PolyGrasp: Reach; Myoelectric Prosthetic Hand Iteration

A Senior Project

presented to

the Faculty of the Mechanical Engineering and Biomedical Engineering

California Polytechnic State University, San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Mechanical Engineering, Bachelor of Science

Biomecial Engineering. Bachelor of Science

by

Devon Patrick Augustus

Mighells Blaed Deuel

Ian Noel Fraser

Nicholas Philip Moesser

Quality of Life Plus

Engineering an improved quality of life for those who have served.

PolyGrasp: Reach

Devon Augustus, Mighells Deuel, Ian Fraser, Nicholas Moesser

Advisors: Dr. Mohammad Noori, Dr. Tom Mase. Mechanical Engineering Department.

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Myoelectric Prosthetic Hand Iteration Final Design Report

Mechanical Engineering

CAL POLY

May 30,2012

The Quality of Life Plus (QL+) Program
6748 Old McLean Village Drive
McLean, Virginia 22101

Dear Quality of Life Plus Staff,

Attached is one copy of PolyGrasp: Reach Final Design Report, project number 1A2.

Sincerely,

Team PolyGrasp: Reach

Statement of Disclaimer

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Abstract

Amputations are a common occurrence in soldiers returning home who have suffered the effects of IED and munitions explosions. For upper limb amputees, trans-radial amputations are the most common. Traditional hook devices do not offer an adequate level of normalcy for users, prompting the use of myoelectric devices. While current myoelectric devices do offer a more natural experience, they come with a host of other problems that makes their adoption by service personnel not desirable or not permitted by the VA. PolyGrasp Reach seeks to reduce weight and cost and improve performance. This addresses several of the issues with devices on the market, making them more desirable for returning veterans.

Introduction

Traditionally, upper extremity prostheses are manipulated by using movement to tighten cables attached to a vest. The strength and ease of actuation varies greatly depending on the fit of the harness, the positioning of the cables, and pain or discomfort in the residual limb caused by the motion (Alberto Esquenazi MD, 1996). Myoelectric actuation offers users an alternative to cable/harness actuated devices. Mechanical actuation by a servo or pneumatic system can be activated by simply flexing muscle groups in the residual limb. This creates a more natural-feeling device for amputees.

As of 1996, it is estimated that there are 100,000 arm amputees in the United States. 57% of those amputees have a trans-radial amputation, an amputation through the radius and ulna partway up the forearm (Alberto Esquenazi MD, 1996). This number has increased since the War on Terror began after the World Trade Center bombings in 2001. In 2010, 187 U.S. service personnel returned home missing a major limb as a result of I.E.D. explosion, more than double the 86 that returned missing a limb in 2009 (Dao, 2011).

Actuated myoelectric devices are a favorite among service personnel because they feel more natural than traditional hook prostheses. A myoelectric device operates using motor action potential, the electric impulse the body uses to signal the contraction of muscle fibers. This signal is detected using sensors placed on the users skin, and is used in prostheses to signal input.

Myoelectrically actuated devices have a host of problems that makes their adoption less desirable for some amputees. While specifics will be addressed in the Background section of this report, the major issues these devices face are weight, power, and expense oriented. The PolyGrasp 1.0 (ErbComfortable Grasp Hand) was the first attempt to address these issues in order to increase the adoption rate among veterans as well as the general public. PolyGrasp: Reach seeks to further refine the design of the first two iterations by meeting the goals in Table 1. These changes will focus on the areas that cause the most grief among patients. These are possible because the durability and specific size requirements for the previous PolyGrasp versions have been removed to target a broader market.

Table 1: Main Target Design Parameters

Target Device Parameters	
Parameter	***Value***
Weight	518 grams
Grip Strength	Up to 20 LBS
Cost	$4000 retail
Power Consumption	8 hours, moderate use

We are currently searching for a veteran challenger with a trans-radial amputation to fit this product to once it is completed. It is important to us to find a challenger so that we can be sure we are benefitting a veteran, which is in line with QL+ mission. Until a challenger is found, we will rely on Andrea, a friend of Dr. Mase who has a trans-radial amputation and is a current iLimb user. Andrea is suitable representation of the general market that the product will be equally geared towards.

Background

In a study done in 1988, it was shown that only 21% of prosthetic hand users in the U.S. opted for an active hand (Leblanc, 1988). The driving factor behind this low adoption rate is weight and cost. The most commonly used active hand prosthesis, the iLimb by Touch Bionics has five fully actuated fingers, actuated wrist, and gesture settings, but retails for an exorbitant $17,000 USD (iLimb Ultra Spec Sheet) (Tech", 2008).

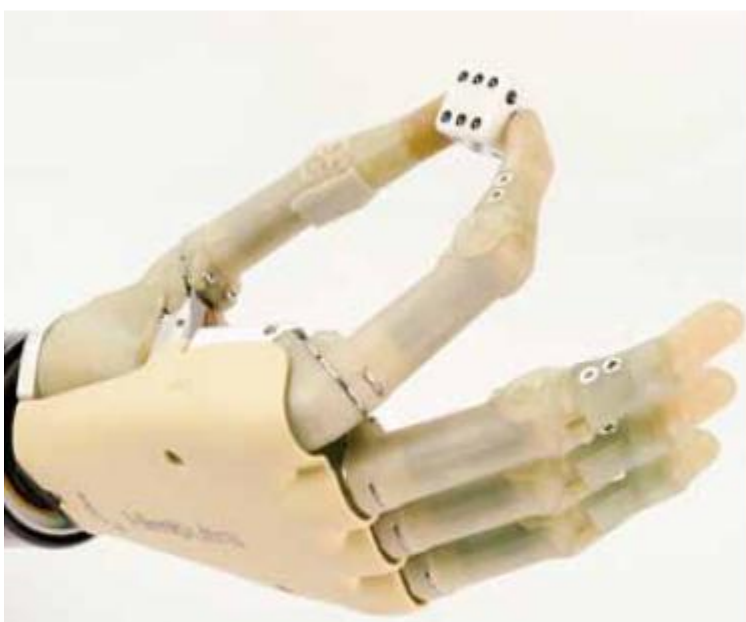


Figure 1.iLimb by Touch Bionics (iLimb Ultra Spec Sheet)

The weight of this device with a quick disconnect wrist comes out to 468 grams, nearly half the weight of a typical male forearm (iLimb Ultra Spec Sheet) (Clauser, 1969). Once a socket, electrodes, and batteries are added to the device, it can end up weighing much more than the original limb. This makes the device uncomfortable and hard to use for the amputee.

The original PolyGrasp was developed in 2009 to demonstrate that myoelectric hand prosthesis could be produced at a much lower cost than what was available on the market. That team developed a redesign of the Erb Prosthetic Hand created in the 1990s. Their hand was also a trans-radial prosthesis. The hand could clamp with about 10 lbs. of force using both of its actuated fingers. That hand lead to the PolyGrasp 2.0 project. The second PolyGrasp was more aligned with QL+. This project was to redesign the first PolyGrasp hand for an active-duty Navy SEAL with a unique amputation. The SEAL had lost all of his fingers and half of his palm. The team wanted to keep the myoelectric circuit but have a mechanical system to use the hand residual as well. The next step, PolyGrasp: Reach, is to return to the idea of the first PolyGrasp and create low cost hand prosthesis for a wide user base.

Product Specifications

As discussed in the introduction, the goal of this project is to improve the performance of the PolyGrasp hand by redesign. The target values for weight, grip strength, cost, and life can be found in Table 1 above. These specifications have been agreed upon by PolyGrasp: Reach and QL+ as reasonable.

Weight

We have chosen 518g, or roughly 1.5 lb. as the target maximum weight for the entire system. This number was chosen because the iLimb hand with quick disconnect wrist comes in at this weight without the socket attachment. By including our socket frame into the total weight requirement, we will ensure the device will more closely replicate the weight of a natural hand. The bulkiness of the iLimb hand can be attributed to the full device weight being concentrated in the hand itself, meaning the moment arm the user is forced to use to support the device is much longer, making the device seem heavier than it actually is. We will be placing out batteries, circuitry, and motors closer to the back of the device and into the support structure representing the forearm as much as possible. This will reduce the moment arm to the device center of mass, lessening the perceived excessive weight.

Strength

The PolyGrasp 1.0 hand was able to accomplish 10lbf in a pinch. It is estimated that roughly 70% of daily activities can be accomplished using only 7lbf of pinch force (Alberto Esquenazi MD, 1996), so the first hand iteration could be considered sufficiently powerful. We wish to address the other 30% of activities such as lifting heavy, slick objects with our device without compromising the cost effectiveness or battery life of the device. This will be accomplished through additional gear reduction, and redesign to the tendon system to increase the mechanical advantage produced.

Cost

Secondary to weight, a main complaint about current myoelectric devices is the excessive cost. Keeping the cost of the device to the agreed upon $4000 will be accomplished primarily will material choices and part selection. The reason the hands such as the iLimb are as expensive as they are is because they use small, powerful motors and very patient specific programming. Each hand’s operating parameters are tuned to the specific patient. The iLimb also has different grip settings to mimic the different ways a

human uses its hand to grip objects. This is very elaborate, but adds much complexity and cost to the device.

While the grip setting and multiple motors seen in the more expensive hands are useful, they are heavy and costly, adding more to cost than they benefit the patient. To address this, PolyGrasp: Reach will follow many of the principles set by the first PolyGrasp hand. A single motor and grip action is sufficient. The single motor will lower cost and weight. The multiple grip forms settings add an extra level of realism, the programming and specialist costs are undesirable. The new hand will have a similar, universal feature that allows the wielder to manually select from different grip strengths.

Expected Battery Life

Tertiary to weight and cost, product battery life is a common complaint among myoelectric device users. For this device, we are looking for a battery system that is high output, long-lasting, small, and lightweight. Unfortunately, small and light-weight behave inversely with power output and charge life. To address this issue, the design will incorporate modular battery packs. This means when the hand runs out of power, the battery may be removed and replaced with another. The batteries will be rechargeable to reduce weight and facilitate a full day's use with multiple packs. This design also allows the hand to be in use and mobile while a depleted battery pack is charging.

Design Development

Design Concepts

The fingers, actuation system, and myoelectric components represent the majority of the design load for this iteration. For this reason, the focus of this quarter's work and the content of this document will encompass these systems.

Fingers and Joints

We have decided to design the finger and hand size to the a 50th percentile female for a variety of reasons. Primarily, the bulk and weight of hands such as the iLimb occur from excess material weight since the hands are designed to fit males. By limiting the space we have available for our hardware to a female sized hand, we will be able to maximize weight reduction. In this case, the size of the fingers and hollow hand chasses can be sized up to fit male specifications, but the power transmission and battery systems can remain small in order to ensure weight requirements are not exceeded.

It was found that index finger length for a 50th percentile woman is 69mm long, or 2.717in (Company, 2003). By measuring our own fingers, we were able to obtain a ratio of lengths for the individual joint links within the finger. It was found that the top two links of a finger are similar in size, and the bottom link is approximately 1.75 times as long as the smaller links.

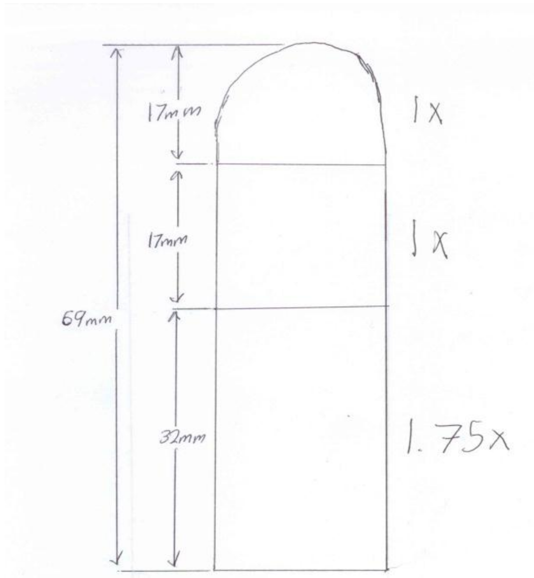


Figure 2: Finger Proportions for 50th Percentile Female

Many different joint options were explored for the design of this hand. Among these options were hinge joints that were used in the previous PolyGrasp designs, 6 bar pinned linkage systems to achieve the desired motions, and a solid piece of rubber with a slot cut into it that when loaded would compress around the slot, causing a bending motion.

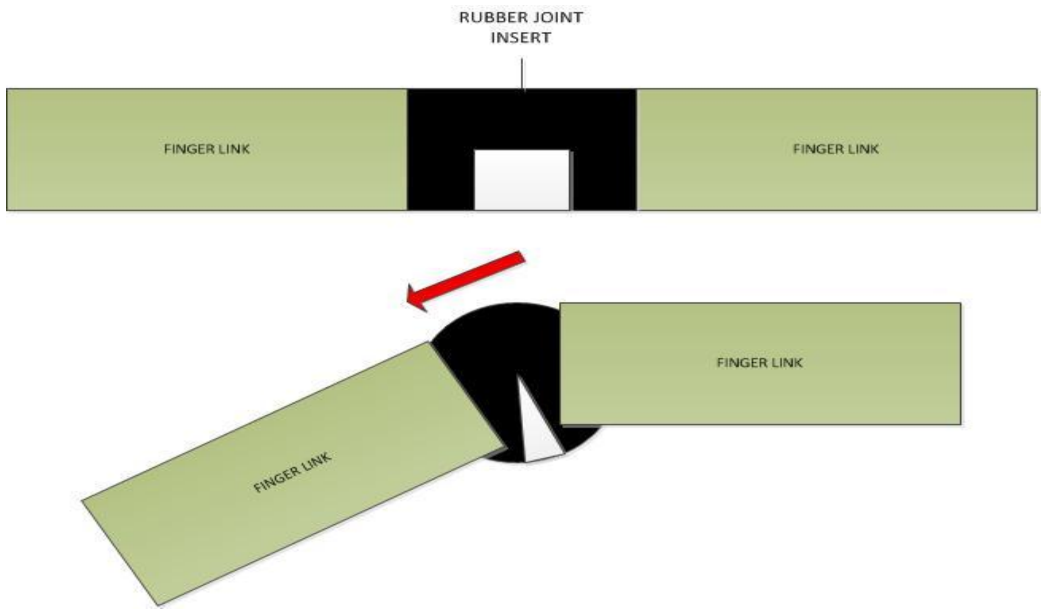


Figure 3: Rubber Joint Concept

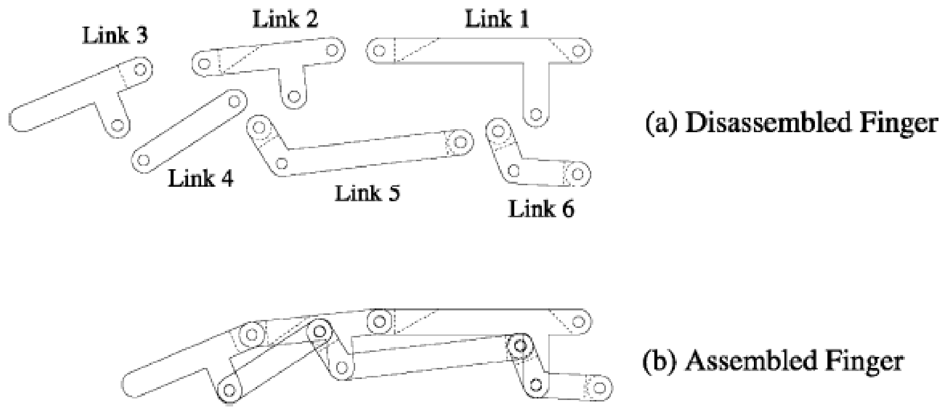


Figure 4: 6 Bar Linkage Developed by Dechev, Cleghorn, and Naumann (Dechev, 1999)

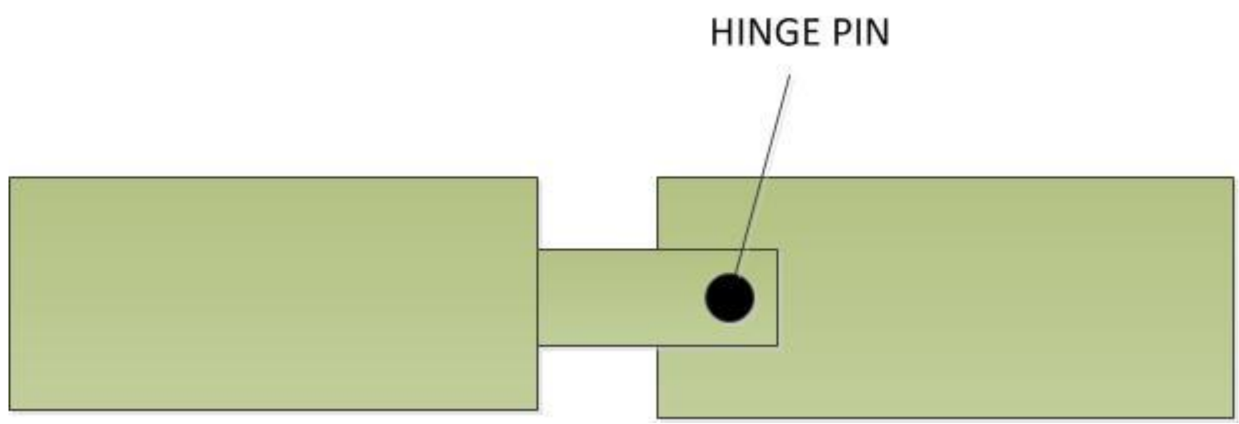


Figure 5: Basic Pinned Hinge

A pinned hinge joint was chosen for this design primarily for its durability and fatigue strength, as well as its simple implementation keeps machining costs low and weight down.

