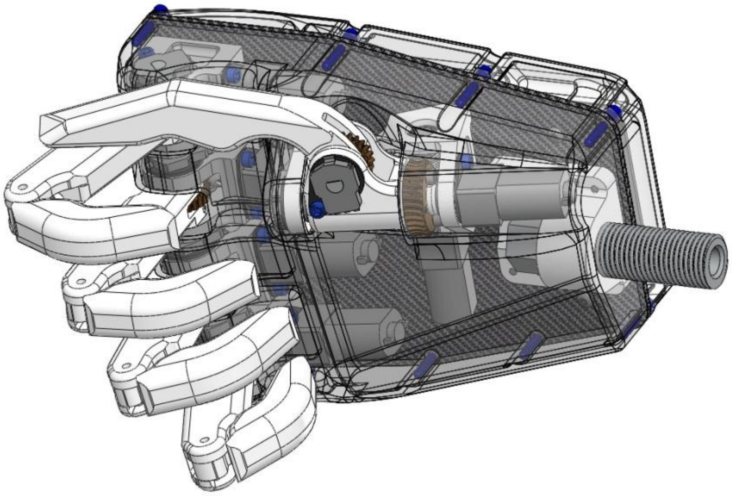

Figure 40 Key Grip 2

Ball Grasp

- All fingers are pre-set to the positions shown in Figure 40
- All fingers except Thumb are powered simultaneously
- Provides maximum gripping strength on round objects

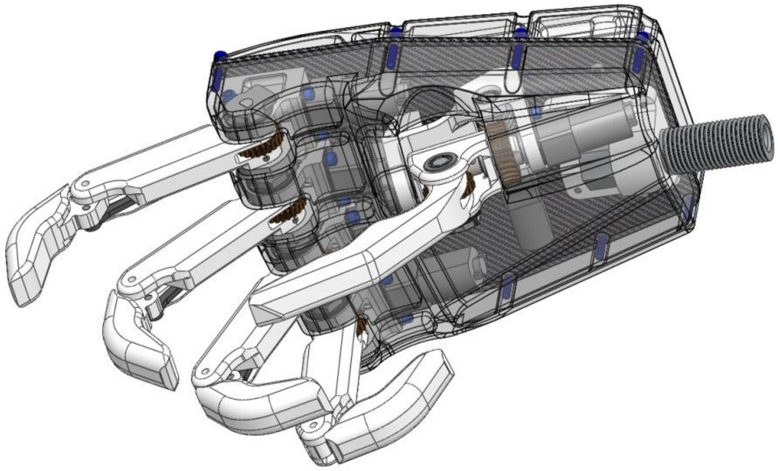

Figure 41 Ball Grasp 1

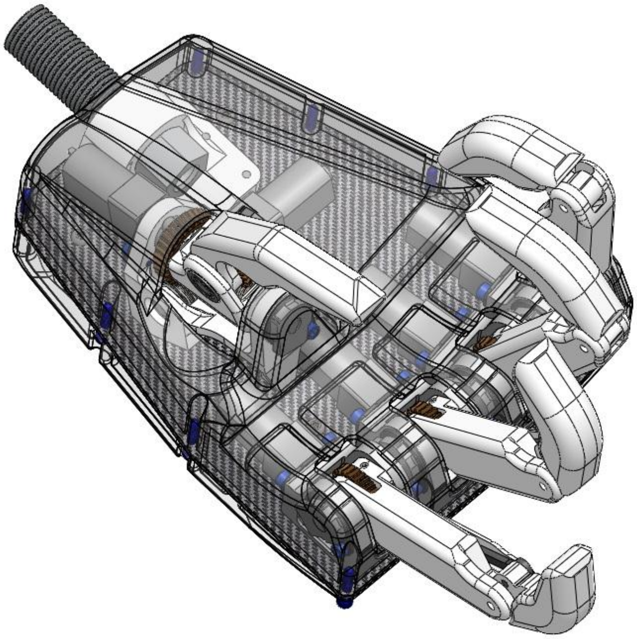

Figure 42 Ball Grasp 2

Open Palm Grasp

- All fingers are pre-set to the positions shown in Figure 42
- All fingers except Thumb are powered simultaneously

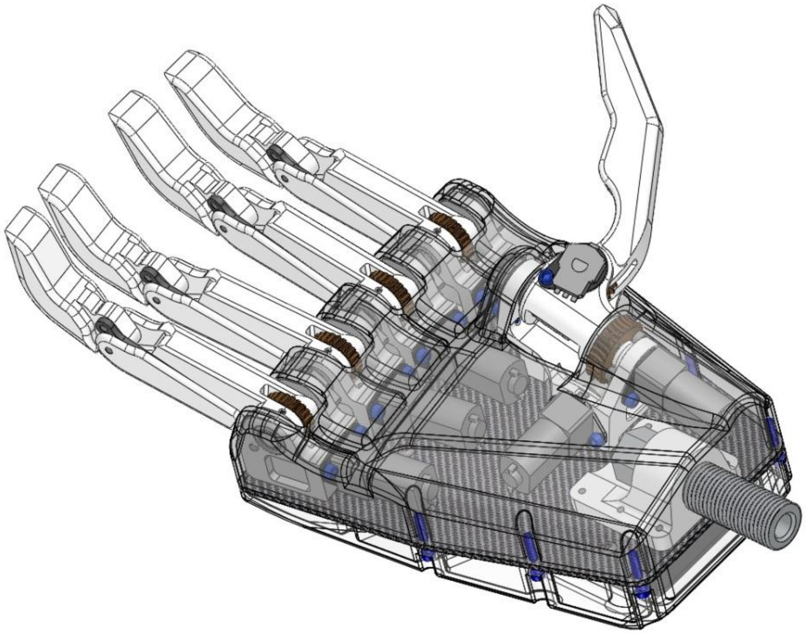

Figure 43 Open Palm Grasp 1

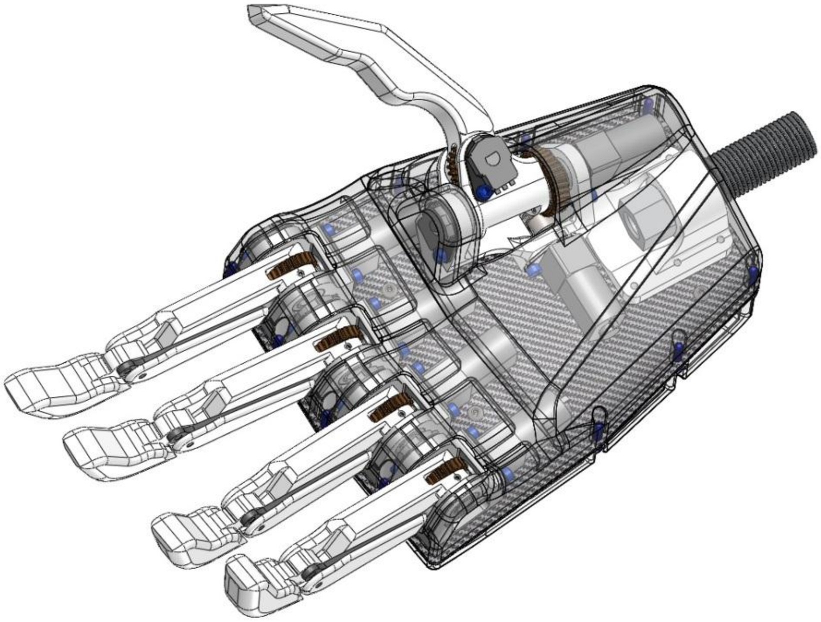

Figure 44 Open Palm Grasp 2

Index Point

- All fingers are pre-set to the positions shown in Figure 44
- Only the Index finger is powered
- Useful for hitting buttons, typing, etc

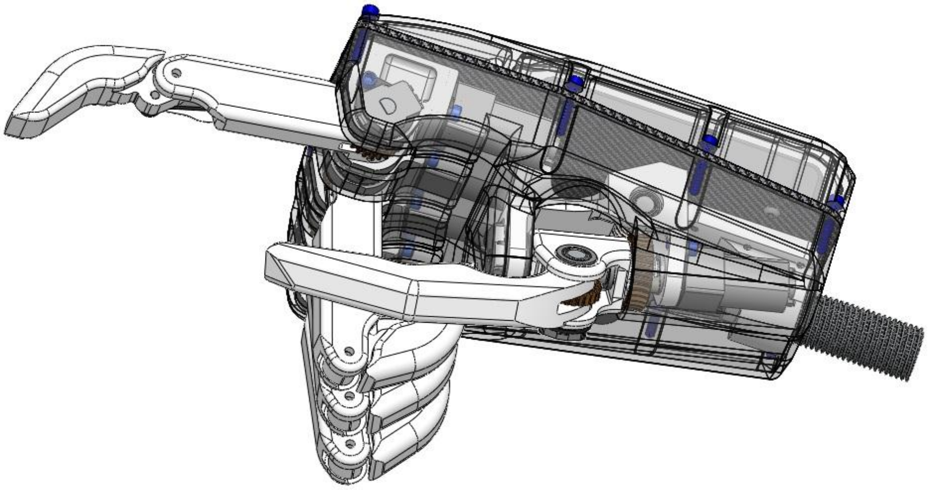

Figure 45 Index Point Mode

4.5 User Control Input

The biggest question people ask about prosthetic hands is, “So, how is it controlled?” This project was focused on the feasibility of a mechanical system, with room for many options on the controls side. There is no one control method that is required for this prosthetic hand design. After listening to the experts speak at the 2012 Neuroprosthetics Symposium at WPI[1], it was made clear that the best control systems would have two characteristics described by Gerwin Schalk in his talk, “Advanced Neural Prosthetics: Prospects and Challenges”; they should be completely non-invasive, and they should be easy to learn to use or adjust. Connecting to nerves through surgery would be an expensive and stressful process, and surgery should always be avoided if possible due to risk of complications and recovery. The best control systems need to be easy to adjust because otherwise a user would have to visit a prosthetist which will cost them additional time, money, and frustration. Any sensors which have to be specifically tailored to a given individual should be avoided if possible.

Toe Operated Switches

The DEKA Luke Arm is actually controlled through “toe operated” switches. This information is not publicly documented or described, but it was confirmed by speakers at the Neuroprosthetics Symposium. They are controlling an entire arm, seemingly without too much difficulty in the various demonstration videos found in the media. The idea of toe operated switches is very intriguing because of its simplicity. A user could have two very small switches, one worn inside of each shoe, which contains a small button cell battery and miniature wireless transmitter. Each switch could just have a pair of force sensitive resistors, one below the big toe, and one above the big toe. This would provide for at least two “actions” per foot, “up” and “down”. Additionally, because the buttons would be analog, a hard push could easily be differentiated from a light tap. There may not be super linear precise control, but there would at least be some variation. The biggest benefit for this system would be that it would not need to be tuned much depending on what muscle or electrical signals could be used on an amputees remaining limb.

For the prosthetic hand, this would allow for two main input channels. One channel would change what grip mode the hand is currently in. The other channel would control an action function while in that mode. That would be the entire system. A user may use their left toe and cycle through the grip modes until they are in the precision pinch mode, then, using their right toe, they would be simply moving the index finger in and out slowly and in a controlled fashion. These actions would be imperceptible to a bystander, because only small movements of the toes should be required. In order to make the mode selections easier for the user, a series of LEDs in a bar graph would display the current mode, 1-6 for example. A system of this nature would not be perfect, but it could work well for most daily tasks. Ideally there would be a small button located on the hand that could be easily actuated to put the hand into a sleeping mode so unwanted signals are not received when someone is walking or actively using their feet for example.