Actuation Methods

There are several different types of actuation methods available for the prosthesis; each with their own benefits and compromises. The table below compares the metrics of several types of these methods to the human muscle.

Table 2: Actuator Metric Comparisons (Love, 2009)

Actuator	Strain (%)	Stress (MPa)	Specific Power (W/kg)	Responsiveness (Hz)	Stiffness (MPa)
Muscle	20	0.35	50	30	20
Electromagnetic	50	0.035	200	30	0.1
Pneumatic	50	0.69	200	50	0.1
Piezoelectric	0.2	110	0.1	1000	400
Magnetostrictive	6	9	5	1000	29
EAP	380	3	35	10	1
Shape Memory	8	200	6	1	83000
Hydraulic	70	20.8	2000	50	1380

Strain defines the range of motion that an actuator can accomplish, however there are many different transmission designs that can expand the range of these actuators. Therefore, this metric is only important in the issue of cost.

Stress is the normalized force the actuator can provide. It is directly related to the grip strength specification of the prosthesis. Transmission systems can be built for each actuator to increase the force that the prosthesis can output. However, space constraints in the hand limit the transmission ratio significantly.

The Specific Power is the normalized mechanical power per kilogram of weight of the actuator. Because one of the primary specifications is weight, the actuator must be able to output a significant amount of force for its weight. An actuation method will be useless if it weighs too much, despite the amount of force it can provide.

Responsiveness relates how well each actuator responds to a signal. One of the specifications for the design is the amount of time it takes for the hand to close in response to a myoelectric signal.

Stiffness is the ability for the actuator to hold the load. The prosthesis must be able to both output and maintain a certain force, and different actuators will require different continuous input levels to maintain a specific force output.

Electromechanical actuators consist of methods such as motors or servos. These actuators are high speed and low torque, which is exactly the opposite of what the design requires. This, however, can be mitigated by including a transmission system. In addition, the low stiffness can be mitigated by using a locking lead screw as part of the transmission system.

The smart material actuation systems (Piezoelectric, magnetostrictive, and shape memory alloys) are all very strong, but suffer from having very small strain and stress values. Again, transmission systems may be able to solve these problems, but the transmission systems may be very complex.

Pneumatic are very similar to electromagnetic actuators, however, they have problems with accuracy. The major drawback to these is the costs associated with making a miniature actuation system. In

addition, pumps able to achieve the needed pressures are roughly one fifth of the total target device weight. Electroactive Polymers (EAP) require very high voltages to use. This means that they are not a good option for a system with a low power specification. Hydraulic actuators are very attractive in all aspects, however the cost of the miniature system may be an issue.

Thumb

We decided to have a manually positioned thumb similar to the PolyGrasp 2.0 hand developed for Tosh. By not actuating the thumb, weight corresponding to actuation and joints is avoided. This decision will also keep the total price of the device low.

Myoelectric Circuit

The myoelectric circuit is the conduit that communicates between the user's body and the robotic actuation. This is accomplished in three parts: detection, filtration, and amplification. Detection occurs when the muscle creates an electrical impulse. This signal is very small and is littered with noise. The filtration helps eliminate the noise of the signal into something that is more defined. The amplification stage brings the signal up to the standard 5V range that most electronics use. In each of these steps there are places for improvement. The previous iteration of this project was moderately successful in interpreting the muscle impulse. There where inefficiencies in the design. The output signal was very electrically noisy and there was no processor for digital signal processing (DSP). This made the motor actuation very clunky and the response time was retarded.

Our current redesign solves these issues. The amplification/ filtration circuit received a huge over-haul. It is smaller and fewer parts to incur less ambient noise. The output is now a differential signal voltage instead of an absolute voltage. This increases response time and also addresses the noise issue. An Arduino microprocessor has been added to further clean the output signal and also take advantage of DSP capabilities for higher level actuation control. All of these improvements have drastically increased the fidelity of our signal and, in turn, create a better user experience.

Force sensors in the finger tips were also added, giving an added input to the control loop. Current myoelectric devices used myoelectric amplitude as a mean of force control, meaning the harder you flew, the more force the hand outputs. While this is an intuitive system, it is flawed since muscle fatigue causes alterations in the myoelectric amplitude, and these amplitude ranges are different for each person requiring lengthy calibration for each user. By allowing the Arduino to measure force output, this variability is taken out, making this system usable by a wide range of people with little to no pre calibration.

Details of the circuit are not included in this report because it was developed by Nicholas Moesser prior to the start of this project. Nicholas is currently pursuing a patent for the technology, meaning the inclusion of the circuit in this project has been done as a "black box".

Concept Selection

Fingers and Joints

Of these options, the simple pinned hinge joint was chosen for various reasons. The linkage option was rejected since its complexity will generate higher costs, weight, and have more points of failure than the simple pinned hinge, as well as pinch points on the inner gripping surface caused by the interaction of the linkage. The rubber insert was rejected for fatigue reasons. Over many cycles, the stress concentration created by notching the rubber to allow it to bend will split the connection material, causing the finger to fall apart. The simplicity of the pinned hinge will make manufacturing cost and time very low.

A quasi-static model of the finger joints was developed to aid in selecting the dimensions of the tendon pulley system.

Initially we planned to use a top joint in order to take advantage of the lessened tension requirement as the finger bends. However, this joint method was also rejected primarily for manufacturing and cyclic loading concerns. The top joint requires that a hole be drilled closer to the edge of the material, meaning a tighter tolerance will be necessary to ensure the individual finger links function correctly, and stress concentrations will be more pronounced. For these reasons, the joints in the PolyGrasp: Reach hand will be placed in the center of the link.

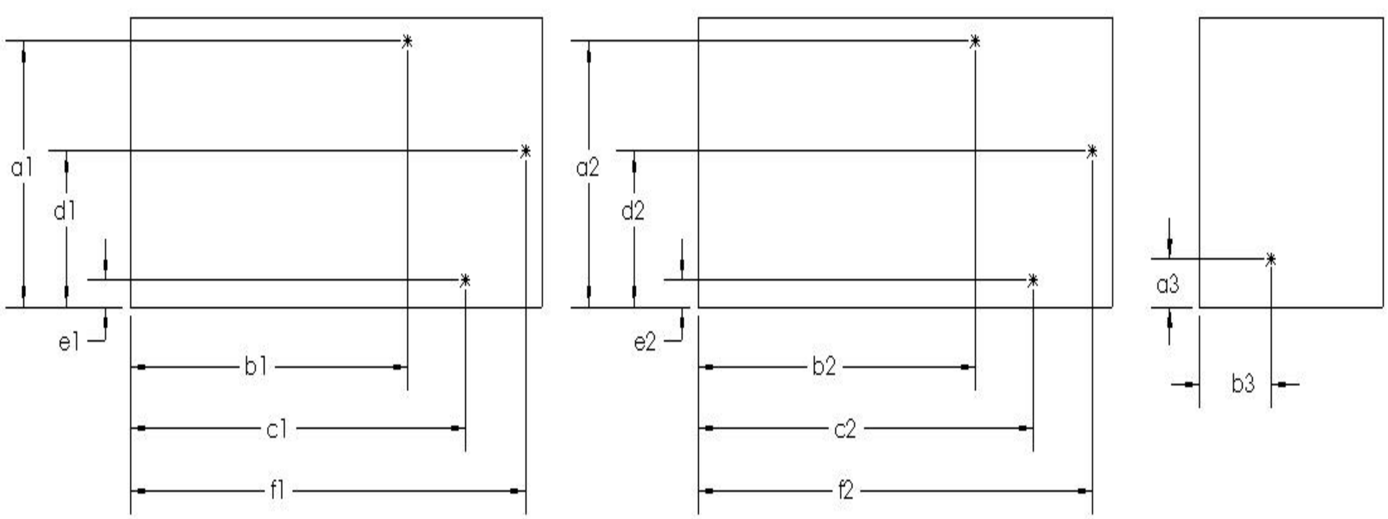


Figure 6: Simple Box Joint Model for Tendon Analysis with Hole Centers Dimensioned from the Side Wall

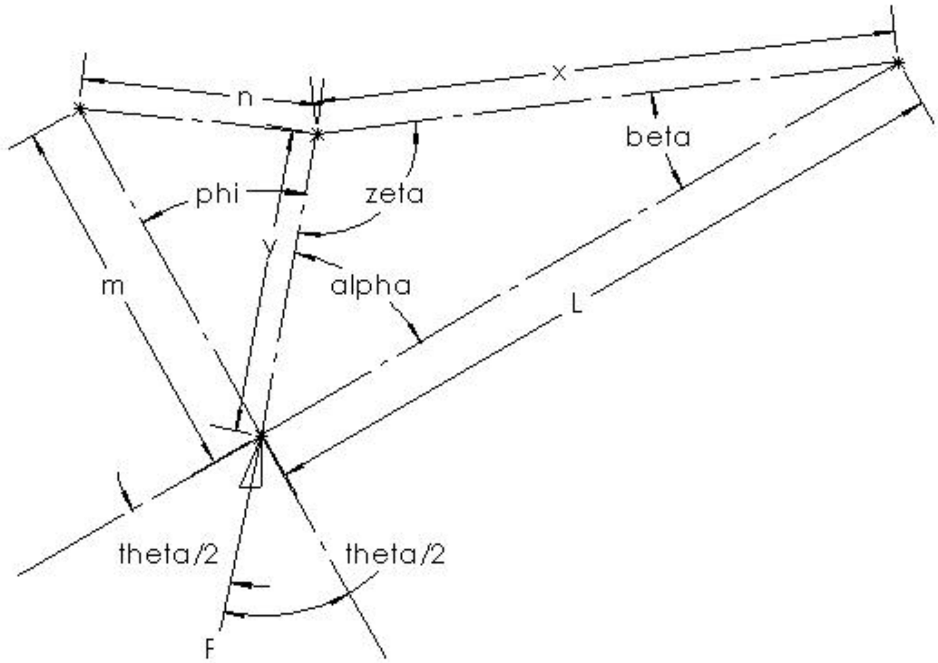


Figure 7: Expanded Geometry from Joint Model with Holes Dimensioned Relative to Each Other

By setting F to 20lbf in accordance with our design requirements, we were able to use this model to optimize the critical design lengths labeled in Figure 7 at a set finger bend angle that will result in a minimum tension requirement in the tendon. We used a built in multivariable optimization protocol that is part of Engineering Equation Solver (EES) to optimize the dimensions of the tendon system. The resulting maximum tension was around 66lbs, but for the purposes of our design we assumed a maximum tension of 80lb to account for friction in the joints and the unspecified returning force to bring the fingers back to their initial positions.

Actuation Methods

It was decided to use an electromechanical motor for actuation. Smart memory alloys would have been the preferred method to use, however they operate too slowly to meet our specification of 0.2 seconds of closing time. Hydraulics had ideal characteristics in terms of strength and stiffness, but the cost to build and obtain the miniature pumps required is prohibitive.

We will be implementing a motor for actuation rather than a servo for a few reasons. Servos have a built in PID controller than causes it to move to a certain position based on an input voltage. Since we will be controlling grip with the Arduino board via pressure sensor feedback, servos do not fit our application. Additionally, servos have relatively low force yield to power consumptions ratios. A servo strong enough to provided adequate grip strength cannot provide the desired battery life.

Though motors are typically high speed and low torque, a transmission system will be utilized to bring the motor's capabilities in line with our specifications. There were two transmission systems being considered for power transmission from the motor to the tendons. The first is a lead screw. A lead screw is compact and has the advantage of being self-locking. Self-locking is important because it allows the hand to maintain its grip with little to no power being applied to the motor.

The second transmission system considered is a pulley system. Like the lead screw, a pulley system is compact. The pulley system, however, has the potential to have a greater force ratio than the lead screw, because each pulley is multiplicative. On the other hand, frictional losses and fatigue are a much larger problem.

Final Design

Finger Links

Originally, we had designed the finger system to include three finger links to mimic a natural hand similar to how the PolyGrasp 1.0 was designed. This added complexity to the tendon system since the top link required actuation before the bottom two to create a natural bending motion, leading to two tendons per finger and a staggered pull actuation method. After discussing this system with Nick Butler, the developer of both PolyGrasp 1.0 and 2.0, he informed us that he went to two link fingers for the second hand to reduce tendon complexity. Through testing, he also determined that the reduction in link numbers does not affect the grip comfort for the user. This motivated us to change our design to have two finger links rather than three. This accomplishes a few things, namely additional weight reduction, reduced material and machining costs, and reduced complexity of power transfer system adds additional cost and weight reduction.

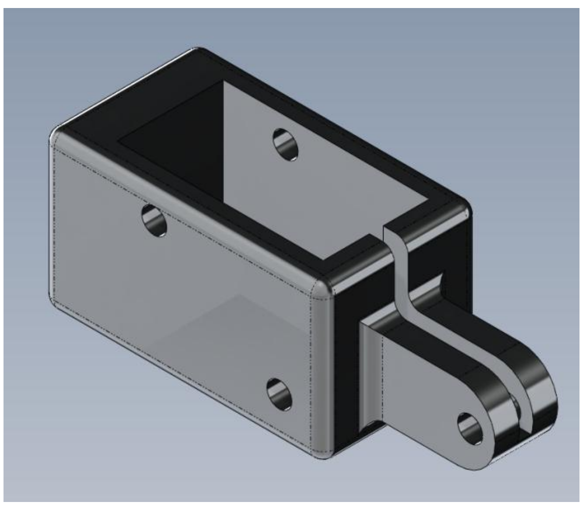


Figure 8: Finger Link: Tip

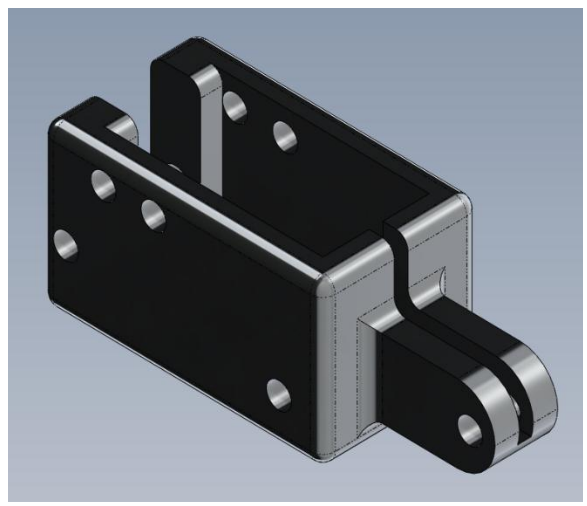


Figure 9: Finger Link: Rear Link

Initially, these links were designed for a CNC environment. However when considering high volume production, CNC becomes ineffective due to lengthy part creation times, tooling costs, and machine costs. For this reason, these links will be produced via aluminum casting.

Knuckle Bar Attachment

Initially, we had designed the fingers to interface with the chassis, however in order to further reduce cost we have designed the chassis to be created out of 1/16 in stock aluminum plate. This made addition of a finger interface difficult since welding would be required which would drive costs up and includes a thermally effected zone as a possible failure point. To simplify the design and allow for better manufacturability, we have separated the finger attachment and chassis into two separate segments. The "knuckle bar" will attach to flanged supports on the chassis with four bolts. The holes to attach the first link for each finger will be a through-hole on the outside support, and a blind hole on the inner support. Drilling a through-hole in all the supports would require a very long, specialized drill bit, so we designed away from this since special tooling will drive production costs up. The two through-holes will be tapped, and special screws with threads only on the upper section of the shaft will be used to hold the finger links in place.

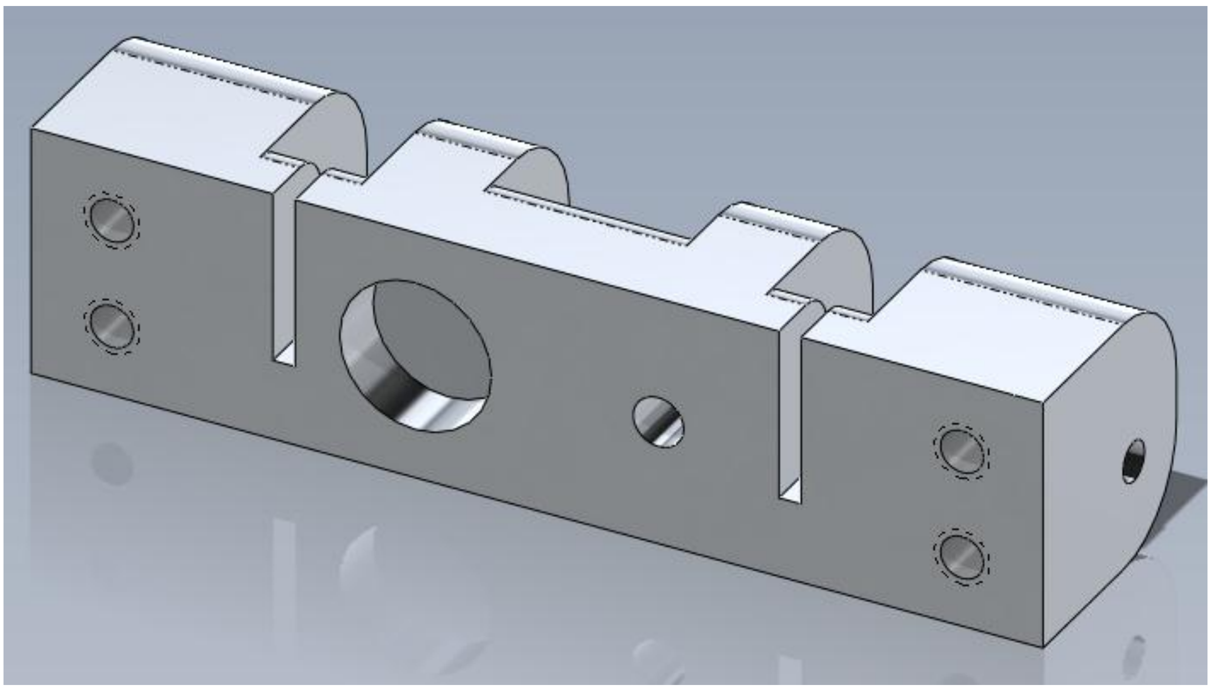


Figure 10: Knuckle Bar

Palm Chassis

The main chassis elements including the box frame and center support will be created out of 1/16 in thick aluminum plate that will be bent to shape. This design allows for stamping processes to be implemented for mass manufacturability while keeping material costs low. Wrist attachments can be added to the chassis via bolts at a future iteration, similar to how the thumb will be attached.

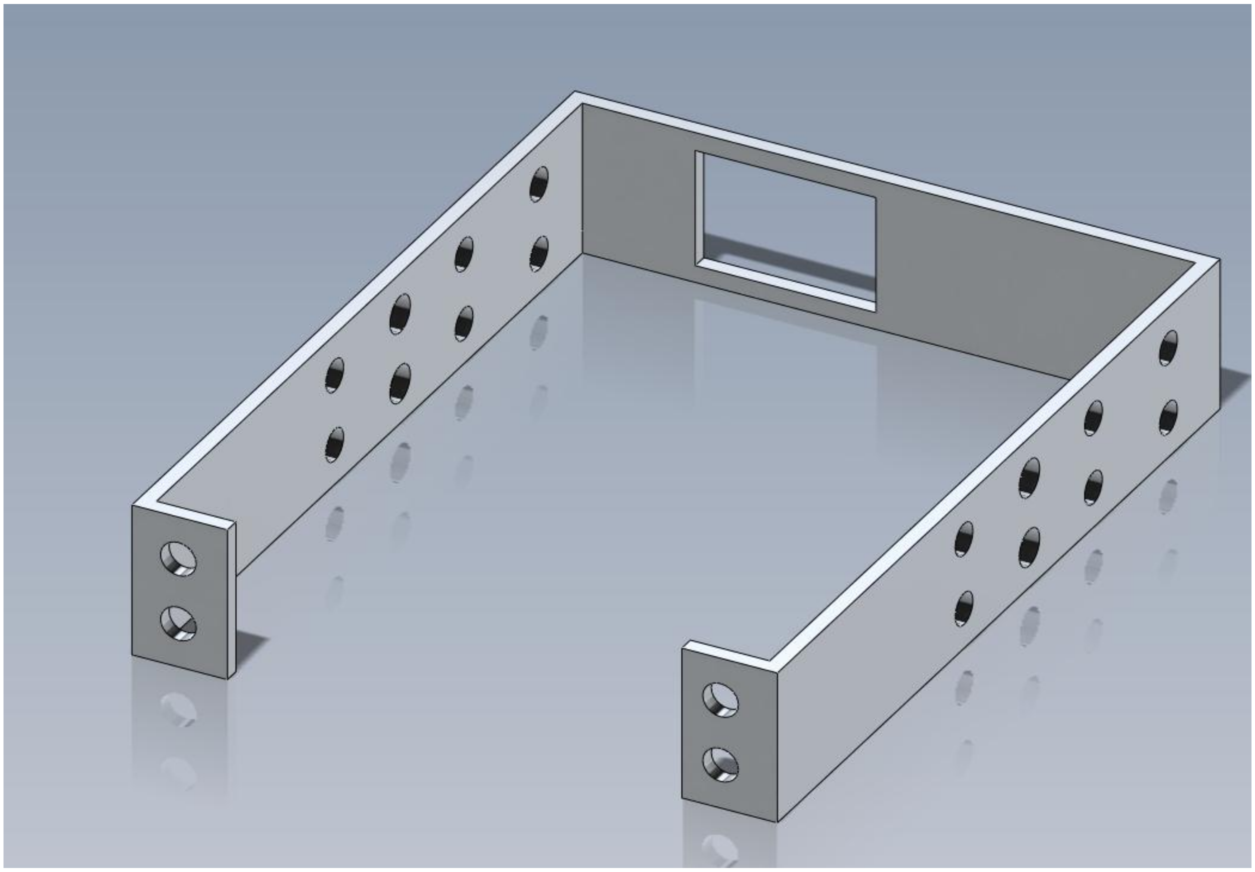


Figure 11: Hand Chassis to be bent from 1/16 inch plate stock

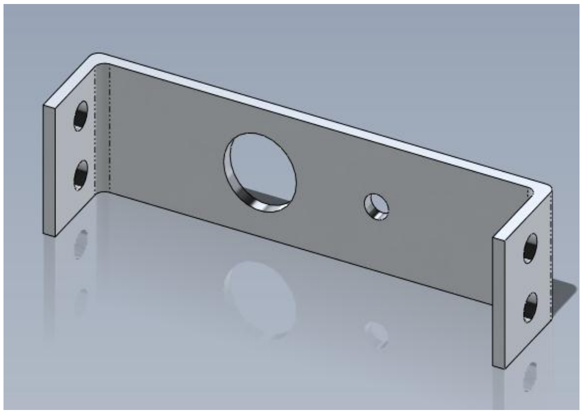


Figure 12: Cross Brace to be bent from 1/16 inch plate stock

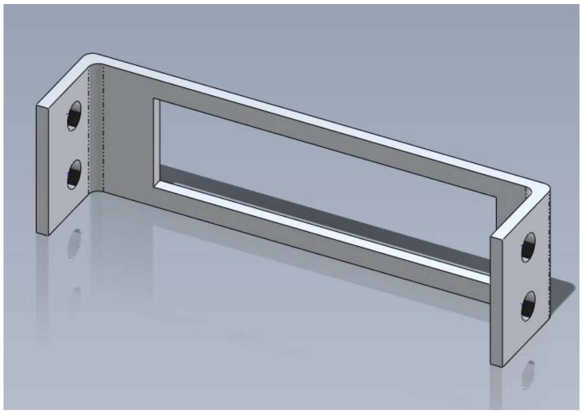


Figure 13: Motor Support to be bent from 1/16 inch plate stock

Cross Brace

The cross brace will support the power screw and the guide rail, securing them to the chassis. The two holes on the side help prevent rotation, which could harm the power screw and potentially interfere with gear meshing and fatigue. This will be made out of the same 1/16 stock as the chassis and will be bent into shape, but ideally moved to a stamping process. The plate will be too small to press fit a

bearing into, so the bearing will be glued into place using a silicone gel or something similar. This will reduce the stability of the power screw but is a better approach than welding the bearing to the cross brace, which could potentially ruin either the cross brace or the bearing.

Motor Support

The mounting of the Maxon EC10 motor and GS 10 Planetary gear set was challenging since their awkward shape and metric tolerances did not mesh well with other parts generated to interface with imperial tolerances. Due to this, two brass mounting bars were created, one was threaded to the M8-0.75 threads on the gear set, and the other had blank holes to provide a clamping surface. These brackets will be bolted together using the #6-32 hex bolts purchased for the chassis attachment with a cross brace in between. This allows for rigid support of the gear train, but also allows for positioning on the motor relative to the lead screw shaft to allow for variable post gear box gearing ratios and gear backlash elimination from out of tolerance machine work. These brackets as well as how they will be attached are depicted below.

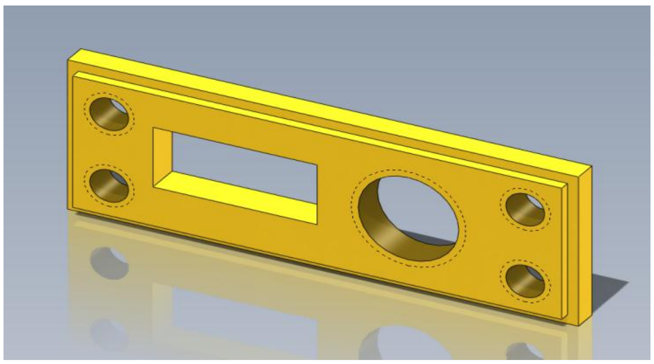


Figure 14: Gear Support with Threaded Holes

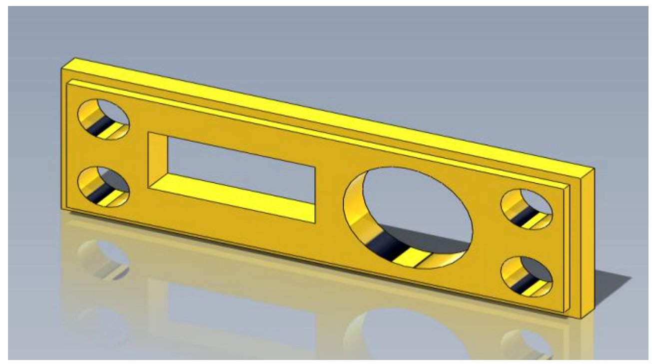


Figure 15: Gear Box Support Without Threads for Clamping

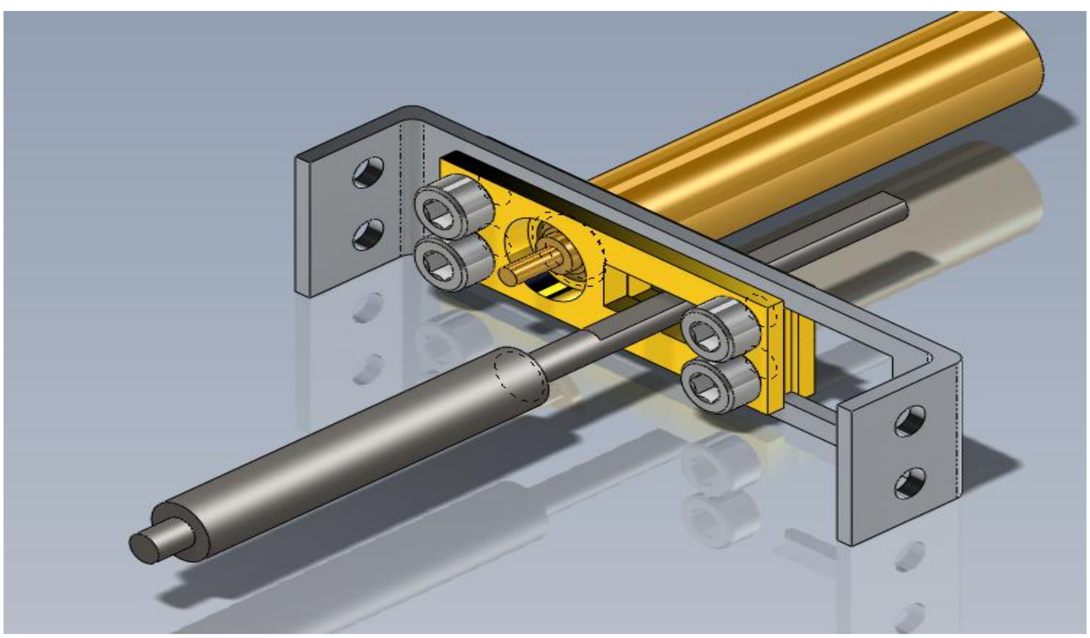


Figure 16: Gear Box Support Brackets Used as Intended. Threaded Version is on Reverse Side

Assembly Image

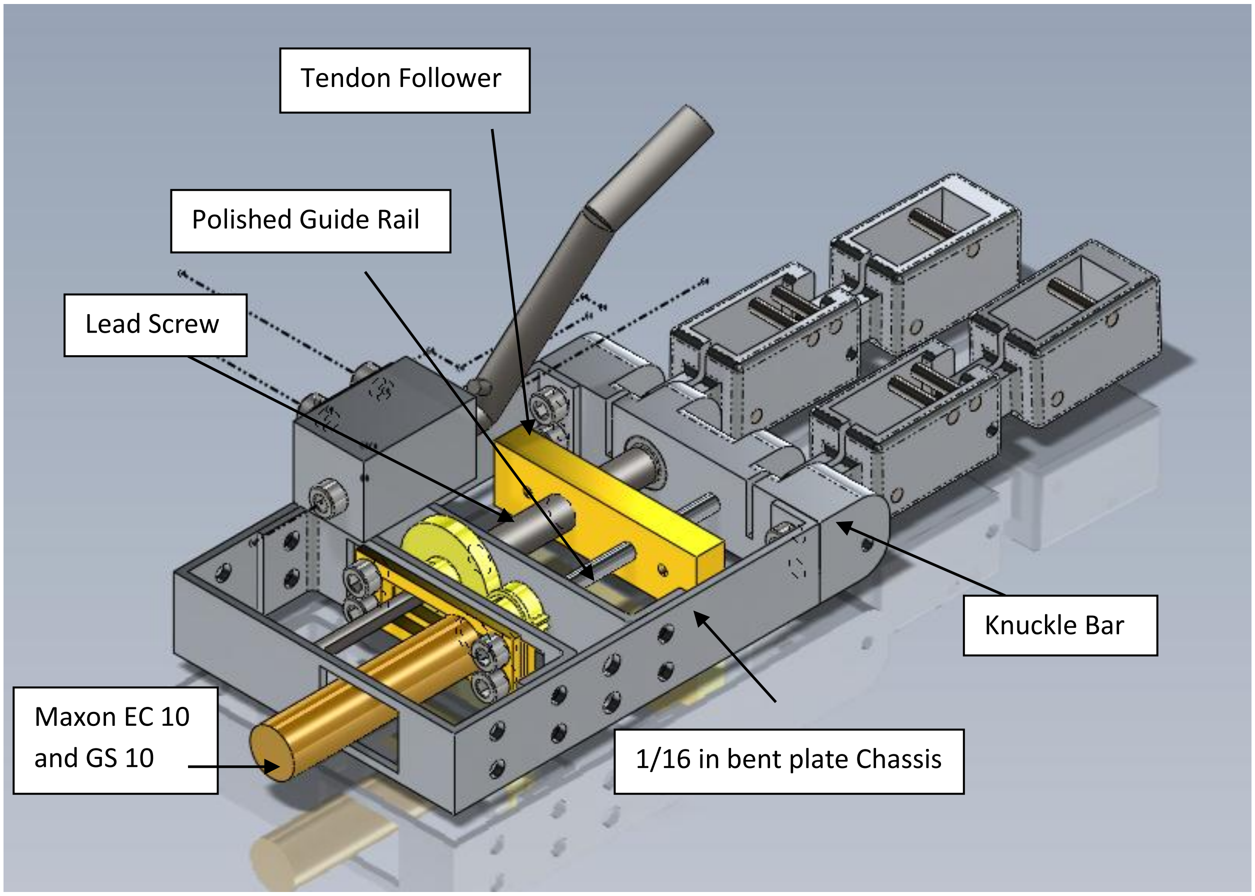


Figure 17: Complete Prosthesis Assembly Image

Material Selection

For this iteration of the PolyGrasp hand, we chose to use aluminum as a primary material for a few reasons. Primary among those reasons is the ease in which aluminum can be formed, and reformed to fix errors. Since the knuckle bar and the finger links were made in a rapid prototyped lost plastic casting method and finished on a mill, aluminum helped keep the tooling costs and run time of the parts down.

Aluminum is also very cost effective for its strength to weight ratio. A primary design goal is the reduction of device weight such that it weighs no more than 518g (1.14lb) when fully assembled. This eliminates steel as a material choice since its high strength characteristics come from a high material density. Titanium would be ideal from a strength and weight perspective, but titanium is prohibitively expensive and very difficult to machine.

Ultimately, an injected plastic would be ideal for this device. This is primarily due to the low stress environment anticipated for the device in a civilian market, which allows for lightweight materials to be used. For active duty service personnel however, aluminum is an ideal material for its strength, corrosion resistance, and durability which is a requirement for any equipment able to withstand harsh combat environments.