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[1] http://www.wpi.edu/academics/Research/BEI/Symposium/abstra206.html

Myoelectric Sensors

Myoelectric sensors are the most commonly used control method with advanced robotic prosthetic hands. (Dailami, 2002) These sensors would be an excellent way of controlling this hand, but they would have to not use a proprietary signal protocol. The hand would need to be programmed to accept serial communication from the sensors. One reason for not aggressively researching and evaluating myoelectric controls is due to the fact that many companies and research institutions have been actively working on them already. Additionally, one of the main goals of this project was to create a simple and low cost system, and the myoelectric sensors could add a tremendous amount of cost and training with many customization visits with a prosthetist.

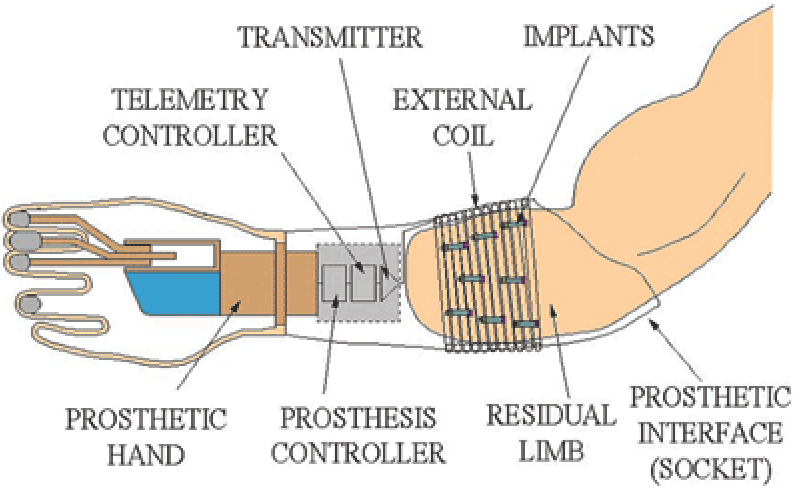

Figure 46 Myoelectric Control Example (Phillipe, 2012)

Linear Transducers

Another option for control input is though a cable pulling on a linear transducer. Similar to a body powered hook, some amputees use a lightweight harness and socket system where a cable is pulling on a variable sensor as opposed to directly pulling open the hook end effector. The benefit of this system is that a user’s power can be directly amplified. It has the same benefits of controlling a body powered hook, but removes the strain and pain caused by pulling on a strap and harness with a lot of force for extended periods of time. There are already off the shelf sensors from several companies which could be interfaced to the control input of the hand through a serial connection or directly into one of the analog inputs. One potential drawback with this system is the lack of having a secondary channel for selecting a certain grip mode. These systems were developed for crude prosthetic hooks and hands with one limited function of “open” or “close”.

5. Manufacturing Considerations and Functional Prototype

Throughout the entire design process, manufacturing was treated as a high priority. Overall, the entire hand only has 11 uniquely machined plastic components, 4 uniquely machined metal shafts, a machined link, one flat carbon fiber plate, 3 unique laser cut plates, and one custom machined fastener. That is a very low number of total components considering the number of parts required to produce a complete prosthetic hand with 6 individually articulated degrees of freedom. Commercial off the shelf components were used whenever possible, and helped keep the overall cost and complexity of the hand both to a low level. This was the priority of the design process, to keep the total number of unique parts as low as possible, and the final solution reflects constant iteration with a reasonable final solution.

Considering the small market for prosthetic hands, it would not be worth the cost of having plastic injection molded parts due to the initial mold and tooling cost considering the complex shape of some of the parts. Instead, the parts have been designed with CNC vertical milling in mind, and have flat and perpendicular faces when possible to aid in fixturing and secondary operations. As opposed to simply assuming what the cost and difficulty of a given part would be to machine, it was decided to use a real company, FirstCut in Minnesota, to produce actual custom quotes for each machined plastic component. The prices and timing were good enough that all components to produce one completely functional final hand were ordered from FirstCut. The rest of the machining which could be done manually was performed in one afternoon by me using the manual mill and lathe in WPI's Higgins Lab shop. The manual machining was used for the aluminum shafts, and modifying the COTS gears by removing their hubs and adding the dowel pin holes, etc. The thin plastic parts were quickly and easily cut using WPI's laser cutter found in Washburn Shops. Finally, the top and bottom covers were 3D printed out of ABS plastic using WPI's 3D printer. As previously stated, one of the goals of this project was not to actually produce a fully functional prototype, but the design of the components proved that every single part of the hand was able to be produced using standard methods in 1-3 days. Assembly of one finger created a functional platform for programming and controls testing.

5.1 Bill of Materials

Outlined below in Table 3, 4, and 5 are the completed cost totals representing all parts necessary to produce one single functional prototype. The costs for COTS parts came from industrial suppliers, and machined components represent actual quote costs from FirstCut.