Micro Controller State Machine Development

The "brain" of the prosthesis was created and executed as a simple state machine with various inputs that allowed the actuation of the motor to occur based on a series of conditions. This state machine consists of three individual states that control how the motor turns on, reverses, and stops. These states are labeled "On", "Off", and "Reverse". The motor starts in the Off state, and transitions to the On state when a myoelectric signal is input to the processor. This state is held until either the pressure sensors read a maximum grip force, or the end condition switch is pressed that signals the end of the tendon follower throw. Either of these inputs sends the motor into the Off state while myoelectric signal is constantly applied. When a myoelectric signal is lost (stop flexing), the motor transitions to the Reverse state to allow the hand to loosen its grip. This state is changed to On by a re-application of myoelectric signal, or the second end condition switch that signals the full opening of the hand. These transitions are covered in the State Machine Diagram below in Figure 18.

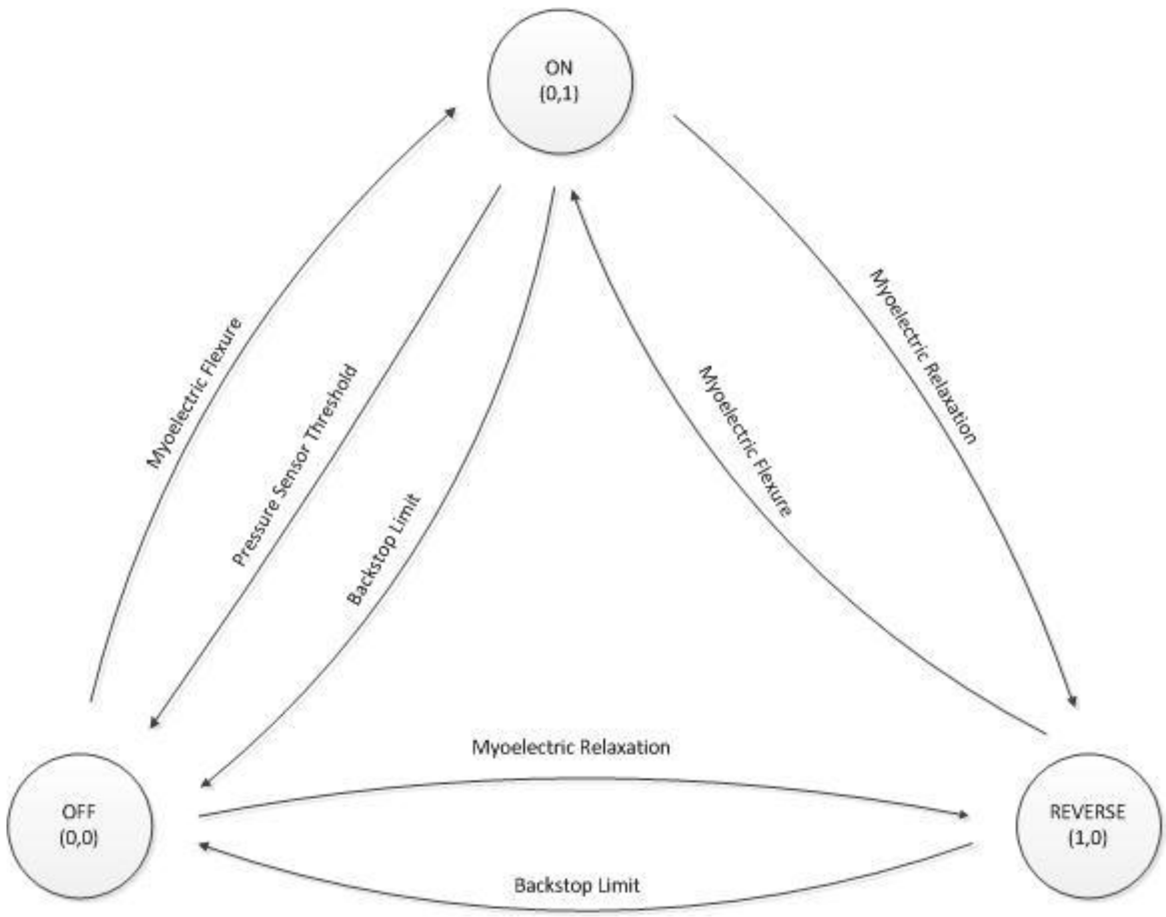


Figure 18: State Machine Diagram

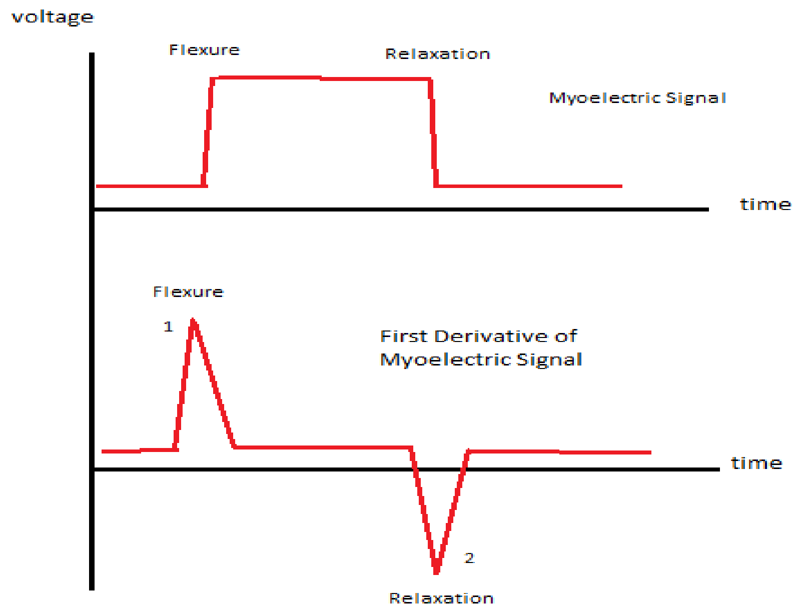


Figure 19: Myoelectric Signal Diagram

The myoelectric transitions between states occur on a change in amplitude in the myoelectric signal. The direct voltage read in the muscle is represented by the top graph above in Figure 19. The processor is actuated when the slope of the signal shifts, which is represented by the lower graph in Figure 19. When either a positive or negative spike occurs in the slope of the signal similar to the spikes seen above, the processor transitions states accordingly based on the current state of the hand.

Output Force Sensor Array

In order for the Arduino to know when the hand reaches the user prescribed grip force, a sensor array to measure that force was needed. In order to accomplish this, Force Sensing Resistors (FSR's) were chosen for their inexpensive implementation. FSR's come in a variety of sizes, but all function in the same way: compressive forces on the pad of the sensor cause a change in resistance across the leads. This is similar to how strain gauges function, however strain gauges are sensitive axially along the sensor array, while FSR's are sensitive transverse to the array. This transverse sensitivity makes them ideal for measuring the pinch force of the prosthesis. A basic layout of and FSR is given below in Figure 20:

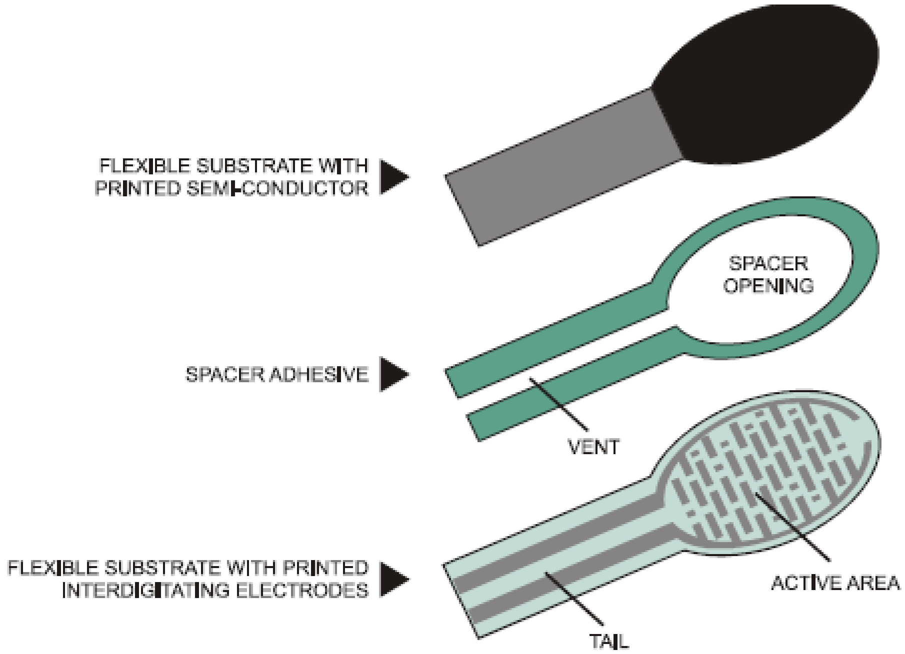


Figure 20: FSR Layout (Electronics)

Based on a variety of recommended circuits for utilizing this resistance change, a simple inverting amplifier circuit was chosen for the relative linear behavior of the output voltage within the force range expected as shown below in Figure 22.

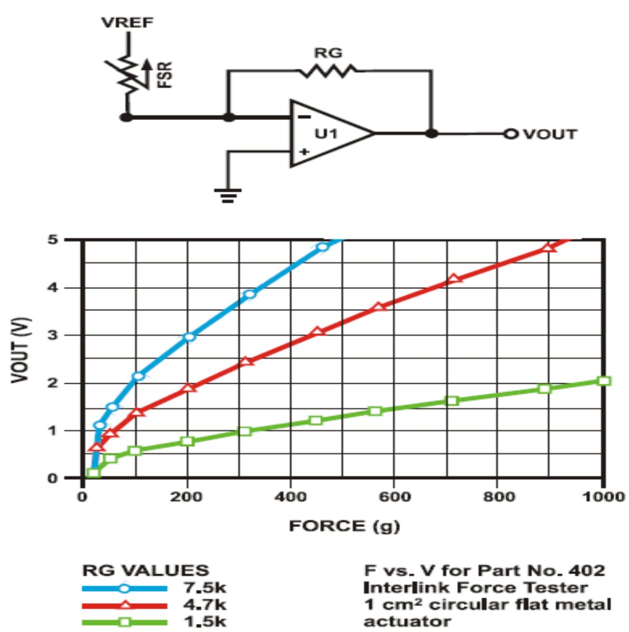


Figure 21: Inverting Amplifier FSR Circuit Recommended in Datasheet (Electronics)

When the resistance of the FSR changes, it causes the gain of the amplifier to change as well, changing the magnitude of the voltage exiting the circuit. This voltage can be applied to an analog input into the Arduino which can apply logic to the signal and interpret that voltage as the force pressing on the FSR. In order to cause the voltage signal to be positive, another inverting amplifier with a constant gain was added since the first amplifier outputs a negative voltage. As shown in Figure 22 below. It was decided that 500Ω was the ideal RG resistance for this application based on bench sensitivity tests of the circuit.

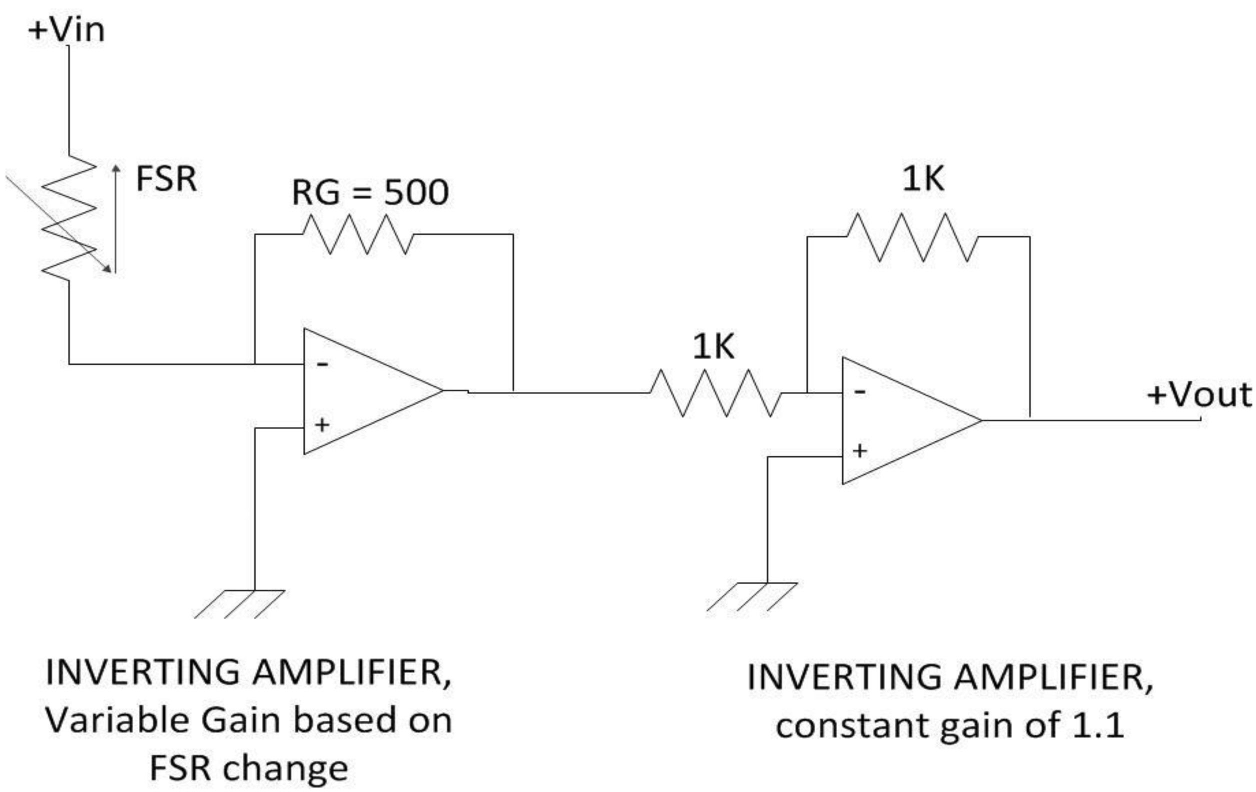


Figure 22: Force Sensing Resistor Circuitry

Motor and Gearing Selection

Based on torque requirements calculated as shown in the Motor Specifications Analysis section of Appendix E, the Maxon EC 10 and GS 10 planetary gears were chosen for this application. With both components having a total diameter of 10mm, this combination ideal since its small footprint will more easily fit within the confines of the hand chassis while maintaining high output characteristics needed for strong grip. The current design has the motor facing into the hand from the rear as shown above in Figure 17, however a concept has been developed to side mount the motor suing bevel gears to contain it fully in the chassis. This option could not be produced in the duration of this project due to long shipping times from Sweden for the motor and gearing which would make fabrication of this new assembly difficult. This concept will be passed along to future PolyGrasp teams to develop further and utilize and is depicted below in Figure 23.

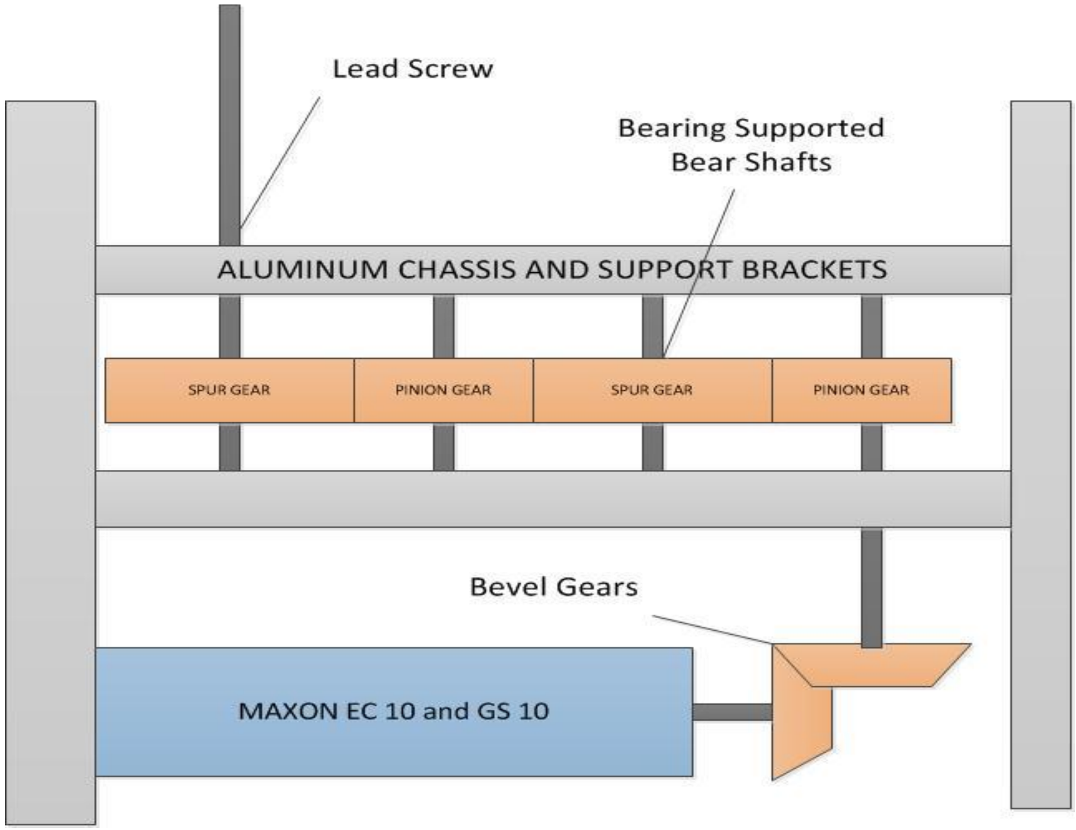


Figure 23: Future Motor Mount Concept Image

Manufacturing

We have designed the hand to be assembled easily in a manufacturing environment. Before assembly, the chassis, chassis crossbar, lead screw, guide rail, follower, motor and gearing, knuckle bar, and individual finger links are all individual parts. Assembly of the hand moves linearly in the following order:

1) Chassis supports are riveted into Chassis frame
2) Guiderail and lead screw are inserted into the Chassis support slots
3) Motor and gears are mounted
4) Tendon Follower is threaded onto the lead screw and guide rail
5) Knuckle bar is bolted to the chassis with guiderail and lead screw supported in their respective grooves
6) 2 finger links are then attached to the knuckle bar, and the remaining links are attached to the links already attached to the knuckle bar
7) Tendons are attached to end links and routed to follower
8) Pretension the tendons and apply a crimp

Final Design Verification

Supporting Analysis

Finite Elements Analysis (FEA) models have developed to explore various failure modes for finger links and chassis deflection in order to verify the validity of the design. Hand calculations for chassis deflection and maximum transverse impulse can be found in Appendix E.

For chassis deflection, a single cantilever analysis was used to predict deflection of the chassis based on a fixed boundary condition on the back surface. As is, the chassis is expected to deflect 0.02 inches under loading consistent with supporting 50lbs with the finger as shown below in Figure 24. This deflection does not account for additional stiffness introduced but the cross braces and drive train assembly. The model developed to explore the chassis behavior under load was simplified to symmetric shell elements to expedite run time.

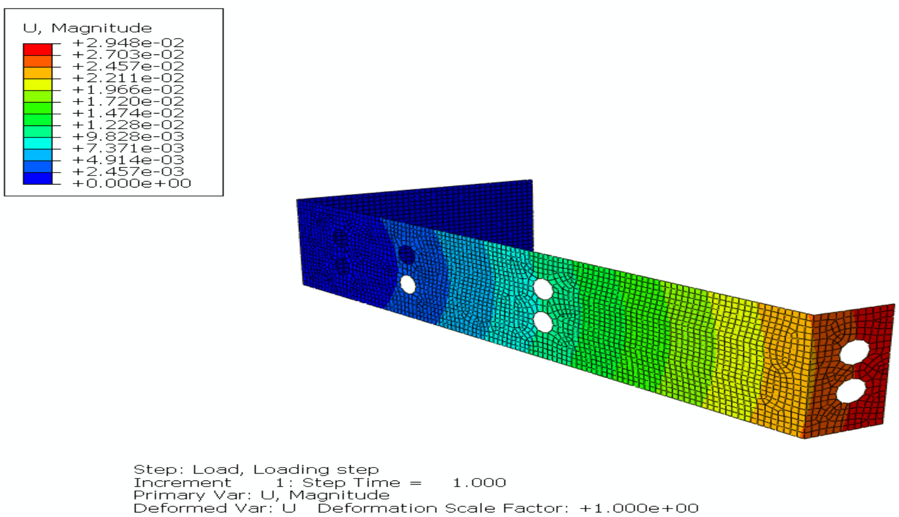


Figure 24: Defection Plot of Symmetrical Chassis Section Under Support of 50lbf

Additionally, weight reduction methods were explored via cutouts in the section between the front holes and cross brace holes. Additional models were generated with different shaped holes cut into the chassis as shown below in Figure 25.

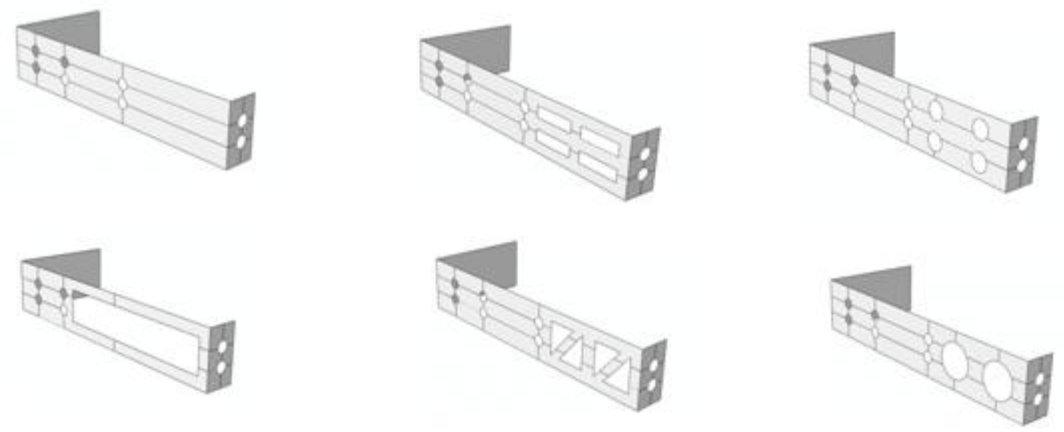


Figure 25: Material Removal Cutout Shapes for Weight Removal Study

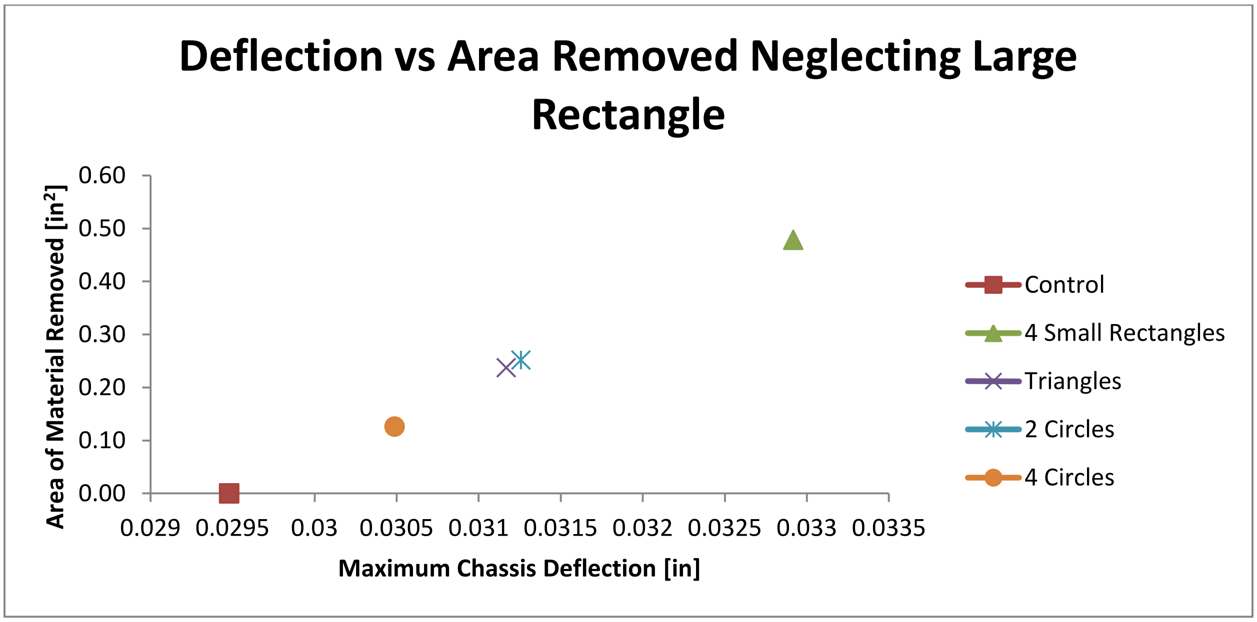


Figure 26: Chassis Deflection as a Function of Material Removal Area

As shown above in Figure 26, small rectangles yield the most promising weight reduction possibilities for weight reduction of the chassis structure. For a more detailed analysis of the results of this FEA study, please refer to the accompanying document: "A Standard FE Model of a Prosthetic Hand Chassis."

Another major area of possible failure is a sudden impact load to the side of the finger links, causing transverse shear and possible failure of either the finger link tongue or the pin holding the links together. To simplify analysis, impact loads can be approximated as a static load condition of twice the magnitude; so all static loads were doubled in this analysis to account for this. The loading was changed into an equivalent pure bending moment to ease hand analysis as well. It was found via hand calculations that impact loading conditions of 164.57 lbs. and 42.20 lbs. would cause failure and yield in the link pin respectively. The yield condition is of notable concern since it is so low and likely to be seen under normal use.

For finite element analysis, a defeatured mockup of the finger link assembly was created in ABAQUS, as seen in Figure 27. The knuckle piece was held in place with an encastre constraint on the back face. Other critical constraints were contact between the knuckle and the finger link tongue and between the pins and each of the pin holes to hold them together. Distant mates were also used to hold the pins within the links. The force was applied as a static pressure over a small area to avoid point load abnormalities.

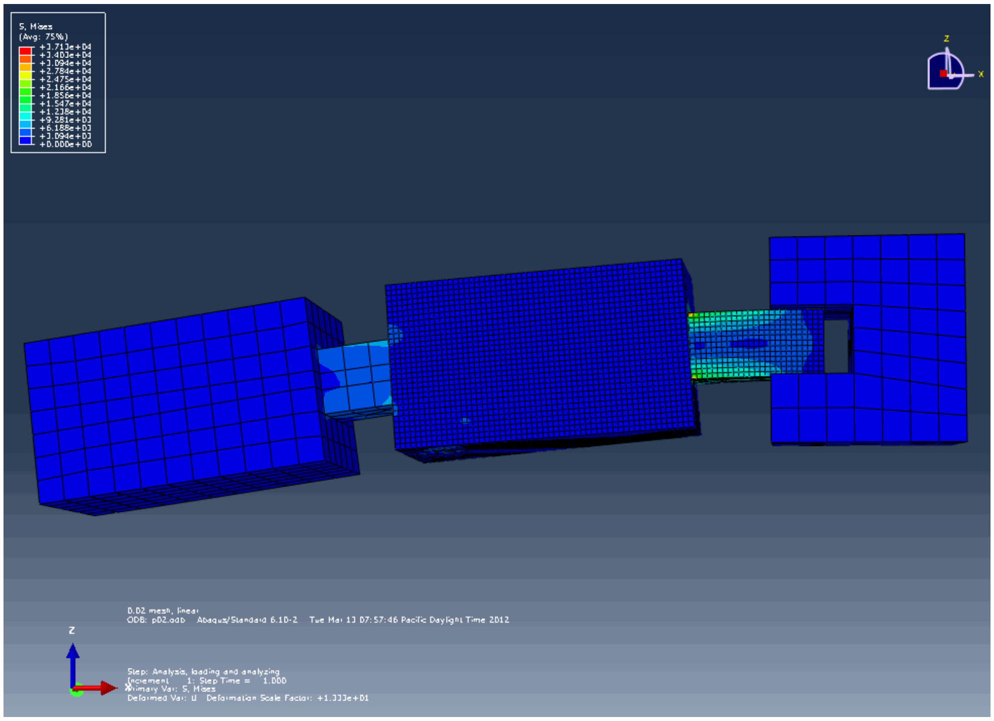


Figure 27: Finger Assembly Impact Stress FEA

The analysis confirmed the trends expected from the hand calculations. There were large but manageable stress values in the tongue and large stress values in the joint connecting pins, shown more clearly in Figure 28. Physical testing would still be useful and should be conducted.

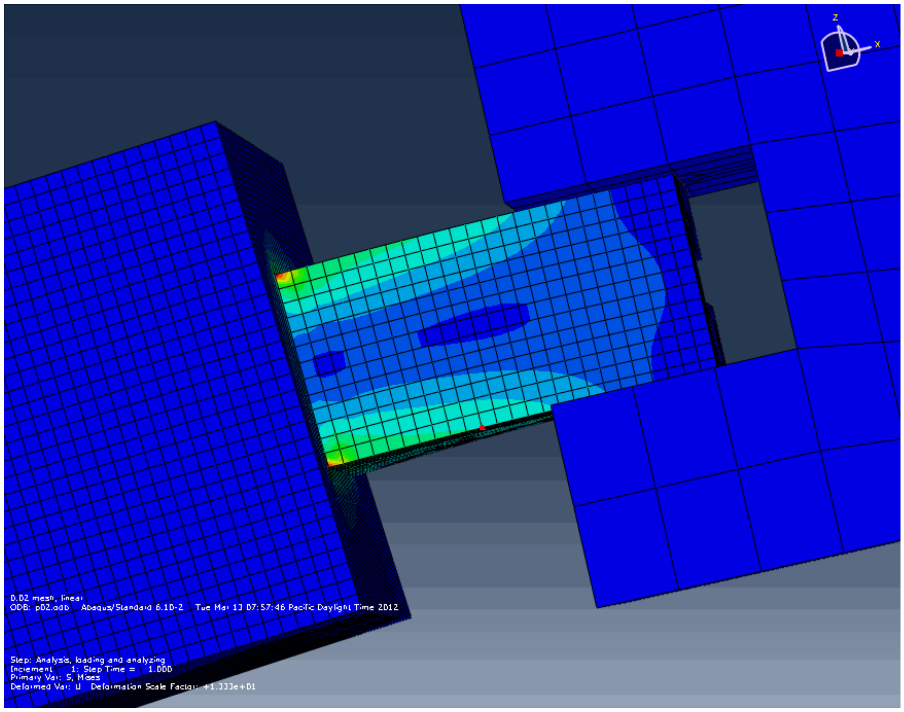


Figure 28: Close-Up Impact Stress Trends FEA

In addition to these loading conditions, link pin stress distribution for the pins holding the finger links together was determined based on tendon tension to ensure pins will not fail under mechanical actuation of the fingers. A finite element analysis of the finger joints was done to model the stresses in the fingers for the maximum loading condition at two finger configurations: open and closed as shown by Figures 29 and 30.

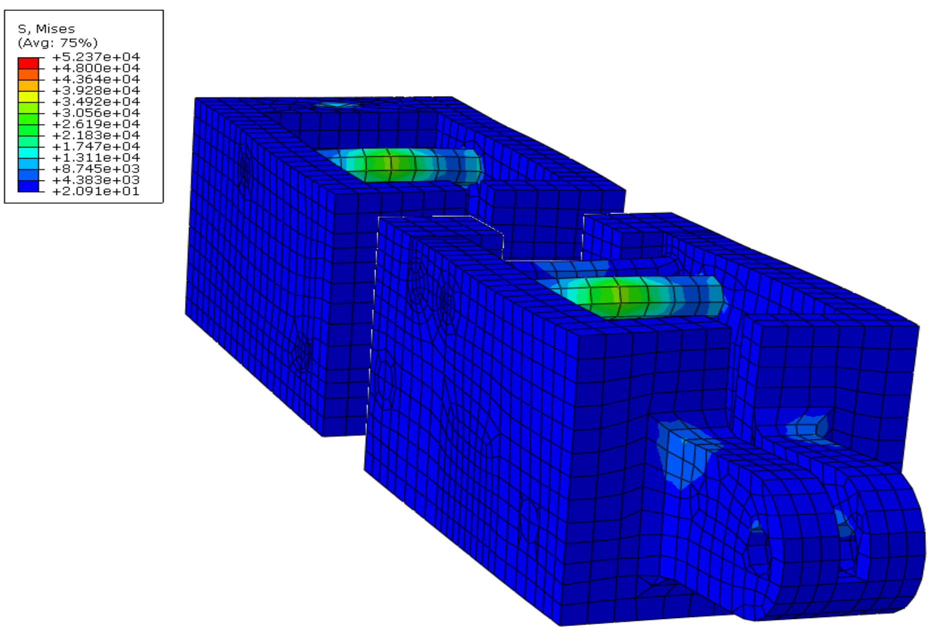


Figure 29: Open Position FEA Results

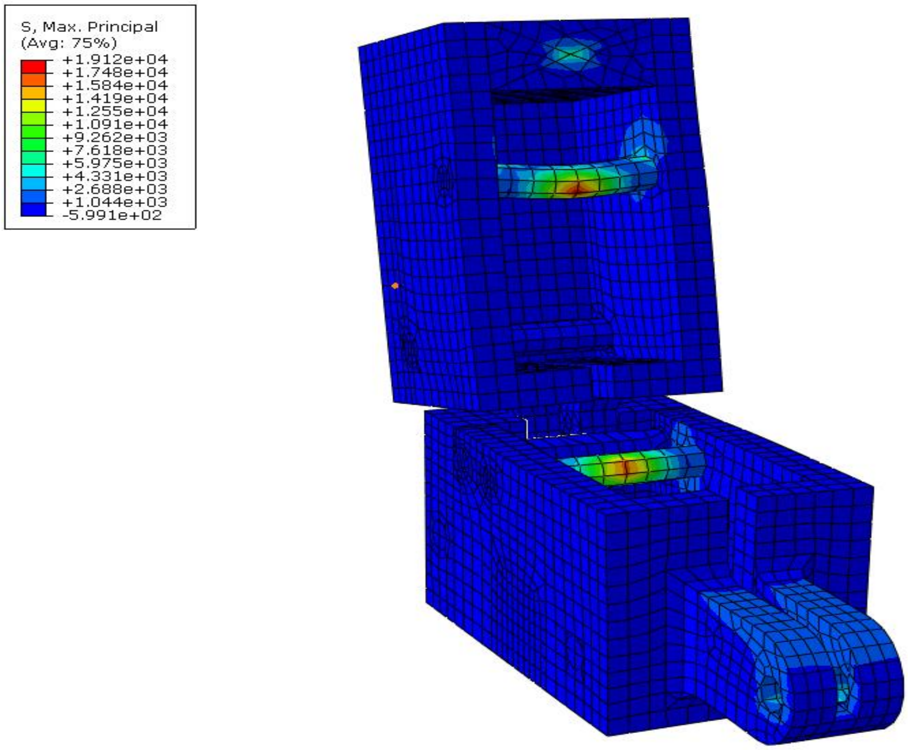


Figure 30: Closed Position FEA Results

The maximum stresses in each joint and the contact force between the joint and the pin in the closed model were compared to the allowable stresses.