Table 3 BOM for 1 Complete Finger Assembly

Part Name	Qty	Total Cost @ 1x
--1 Complete Finger (x4)--		
Finger GB Body	1	**$116**
Finger Joint 1	1	**$93**
Finger Joint 2	1	**$42**
Linkage	1	**$28**
Motor Mount	1	**$2**
Pot Mount	1	**$2**
Worm Shaft	1	**$15**
Main Joint Pivot Shaft	1	**$15**
Steel Worm 48 DP	1	**$15**
Brass Worm Gear 24 T	1	**$20**
3/32 x 7/16 dowel pin	4	**$0.5**
3/32 x ¼ dowel pin	2	**$0.5**
1/16 x 5/16 dowel pin	2	**$0.5**
SHCS 2-56 x ¼ AL	3	**$1**
SHCS M 1.6 x 3	2	**$0.5**
FR3ZZ Bearing	2	**$6**
FR3ZZ Bearing Extended	2	**$7**
Pololu 250:1 Gear Motor	1	**$16**
TinyESC	1	**$35**
Potentiometer	1	**$2**
2-56 x 1/8 Set Screw	1	**$0.5**
3-48 x 1/8 Set Screw	1	**$1**
		Total Cost @ (1x)
		= $419

Table 4 BOM for 1 Complete Thumb Assembly

Part Name	Qty	Total Cost @ 1x
--Complete Thumb--		
Compound Thumb GB	1	**$205**
Thumb Roll GB	1	**$228**
Thumb	1	**$133**
Thumb Pot Shaft Adaptor	1	**$110**
Motor Mount	2	**$2**
Thumb Pot Mount	2	**$2**
Roll Worm Shaft	1	**$15**
Compound Joint Pivot Shaft	1	**$15**
Thumb Flex Pivot Shaft	1	**$15**
Steel Worm 48 DP	2	**$30**
Brass Worm Gear 24 T	1	**$20**
Brass Worm Gear 30 T	1	**$27**
SHCS 2-56 x 5/16	2	**$0.5**
1/16 x 5/16 dowel pin	4	**$0.5**
SHCS 2-56 x ¼ AL	6	**$2**
SHCS M 1.6 x 3	4	**$0.5**
FR3ZZ Bearing	2	**$12**
FR3ZZ Bearing Extended	5	**$35**
Pololu 250:1 Gear Motor	2	**$32**
TinyESC	2	**$70**
Potentiometer	2	**$4**
2-56 x 1/8 Set Screw	1	**$0.5**
3-48 x 1/8 Set Screw	2	**$2**
		Total Cost @ (1x)
		= $961

Table 5 BOM for Miscellaneous Hand Components

Part Name	Qty	Total Cost@ 1x
--Other-		
Lithium Polymer Battery	1	**$20**
Wire	5ft	**$2**
Top Cover	1	**$28**
Palm Cover	1	**$34**
Carbon Fiber Plate	1	**$12**
Stud Mount	1	**$152**
Aluminum Stud	1	**$23**
BHCS 2-56 x ½”	10	**$2**
BHCS 2-56 x 1/4”	30	**$5**
Arduino Pro Mini	1	**$18**
		Total Cost @ (1x)
		= $296

The total completely functional hand prototype cost =

4 x (fingers @ $419) + 1 thumb @ $961 + misc @ $296 = **$2,933**

6. Commercialization Considerations

One goal of this project was to consider the design of the prosthesis as something that could become a real product and not just a fancy demonstration tool. Cost is obviously one factor when producing a product to be sold. The usability is the single most important factor when considering a human hand prosthesis. If there was enough time, then rough prototyping and field testing of products with users would be the proper way to create a real product of this nature. In the short time frame of a project of this nature however, field product testing and reiteration is not feasible. Instead, options for improvement or adaptability are considered, so changes could be made in the future once testing can finally take place.

Overall, the design components can all be simply manufactured by multiple different processes. By not restricting the manufacturability, it is easier to scale future production if 100 hands are desired to be produced versus 5,000. The components such as the drive motor and speed controllers could even be easily changed out even though they are an integral aspect of the overall design. The motors simply have a faceplate which bolts into the mechanically independent joint gearboxes.

6.1 As A Prosthesis

The long term hope for this project is to produce an actual prosthesis product. That product would have to be functional and easy to use. Additionally, it would have to be affordable and durable enough to be used each day for many years. When designing the overall hand, the idea of using a universal prosthetic standard attachment seemed obvious. People already have custom molded sockets and forearms ready to accept various terminal devices such as body powered hooks. It was important to incorporate the common ½-20 male threaded stud attachment so this hand could screw into place and be ready for use without additional customization. The challenging part of creating custom sockets has been solved by many other companies already. Safety is a high priority for a product which would be directly interacting with a human all the time. In general, the joints and fingers are slow moving so as to not pose an immediate danger. The fingers are capable of applying high force, but that would always take active user input, and would only be allowed in certain modes as needed. All of the external parts have sharp edges removed, and are made of plastics which are easy to clean and are incredibly durable. Polycarbonate which is used for the fingers is the same material used for bullet-proof shields.

Another aspect of a products safety is covered by FDA approval. Here, Morgan Stanfield describes the convenient FDA classification process, “Currently, nearly all O&P devices are Class I. Ironically, this lumps items as complex as microprocessor knees and multi-articulating hands in with more prosaic Class I denizens, including tongue depressors, reading glasses, and arm slings. According to Syring, Class I devices are classed as such because the FDA has decided that they "present minimal potential harm to the user" and are "simple in design and manufacture [with] a history of safe use." Much of the time, Class I devices are essentially "waved through" the classification process, and the FDA doesn't require their manufacturers to jump through classification hoops or demonstrate good manufacturing processes.” (Stanfield, 2010) Ultimately however, the hand design would have to go through extensive user testing and several more iterations before it would be up to the levelof being released as an actual product.

6.2 As a Research Platform

A simpler and more attractive way to turn the hand prosthesis into a product is to release it as a mechanical testing and research platform for universities and other interested parties. In the prototypes current state, it would almost be ready to go as a functional demonstration tool. Many people are performing advanced electrical signal research, or brainwave nerve mapping, and they are planning on controlling prosthetic devices eventually. There aren't really any products designed as tools that have the form and function of a human hand with the ability to undergo strenuous testing or be easily adapted. All of the control code would be made available as an open source library. The Arduino is commonly used by hobbyists and professionals, and it is easily communicated with serially through a USB connection. This was what drove the selection of the microcontroller, it is easy for others to interface with. On the controls side, people could test adding many touch and grip sensors and seeing how they could be used to increase the functional performance of prosthetic hands. One example on the mechanical side would include designing new fingertip shapes which can easily be machined out of different materials to test how that affects the user's experience. The hand prosthesis would be very valuable for a team working on a design that wants to have something in hand quickly to get a feel for what to expect, even if they are working on their own more advanced alternative.

7. Conclusion

A complete mechanical design of a prosthetic hand was developed in a short time frame. It was proven to have increased functionality over currently available products. The use of a novel compound thumb gearbox allowed for powered articulated thumb roll actuation. The carefully thought out use of universal components allowed for a tight packaging of the complete system while keeping costs to a minimum. The ease of manufacturing of the components for one hand was proven by having outside companies actually produce the parts needed. It is clear that there are going to soon be many more prosthetic hand options as more companies decide to enter the market and produce competitive hands. A lasting test platform has been developed which will make programming and algorithm development have real functional tests. With the commonly available hobby and remote control industry components developed today, there is less need to seek out the absolute top of the line precision industrial components. In a large company there is a standard way of designing and creating new systems, and that mostly involves using the highest level of components possible because the designers are not directly paying for the research and development, nor do that care much about the final cost of a high end item. When an individual designs a new system, not working for a company, they are able to challenge traditional design and manufacturing methods to produce an equivalent product more quickly and easily.

7.1 Future Recommendations

- Complete assembly of the full hand
- Develop control algorithms for the various grip modes
- Perform functional testing of hand actuation and use
  - Re-iterate the programming as needed
- Watch for signs of wear or damage of mechanical components
  - Re-iterate the mechanical design as needed
- Show the device to prosthetists and amputees and get their feedback on the current system
- Develop toe-operated control system
- Integrate controls with off the shelf myoelectric sensors
- Test what happened to the fingers with no compliance compared to other hands which have compliant fingers
- Redesign mechanical packaging to further reduce the size and weight of the system

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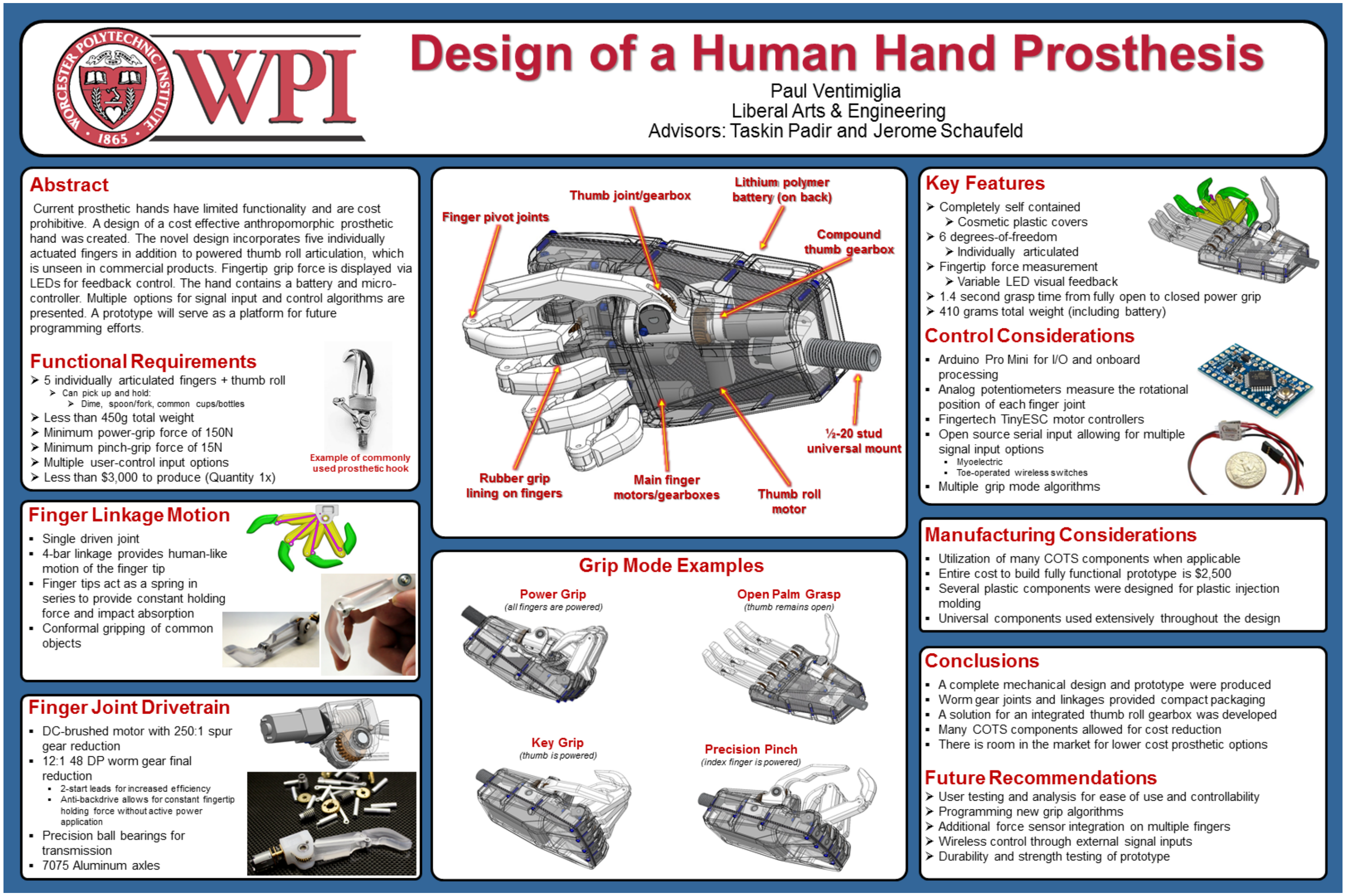
Appendices



Design of a Human Hand Prosthesis

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Abstract

Current prosthetic hands have limited functionality and are cost prohibitive. A design of a cost effective anthropomorphic prosthetic hand was created. The novel design incorporates five individually actuated fingers in addition to powered thumb roll articulation, which is unseen in commercial products. Fingertip grip force is displayed via LEDs for feedback control. The hand contains a battery and micro-controller. Multiple options for signal input and control algorithms are presented. A prototype will serve as a platform for future programming efforts.