Table 3: Maximum Stress Comparison for Finger Link FEA

	Maximum Stress [psi]		Contact Stress [psi]	Allowable Stresses [psi]
	Tip Joint	Middle Joint		
Fully Open	9,562	4,843	N/A	58,000
Fully Closed	3,244	3,098	1304	

The stresses in the finger joints were far below the allowable stress in the aluminum joints and the pin. This proves that this design is acceptable. For more detailed analysis, please refer to the attached document: "A Finite Element Model of Finger Joints of a Myoelectric Prosthetic Design."

Testing Protocols

Testing of the device is necessary to ensure proper functionality and safety. Are three main categories of tests to be conducted: case deformation and finger link failure, crimp failure properties of the tendon, and electrical noise and power consumption. Currently, only finger link failure tests were able to be conducted, however other test categories will be completed by Devon during his thesis work as a first step in further development of this hand.

The first will be focused on obtaining the mechanical properties of our design. This test will apply a variable load to different, very specific areas of the hand, as seen in Figure 31.

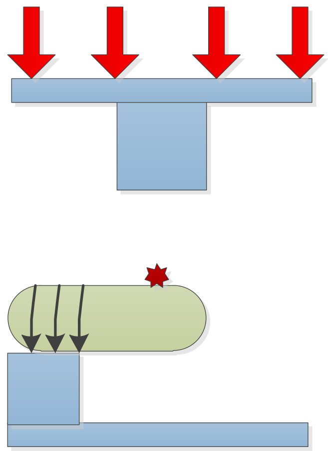


Figure 311: Structural Deformation of the Chassis

The joint was be mounted sideways to a platform and a load was exerted in the direction normal to the finger flexion. This test was conducted to see how much force must be exerted to cause the finger joint to fail. This test was conducted with a simple force transducer and cable which attached in a cantilever orientation to the link mounted to the table. For this to meet the set requirements, the finger will have to withstand within 20% of the calculated maximum force.

Physical testing for transvers joint shear similar to the second FEA model and hyperextension were conducted to verify the mechanical soundness of the finger links by statically loading the finger links until failure.

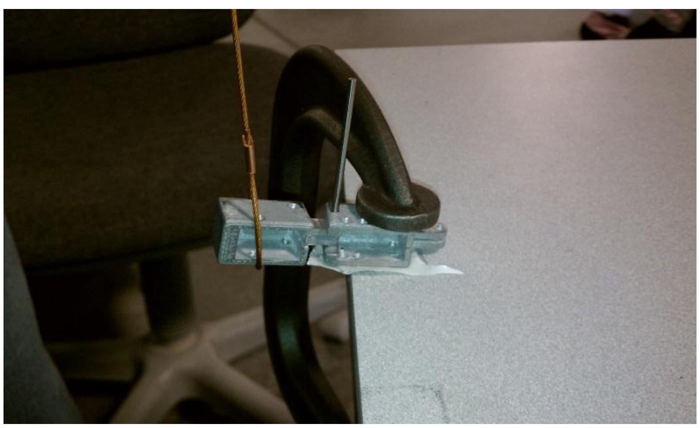


Figure 33: Transverse Testing

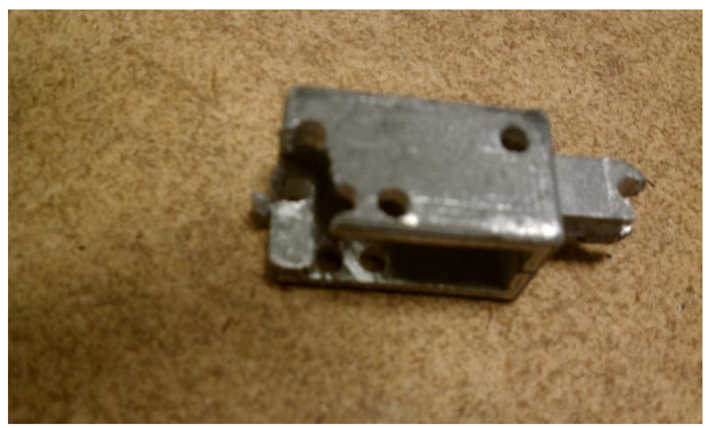


Figure 32: Typical Finger Link Failure

Table 4: Physical Test Results

Physical Testing Results			
	Static Failure Point [lbs]	Impact Failure Point [lbs]	Hand Calculations [lbs]
Transverse Collision	37.30	18.65	42.00
Hyper-Extension	60.50	30.25	n/a

Impact loads were calculated using the principle that under a dynamic impact load can be approximated as one half of the corresponding static load. As seen in Table 4, the impact strength of the finger links was half of what the FEA model predicted. This can be attributed to inconsistencies in assumptions made for the FE process as well as non-uniform material properties introduced in the material due to the casting process.

The second structural test Devon will be conducting will be done to the case. The set up for this test will be the same. Force will be exerted on to the housing in the same fashion as the finger joint. We will see the maximum force the housing structure can withstand before plastic deformation. For this to meet our requirements, the casing must withstand within 20% of the calculated maximum force.

The next test is to be done to the crimp that acts on the tendon. A simple looped crimp will be constructed on the cable tendon and will be then be put into a tensile tester. The tensile tester will apply a force in the tensile direction, as shown in Figure 34. This force will be recorded along with deformation and elongation. With these data points it is possibe find the maximum tensile stress that is able to be withstood by the crimp without catastrophic failure. To meet design requirements, the crimp must be able to hold 120% of the maximum force designed for finger use.

Figure 34: Crimp Tensile Integrity

The last set of tests will be focused towards electrical emissions and power consumption. Both can be tested simultaneously with the set up shown in Figure 35. For power consumption, the motor will support a set load and run continuously until the battery has no power left. This event will be marked when the motor ceases to support the described load. To pass requirements, the motor must operate continuously for 4 hours (according to our assumptions made about non-continuous user use). Concurrent to this test, testing of the myoelectric circuit without a faraday cage will be done to see if there is any electrical interference. To pass requirements, the circuit signal must be within 20% of the designed amplitude.

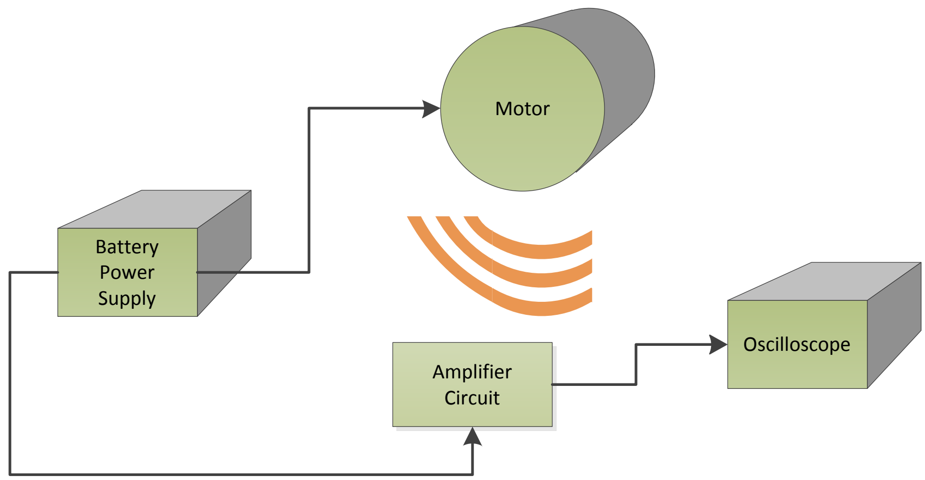


Figure 35: Electro Magnetic Interference and Power Consumption from the Motor

Safety Considerations

There are three main categories to consider for safety: during fabrication, during testing, and during electrical model validation.

During the fabrication process, safety of the constructor must be accounted for. All safety requirements that are normally implemented in the machine shop will be followed. These include the use of goggles, gloves and other safety equipment. Caution will also be taken during the assembly of ordered and fabricated parts. Examples include filing sharp edges of newly machined parts and inspecting structural integrity before actual testing occurs.

The testing phase of the project will need very strict safety requirements. During destructive testing, all people in the surrounding area need to be wearing goggles and gloves (if handling equipment). This is due to the fact that particulates will most likely be flung from the part during destructive testing.

There are also certain hazards associated with working on an electrical system. Before testing with human subjects, all circuitry will be thoroughly tested using measuring equipment. This is to protect the user from the circuit. The circuit will also be protected from the motor battery power supply. This will be ensured by thoroughly checking grounding wires and all other connections to ensure proper safety of the circuit to further ensure safety of the user.

Product Realization

Motor Used in Prototype

There was one major change in the prototype of the prosthetic hand. A decision was made to replace the Maxon EC 10mm motor with another motor.

The Maxon EC 10mm motor is a brushless motor from a Swiss company. The motor has three windings that are turned off and on intermittently to rotate the motor shaft. The motor must be commutated at a precise timing in order to run this motor at maximum efficiency. The usual method for determining the

time to commutate is through Hall Effect sensors in the motor casing detecting the passing of the motor aperture. There is also another method that uses the back electromagnetic force (EMF) peak in each of the windings to determine when to commutate the motor. The Maxon EC 10mm motor that was ordered did not come with the Hall Effect sensors, and the circuit required to control the motor using the back EMF was not able to be fit onto the Arduino board that was being used to control the prototype. Maxon offers DC brushed motors and controllers for their brushless motors; however, the time it takes to ship those parts was unfeasible for our project time frame.

The goal of the prototype was to only display the kinematics of the prosthesis. The motors available to us that were sufficiently small enough to mount did not supply adequate torque to move the mechanism. However, spinning the gear the motor would mesh with does demonstrate the actuation of the fingers.

To graft the new motor onto the prototype, several alterations were made. First, the motor mounting brackets were changed. The tapped hole the holds the EC 10mm motor was milled out in order to fit the new motor's alternative casing design. This alteration was necessary to fit the new motor. Second, the motor casing required removal of the back bar of the prototype to fit the motor. Third, the new motor was epoxied on to the motor bracket. This minimized the amount of machining that needed to be done to affix the substitute motor to the prototype. Epoxy is a temporary solution to attaching the motor which will last long enough for the kinematics of the prototype to be demonstrated.

The EC 10 motor and GS 10 coupled gearing was ideal for this application because it had high output characteristics within a small package. This motor however is a brushless motor, meaning it runs by applying energy in a pattern to a series of electromagnets inside the coil. Due to a lack of experience with DC brushless motors within the group, our circuit designs and controllers were built for traditional brushed motors which only need a voltage applied across terminals to work rather than a specially generated signal. For this reason our system cannot utilize the EC 10 motor, which had to be swapped out for a simple low power stand in motor. We have purchased a motor speed controller and have begun developing controller loops to activate and run the more complicated EC 10, however this was begun too late in the design process to be completed due to long shipping times from Maxon Motors which is based in Sweden. Devon will develop a means of using this motor and replacing the stand in motor as part of his thesis work.

Machining Processes Used

Throughout the prototyping process, we strove to use machining processes which would be easily scaled to large scale production in a manufacturing environment in a quick and efficient manner. The first of these considerations was the use of standard sizing that is commonly available for raw metal stock. This included aluminum in bar, sheet, and round stock in stock, brass bar stock, and steel round stock. By purchasing metal as close the finished dimensions as possible, cuts are reduced which in turn reduces the costs associated with lost material, tooling costs, tooling wear, and technician hours in a production

environment. The processes used to create each part will be discussed in more detail below, but an outline of each process follows.

Aluminum Casting

The finger links and Knuckle bar were created using a lost plastic casting technique. Plastic representations of the final parts were created using a rapid prototype printer which were then mounted in a steel flask and submerged in liquid plaster.

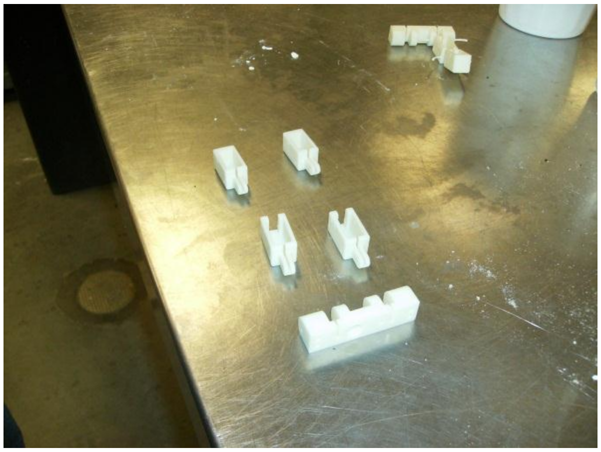


Figure 36: Rapid Prototyped Polymer Parts

Figure 37: Polymers Parts in a Flask Ready for Plaster Pouring

After the plaster dried, the molds were fired in an oven to both set the plaster and burn out the plastic parts, leaving voids into which molten aluminum was poured. Once cooled, the aluminum was broken out of the plaster and finished into their current form. This process can achieve results similar to a die casting process which we envision used in a production environment to create these parts.

Figure 38: Flasks after Metal was Poured

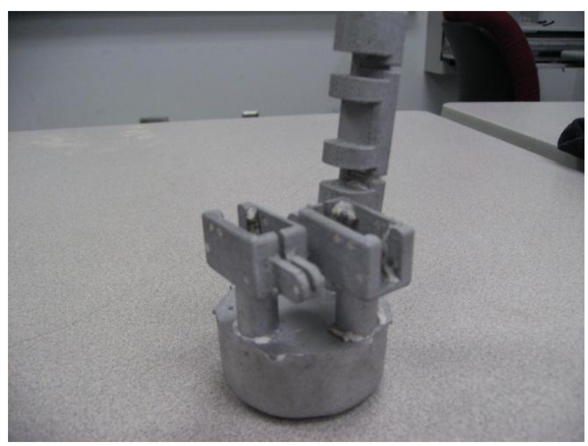


Figure 39: Metal Removed from Plaster Mold

Milling

Features such as slots or grooves, or any feature which required tight tolerances was created using a vertical knee mill. Obtaining tolerances of a few thousandths is possible die to digital distance read outs

and axis zeroing tools such as live centers makes these mills versatile in part creation. Parts such as the thumb housing and motor mounting brackets were created with this process.

Figure 40: Milling Being Done on a Vertical Knee Mill

Drilling

A standard drill press was used to create basic holes in the finger links, chassis, and cross bracing. This tool was used rather than a mill for holes whose tolerances were relatively not important since a drill press is much simpler and quicker to use.

Lathe Work

A lathe was used to create the diameter changes in the leas screw to allow it to be pressed into bearings and have gearing mounted to it. This was a tricky process due to the fragile nature of the screw since an ACME Screw was purchased and the threads were turned off to create the smaller diameter. Small cuts had to be taken to prevent the screw from hitting resonance in the chuck and fracturing during processing.

Figure 41: Lead Screw Being Fixed into Chuck of a Lathe

Sheet Metal Work

The chassis and cross braces were created using a combination of drilling, cutting with a Dremel, sheet metal shearing, and sheet bending. First, the part was laid out flat on a large sheet of aluminum a pencil with extra length added to the bend areas to account from the arc length needed for the bend radius. Holes and other features were cut before bending to ensure gripping in a vice was possible. Once features were cut, each segment was cut from the large sheet using a sheet metal shear. The shear was used since the 1/16 inch plate was not too thick for it to handle and a saw was not necessary. Once each segment was cut, 90® bends were added to create the final shape.

Part Generation

Finger Links

Blank finger links with no holes or grooves were created using a casting process. Plastic parts were created from SolidWorks models using a rapid prototype machine and encased in a plaster flask. The plaster is fired in an oven, allowing the plastic parts to melt out and leave a cavity representing the part desired. Molten aluminum is poured into these molds which sit on a vacuum platform to pull metal down into the mold uniformly.