Functional Requirements

- 5 individually articulated fingers + thumb roll
  - Can pick up and hold:
    - Dime, spoon/fork, common cups/bottles
- Less than 450g total weight
- Minimum power-grip force of 150N
- Minimum pinch-grip force of 15N
- Multiple user-control input options
- Less than $3,000 to produce (Quantity 1x)

Example of commonly used prosthetic hook

Finger Linkage Motion

- Single driven joint
- 4-bar linkage provides human-like motion of the finger tip
- Finger tips act as a spring in series to provide constant holding force and impact absorption
- Conformal gripping of common objects

Finger Joint Drivetrain

- DC-brushed motor with 250:1 spur gear reduction
- 12:1 48 DP worm gear final reduction
  - 2-start leads for increased efficiency
  - Anti-backdrive allows for constant fingertip holding force without active power application
- Precision ball bearings for transmission
- 7075 Aluminum axles

Grip Mode Examples

Power Grip
(all fingers are powered)

Open Palm Grasp
(thumb remains open)

Key Grip
(thumb is powered)

Precision Pinch
(index finger is powered)

Key Features

- Completely self contained
  - Cosmetic plastic covers
- 6 degrees-of-freedom
  - Individually articulated
- Fingertip force measurement
  - Variable LED visual feedback
- 1.4 second grasp time from fully open to closed power grip
- 410 grams total weight (including battery)

Control Considerations

- Arduino Pro Mini for I/O and onboard processing
- Analog potentiometers measure the rotational position of each finger joint
- Fingertech TinyESC motor controllers
- Open source serial input allowing for multiple signal input options
  - Myoelectric
  - Toe-operated wireless switches
- Multiple grip mode algorithms

Manufacturing Considerations

- Utilization of many COTS components when applicable
- Entire cost to build fully functional prototype is $2,500
- Several plastic components were designed for plastic injection molding
- Universal components used extensively throughout the design

Conclusions

- A complete mechanical design and prototype were produced
- Worm gear joints and linkages provided compact packaging
- A solution for an integrated thumb roll gearbox was developed
- Many COTS components allowed for cost reduction
- There is room in the market for lower cost prosthetic options

Future Recommendations

- User testing and analysis for ease of use and controllability
- Programming new grip algorithms
- Additional force sensor integration on multiple fingers
- Wireless control through external signal inputs
- Durability and strength testing of prototype

Figure 47 MQP Poster

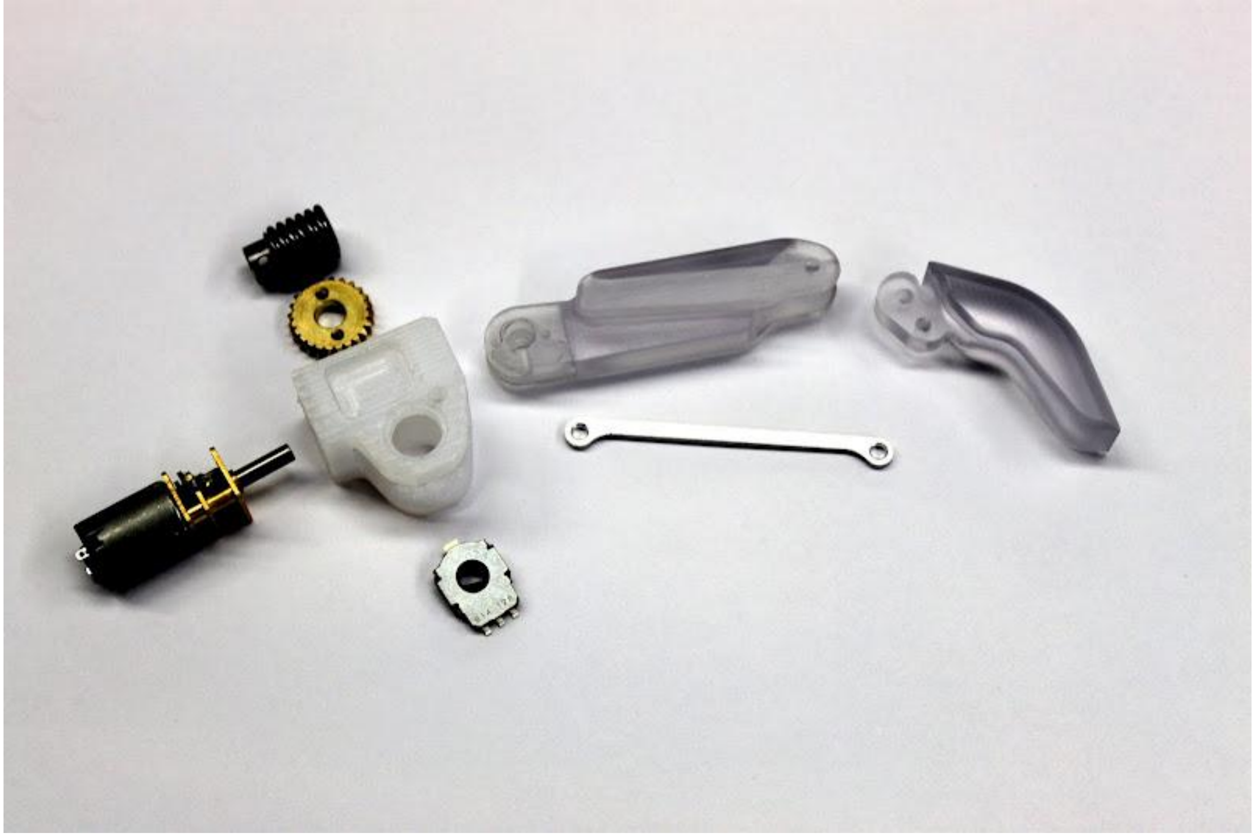

Figure 48 Finger Assembly Componenets

Figure 49 Prototype Finger Assembly Side View

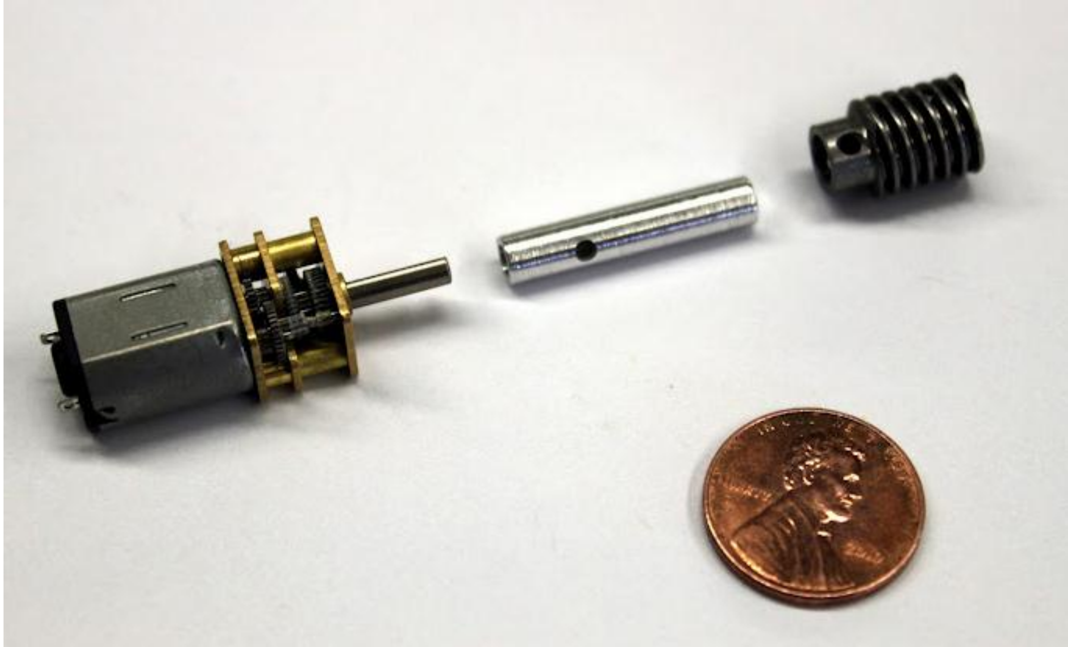

Figure 50 Motor With Input Shaft and Worm

Figure 51 Lithium Polymer Battery for Prototype

Figure 52 Aluminum 1/2-20 Stud Turnbuckle Awaiting Modification

Figure 53 Laser Cut Motor Mounts and Potentiometer Mounts

Figure 54 Laser Cut Delrin Chassis Plate Standing In for Carbon Fiber

Figure 55 7075 Aluminum Final Gearbox Shafts

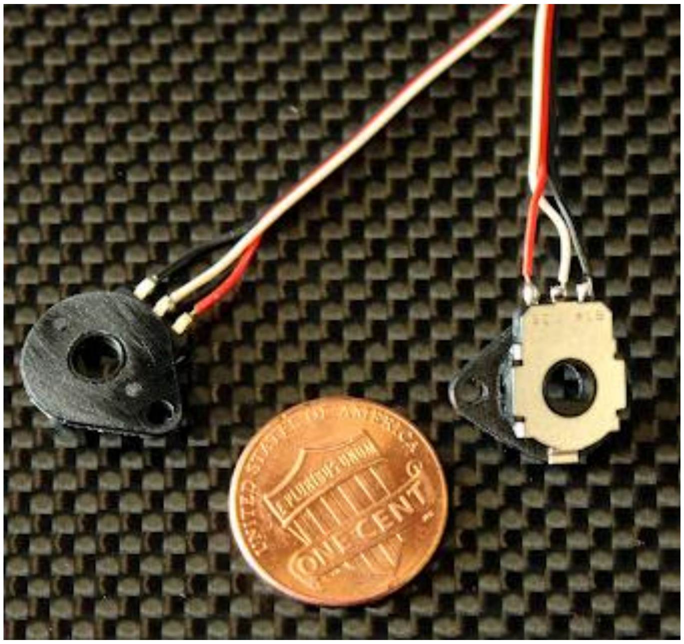

Figure 56 Potentiometer Glued to Delrin Potentiometer Mount with Soldered Wires