Figure 42: Metal Being Poured into Molds

Figure 43: Filled Molds Cooling on Table

Once the metal is cooled, it can be broken out of the plaster. Once the plaster is removed, steps are as follows for creating the finger links:

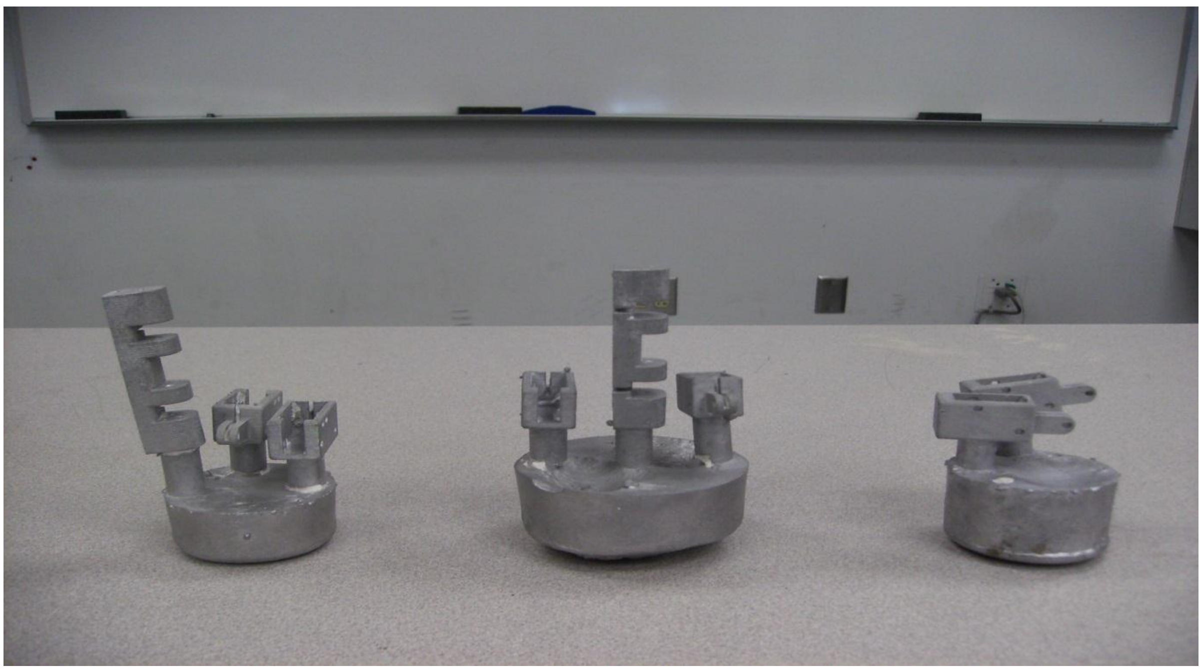


Figure 44: Metal Result of Casting Process

1) Clean solidified pieces in sand blaster cabinet
2) Using a band saw, cut desired parts off of casting basin and grind remaining casting sprue off or part with a wheel grinder.
3) Map out holes for pins in parts
4) Using a #39 drill bit and a drill press, drill holes for tendon pins to be pressed into
    a. NOTE: use a #38 bit for joint holes to allow for clearance
5) For rear links, use and mill with a ¼ in end mill to cut groove for front link to fit into
6) Use a Dremel with a cut off wheel to create tendon grooves
7) Tendon pins should be press fit into holes

a. NOTE: This prototype has the pin holes oversized and pins glued in place to allow for deconstruction of the tendon pulley system

Tendons

The original tendons were to be made from the purchased 1/32 inch nylon coated steel cable. We created a loop in the cable by stripping the nylon from the edge and brazing it together to form a loop. Unfortunately the cable was too stiff to act within the tight constraints of the pulley system and would not actuate the fingers. For this reason, we moved over to the 150lb spectra line used in the PolyGrasp 2.0 hand. This was a temporary fix, and we suggest the use of jewelry cable or high strength fishing line with further research to justify the decision.

Tendon Follower

The tendon follower was made of brass for its self-lubricating properties since the threads will be interacting with steel and the guide rail will be polished aluminum. This part was relatively easy to make since it has simple geometry.

1) Cut a section off of stock bar to roughly 1.85 inches
2) Grind length down until it is 1.80 inches
3) Measure and drill holes
    a. 2 holes for tendon to pass through (any size desired within reason)
    b. 1 ¼ inch hole for the guide rail
    c. 1 #7 hole to become ¼-16 threads
4) Tap the #7 hole with ¼-16 special tap

Knuckle Bar

The knuckle bar was created as a rough casting using the same process as the finger links. Features that were removed from the solid model include finger link attachment holes and chassis bolt holes for threads. Once the casting is cut from the sprue and prepared for post processing, follow these steps:

1) Using Drill press, drill chassis bolt holes using #36 drill bit
2) Drill finger link attachment holes using #38 drill bit 0.25 inches deep
    a. Drill through both sides of a finger support on each side to ensure holes line up
3) Drill guide rail support hole using 1/8 inch drill bit 0.25 inches deep
4) Using a mill and a 3/8 inch end mill, clean out bearing hole
5) Tap 4 chassis bolt holes using #6-32 tap to roughly the bottom of each hole

Chassis and Cross Bracing

The chassis and all cross bracing was developed in the same way. The holes and cuts were laid out on a flat sheet of 1/16 thick 6061 aluminum plate with a 0.0982inch length set aside for bends as that is the arc length associated with a bend radius of 0.0625 inches based on Cal Poly tooling. Creation steps are as follows:

1) Lay out lengths and holes on flat sheet. NOTE: leave a distance of 0.0982 inches for bends based on sheet bender radius.
2) Cut outline of parts out of sheet using a sheet metal sheer
3) Drill or cut features into parts. This includes rivet holes, holt holes, bearing holes, or motor slots

4) Bend angles into sheet using a sheet metal bender

Lead Screw

The lead screw was created from ¼-16 Acme lead screw stock. For this design, the ends of the screw needed to be machined down to fit inside the 1/8 bearing holes. In addition, the slot for the set screw of the gear needed to be machined. The important tolerances on the lead screw are the shaft diameters and the concentricity of the shaft with the threads. To reach the appropriate tolerances on the shaft diameter, the shaft was be ground down on a lathe with abrasives until a bearing could be pressed into place. The shaft concentricity tolerance was be met by machining the part on a lathe. The following steps were used to machine the lead screw:

1) Cut stock lead screw to about 3.25 inches
2) Wrap screw in paper and put into lathe chuck. Set speed to 1875
3) Face piece to 3.21 inches
4) Expose at least 1.6 inches of screw and live center it
5) Turn down a length of 1.6 inches to a 0.13 diameter with small passes of 0.01 inches
6) Using abrasives, grind diameter down until the bearing can fit snuggly next to the threads
7) Repeat process for a length of 0.16 Inches on the other side

It was discovered that wrapping the screw in paper displaced the center of the shaft a few thousandths off. One alternative method that was suggested was to place two nuts onto the lead screw and then clamp the lathe chuck on to the nuts. This was not attempted due to a lack of nuts available for the lead screw.

Guide Rail

The guide rail was created from the 1/8 aluminum bar stock that was used to create other pieces. There were no especially important tolerances on this part. To create the guide rail, the following steps were used:

1) Cut 1.8 inch piece of bar stock off with snips.
2) De-burr and break hard edges

Gear Box Support Brackets

These brackets were created from the brass stock purchased for the tendon follower. Brass was chosen not only for the availability in our lab, but also for its ease of machinability and fabrication. The following processes were undertaken to create these parts:

Figure 45: Milling of the Lead Screw Clearance Slot

Figure 46: Facing the Motor Support the 1.40 Inches

1) Cut brass 1/2 x1/4 inch bar stock into two 1.5in lengths on a band saw
2) Clamp piece in a mill, measure length and face off until part is 1.4 inches long
3) Zero mill axes, cut small channel around outside of part
4) Cut lead screw groove
5) Remove piece, clamp into drill press
    a. Drill 4 bolt holes on 1 part with #36 drill bit
    b. Drill Gear box mounting hole with 7mm drill bit
6) Second piece will be unthreaded; clamp into drill press
    a. Drill 4 bolt holes with #32 drill bit (larger than last piece)
    b. Drill motor hole with 8.5mm drill bit
7) Tap holes on first price with #6-32 tap and M8-0.75 tap

Thumb Bar

The thumb is manufactured out of aluminum for bending and drilling purposes, also it is inexpensive. The manufacturing steps are:

1. Cut 1/4in aluminum bar into 3.5in on chop saw or vertical band saw
2. Grind end flat
3. Center drill the #6-32 tap hole into the bottom using a lathe
4. Drill pin hole using drill press and size 39 bit
5. Clamp the thumb in a vice then place a tube over it to bend it to angle

Thumb Housing Bracket

The thumb brace was made from the 1/16" aluminum plate to because it is easy to machine and is used frequently in the design. The slot was cut out first so that there was enough material to hold on to while operation the saw. The punched area was made a little larger so it could be ground to size later. To make this part:

1. Cut the .15" slot into 1/16" plate using vertical band saw
2. Drill 4 bolt fastener holes using size 38 bit (.105") on the drill press
3. Punch out part using a sheet metal corner punch
    a. Optionally, can be cut out using tin snips but will need to be bent back into shape

Thumb Housing

The housing was made out of 5/8” aluminum square bar for easy machinability. The part wasn’t moved between drill passes on the thumb slot to reduce changes to misaligning the holes.

1. Cut the 5/8” bar stock into 1” lengths using a chop saw or vertical band saw
2. Drill the 4 fastener holes into the side with a size 36 bit
3. Drill the 1/4" thumb hole using a 17/64” bit
4. Without moving the part, change the bit to 9/64” to drill the 1/8” hole through the bottom
5. Drill the 1/8” slider hole using the 9/64” drill bit
6. Mill the face using a 1/16” mill bit on the mini mill at a high speed
7. Mill the slot in the side using the 1/16” mill bit.

Appendix A:Management Plan and Gantt Chart

Table 5: Team Responsibilities Matrix

	Devon Augustus	Mighells Deuel	Ian Fraser	Nicholas Moesser
MANAGEMENT				
Meeting Notes	X	X	X	X
Sponsor Contact	X			
Team Leader		X		
Report Writing/Editing	X	X	X	X
RESEARCH				
Myoelectrics				X
Finger/joints		X		
Tendons/Actuation			X	
Current Products	X			
DESIGN AND FAB				
Myoelectric Circuit				X
Pressure Sensor				X
Finder/Joint	X	X	X	
Palm/Thumb	X	X	X	X
Tendons	X	X	X	
Actuation			X	
Energy Storage	X	X		X
Material Choice		X		
Programming			X	X
Machining	X	X		

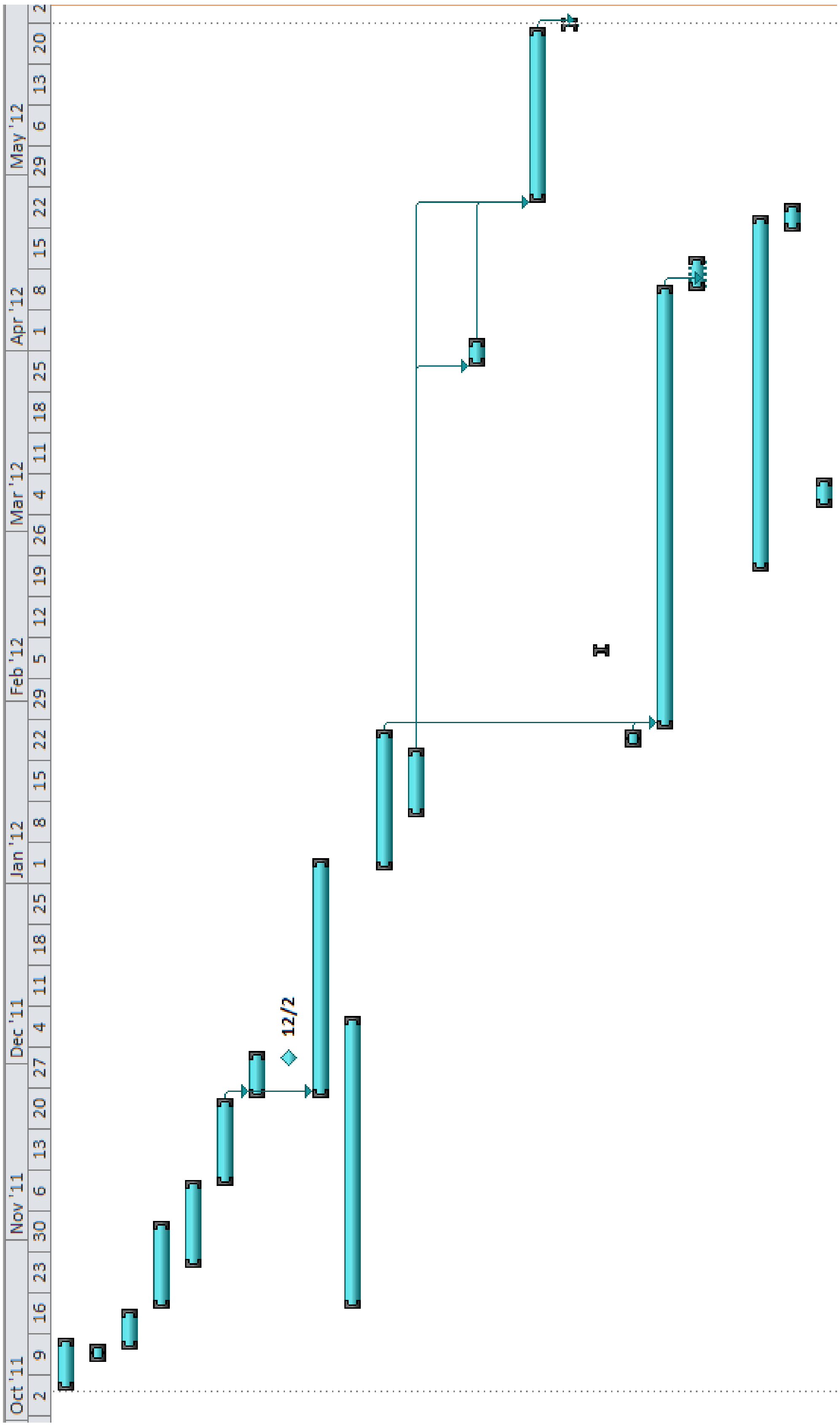


Figure 47: Gantt Chart Bar Section

Table 6: Gantt Chart Task List

Task Mode	Task Name	Duration	Start	Finish	Predecessors
Manually Scheduled	Research	7 days	Thu 10/6/11	Fri 10/14/11	
Manually Scheduled	Specifications	3 days	Tue 10/11/11	Thu 10/13/11	
Manually Scheduled	Preliminary Proposal	5 days	Thu 10/13/11	Wed 10/19/11	
Manually Scheduled	Brainstorming	11 days	Thu 10/20/11	Thu 11/3/11	
Manually Scheduled	Idea Analysis	11 days	Thu 10/27/11	Thu 11/10/11	
Manually Scheduled	Conceptual Design Finalization	11 days	Thu 11/10/11	Thu 11/24/11	
Manually Scheduled	Conceptual Design Report	6 days	Fri 11/25/11	Fri 12/2/11	6
Manually Scheduled	Conceptual Design Report Due	0 days	Fri 12/2/11	Fri 12/2/11	
Manually Scheduled	Bill of Materials	29 days	Fri 11/25/11	Wed 1/4/12	6
Manually Scheduled	Myoelectric PCB Design	36 days	Thu 10/20/11	Thu 12/8/11	
Manually Scheduled	EES Tension Optimization	18 days	Tue 1/3/12	Thu 1/26/12	
Manually Scheduled	Final Finger Design (Talk to Ladd)	8 days	Thu 1/12/12	Mon 1/23/12	
Manually Scheduled	Order Parts for Alpha Construction (from IME)	3 days	Thu 3/29/12	Mon 4/2/12	12
Manually Scheduled	Alpha Prototype Building	22 days	Thu 4/26/12	Fri 5/25/12	12,13
Manually Scheduled	Prototype Testing	1 day	Sat 5/26/12	Sat 5/26/12	14
Manually Scheduled	Critical Design Review	1 day	Thu 2/9/12	Thu 2/9/12	
Manually Scheduled	Select Lead Screw and Follower	3 days	Tue 1/24/12	Thu 1/26/12	
Manually Scheduled	Select Motor and Spur Gearing	54 days	Fri 1/27/12	Wed 4/11/12	11,17
Manually Scheduled	Select Battery System	4 days	Wed 4/11/12	Mon 4/16/12	18
Manually Scheduled	Design Itteration	43 days	Thu 2/23/12	Mon 4/23/12	
Manually Scheduled	Thumb design Inclusion	4 days	Sat 4/21/12	Wed 4/25/12	
Manually Scheduled	Pressure Sensor Placement Design	5 days	Mon 3/5/12	Fri 3/9/12	

Appendix B: Decision Matrices

Table 7: Finger Cross Section Decision Matrix

Finger Construction				
Criterion	**Weight**	**Hollow Tube**	**Solid Bar**	**DATUM: Hollow Rectangle**
Cost	4	0	-1	0
Weight	5	0	-1	0
Life Expectancy	3	0	0	0
Manufacturability	3	-1	0	0
Grip Ergonomics	4	-1	0	0
Size	3	0	0	0
TOTALS:		-7	-9	0