Figure 57 Finger Prototype Assembly 1

Figure 58 Silicone Grip Attached to Finger

Figure 59 Finger Prototype Assembly Vertical

Figure 60 Thumb Compound Gearbox Housings

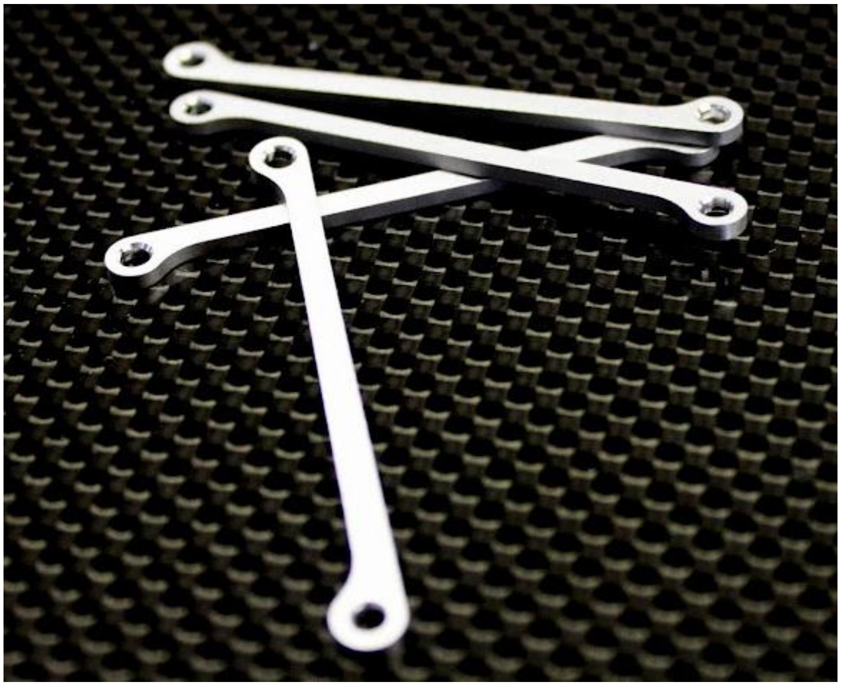

Figure 61 7075 Aluminum Finger 4-Bar Linkages

Figure 62 Final Polycarbonate Finger Parts Next to Earlier Finger Parts

Figure 63 Final Base Link of Finger

Figure 64 Finger Prototype Assembly Upside Down

Figure 65 Final Finger Next to Human Finger Flexed

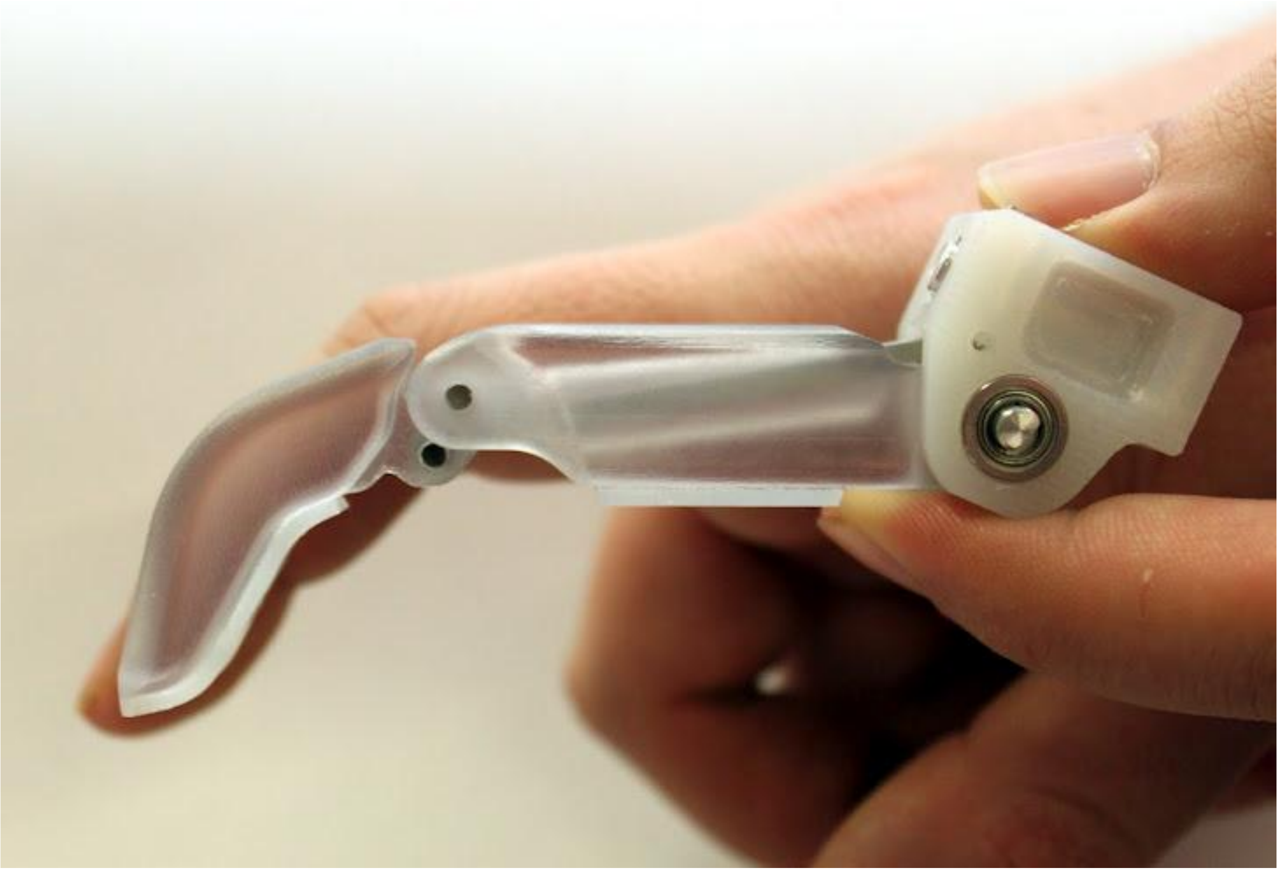

Figure 66 Finger Next to Human Finger Partially Extended

Figure 67 Assembled Finger With Parts in Background

Figure 68 Finger Assembly with Motor