Table 8: Joint Construction Decision Matrix

Joint Construction					
Criterion	**Weight**	**Knuckle Link (2 pinned hinges)**	**Linkage**	**Snake Grip**	**DATUM: Pinned Hinge**
Cost	4	0	-1	0	0
Weight	5	-1	-1	-1	0
Life Expectancy	4	0	0	-1	0
Manufacturability	2	0	-1	-1	0
Grip Ergonomics	4	0	1	1	0
Size	2	-1	-1	0	0
TOTALS:		-7	-9	-7	0

Table 9: Power Storage Decision Matrix

Power Storage				
Criterion	Weight	Power Packs	Lithium Ion Batteries	DATUM: Rechargeable Power Pack
Cost	3	0	-1	0
Weight	5	1	0	0
Life Expectancy	5	0	-1	0
Manufacturability	2	0	0	0
Charge	4	0	1	0
Size	3	1	0	0
TOTALS:		8	-4	0

Table 10: Finger Material Decision Matrix Developed my Mustang Bionics for PolyGrasp 1.0

		Finger Material					Cross-Section		
Characteristic	**Weight Factor**	**Brass**	**Aluminum**	**Titanium**	**Stainless Steel**	**Carbon Fiber**	**Square**	**Circular**	**Closed Section**
Cost	0.2	4	5	2	4	1			
Weight	0.8	1	5	4	2	5			
Strength	1.0	1	4	5	3	5	3	3	5
Stiffness	0.7	3	2	4	5	5	4	4	5
Ease of Hinging	0.6	5	5	3	4	2	5	1	4
Availability	0.8	5	5	2	5	4	5	5	1
Anatomic Fidelity	0.3						3	5	4
	Total:	**11.7**	**17.4**	**14.8**	**15.3**	**17.1**	**13.7**	**11.9**	**12.9**

Appendix C: Quality Functional Deployment (QFD)

Larger is Better
Nominal is Best
Smaller is Better

◎ - Strong Positive Correlation
○ - Positive Correlation
× - Negative Correlation
⋇ - Stong Negative Correlation

Customer Desciption:
1 =
2 =
3 =

Customer Ratings: Bad 1 2 3 4 5 Good

Grouping	Customer Requirements (Whats)	Item No.	Importance	A Mass	B Size	C Battery Life	D Grip Strength	E Grip Modes	F Response Time (arm to circuit)	G Covering	H Cost	I Pressure Sensing	J Activation Time (circuit to activation)	K Closing Time	L Actuated Fingers
General	Light Weight		###	9	9	3				1	3				3
General	Proportional Size		###	1	9	1	1			3	1	1			1
General	Long Expected Life		8.0			9	1			9	3				3
Product Specs	Long Battery Life		###	9	3	9	9	1			9	1		1	3
Product Specs	Fast Closing Speed		7.0			1					3	3		9	
Product Specs	Powerful Grip Force		7.0	1	1	9	9				9				
Product Specs	Fast Activation Response		8.0								1		9		
Product Specs	Low Retail Cost		###	3	3	3	9			9	9	1	1	1	1
Product Specs	Quiet		4.0				3			1	1		9	9	3
Interface	Fits in lifelike silicon hand cover		4.0		9	1				9	3				1
Interface	Comfortable, Secure attachment		###	9	9										

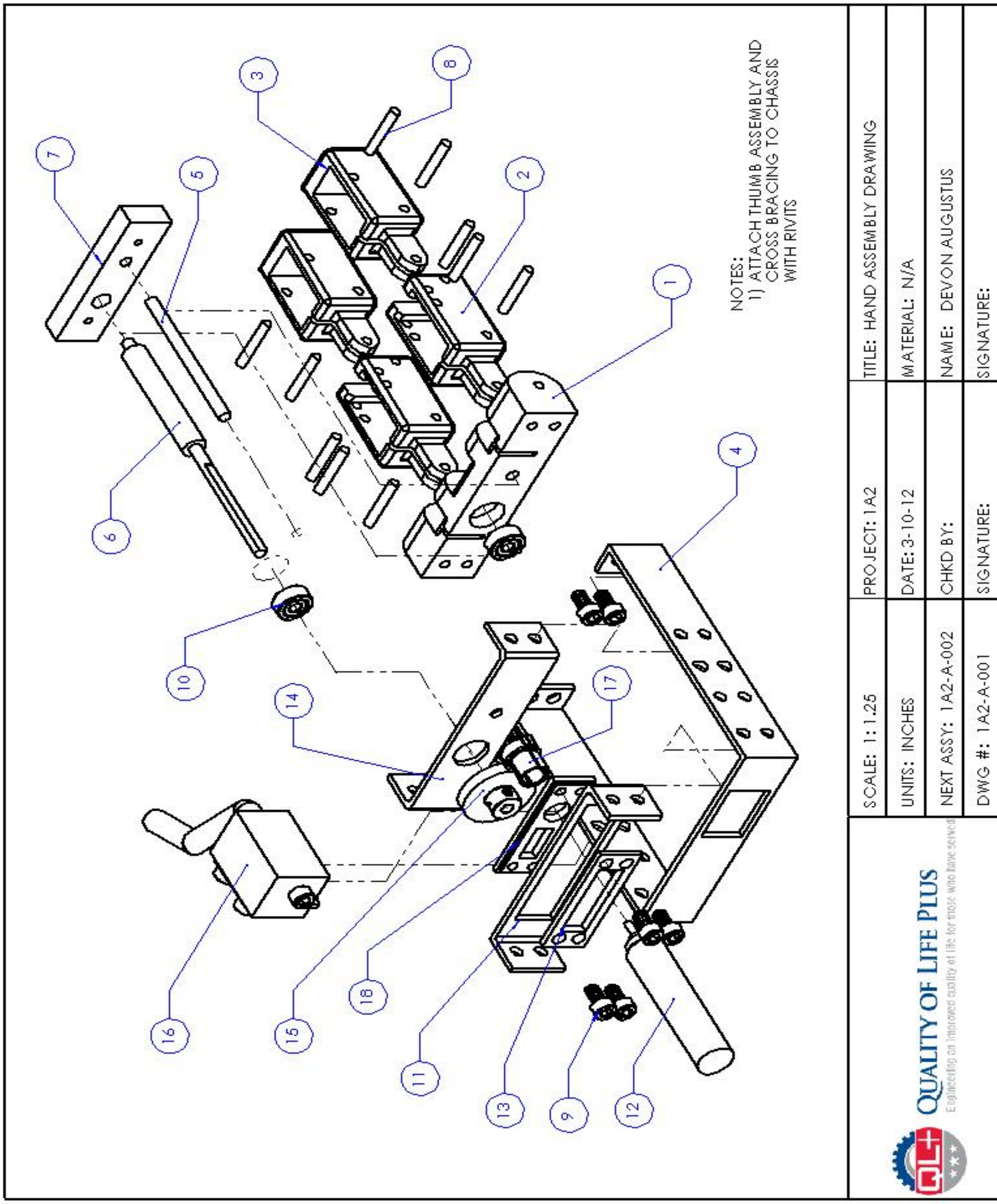
Strong - 9 ◎
Medium-3 ○
Weak - 1 △
Relationship Strength

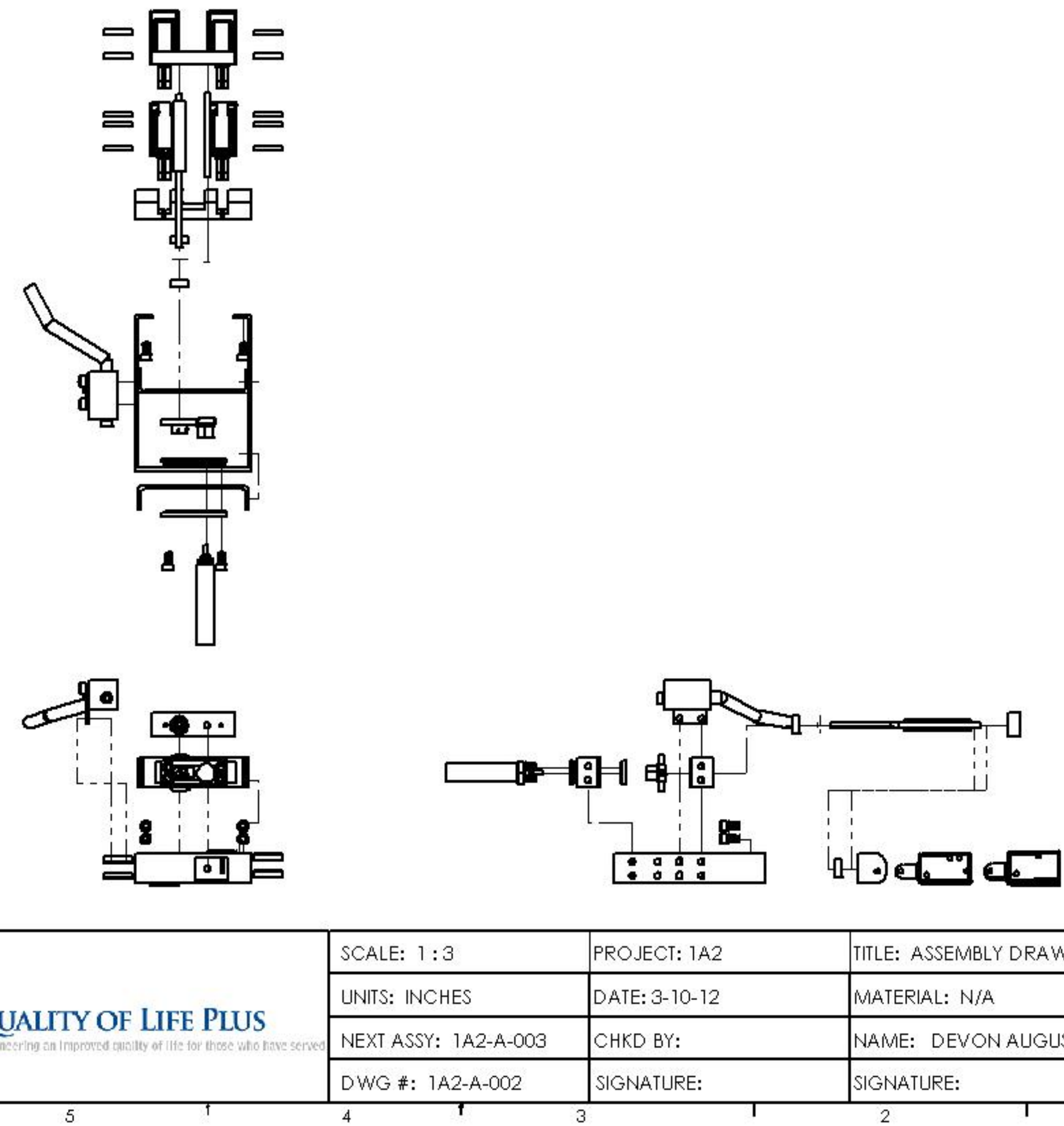
Company Ratings: Good 5, 4, 3, 2, 1 Bad

	A	B	C	D	E	F	G	H	I	J	K	L	Total
Targets	518 grams	50th percentile female	8 hours	20 lbf	3 grip modes	0.1 seconds	Go/ No Go	$4,000	Go/ No Go	0.25 seconds	1.5 seconds	2 fingers	
Weighted Importance	426	351	366	318	15		247	412	56	118	124	150	2583
% Importance	16.5%	13.6%	14.2%	12.3%	0.6%		9.6%	16.0%	2.2%	4.6%	4.8%	5.8%	

NOTE: QFD is still under construction. Meetings with amputees and prosthetists are scheduled to refine data on consumer wants and competing device characteristics.

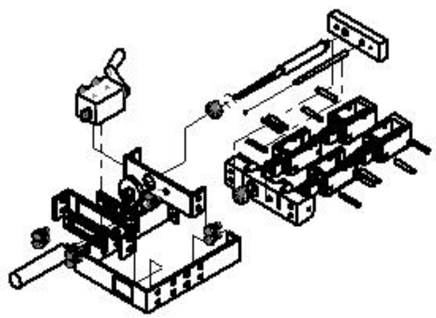
Appendix D: Assembly and Part Drawing Package





QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served

SCALE: 1 : 3	PROJECT: 1A2	TITLE: ASSEMBLY DRAWING 2
UNITS: INCHES	DATE: 3-10-12	MATERIAL: N/A
NEXT ASSY: 1A2-A-003	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-A-002	SIGNATURE:	SIGNATURE:



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1A2-P-003	KNUCKLE BAR	1
2	1A2-P-002	FINGER LINK BASE	2
3	1A2-P-001	FINGER LINK TIP	2
4	1A2-P-004	CHASSIS	1
5	McMaster 8974K14	POLISHED GUIDE SHAFT 1.8 INCHES LONG	1
6	1A2-P-008	LEAD SCREW	1
7	1A2-P-007	TENDON FOLLOWER	1
8	3009A253	.10 STEEL PIN MCMASTER-CARR	10
9	91251A144	#6-32 SOCKET SCREW MCMASTER-CARR	10
10	60355K41	R2 DOUBLE SHEILD BEARING MCMASTER-CARR	2
11	1A2-P-006	CROSS BRACE MOTOR	1
12	MAXON MOTORS EC10 / GS10	MOTOR AND 64:1 PLANETARY GEAR SET	1
13	1A2-P-009	MOTOR SUPPORT NO THREADS	1
14	1A2-P-005	CROSS BRACE	1
15	s1063z-048s040	SDP-SI 40 TOOTH SPUR GEAR	1
16	1A2-A-004	THUMB ASSEMBLY	1
17	s1166z-048s020	SDP-SI 20 TOOTH SPUR GEAR	1
18	1A2-P-010	MOTOR SUPPORT THREADED	1

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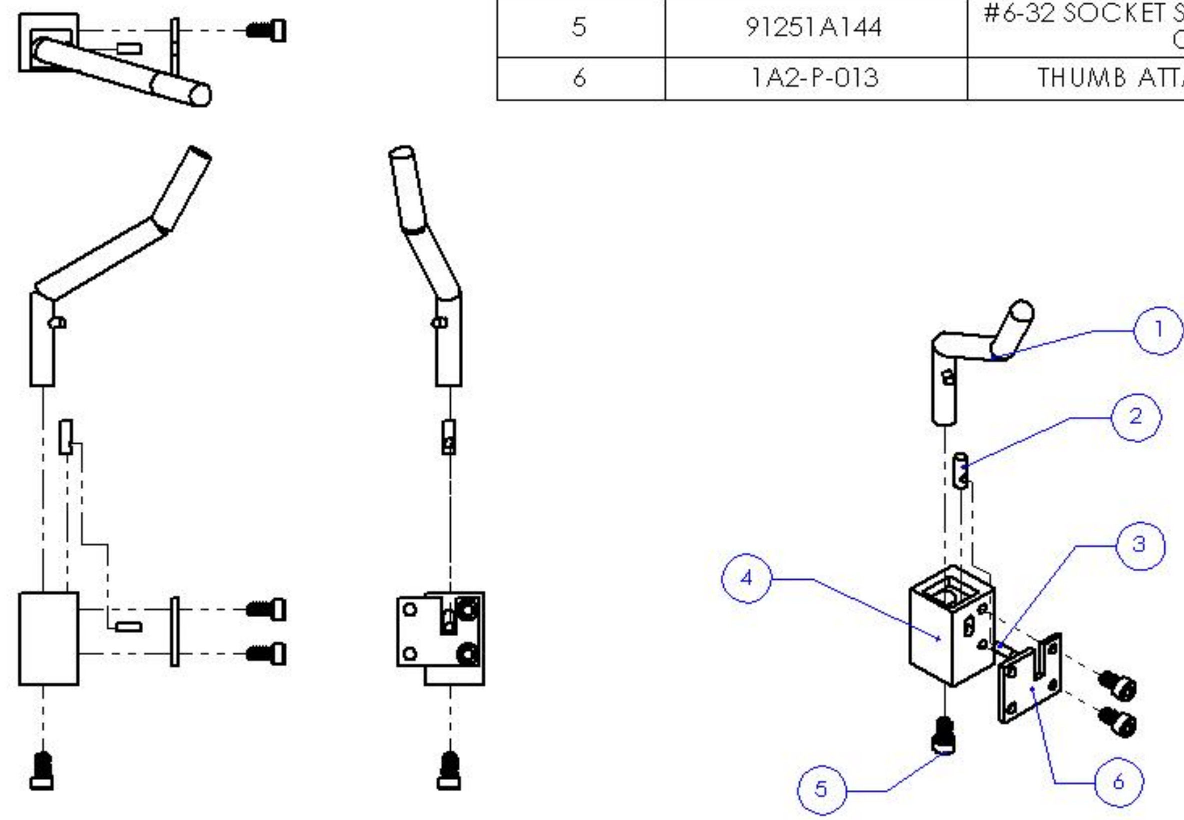
SCALE: N/A	PROJECT: 1A2	TITLE: ASSEMBLY DRAWING 3
UNITS: N/A	DATE: 05-23-2012	MATERIAL: N/A
NEXT ASSY: 1A2-A-004	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-A-003	SIGNATURE:	SIGNATURE:

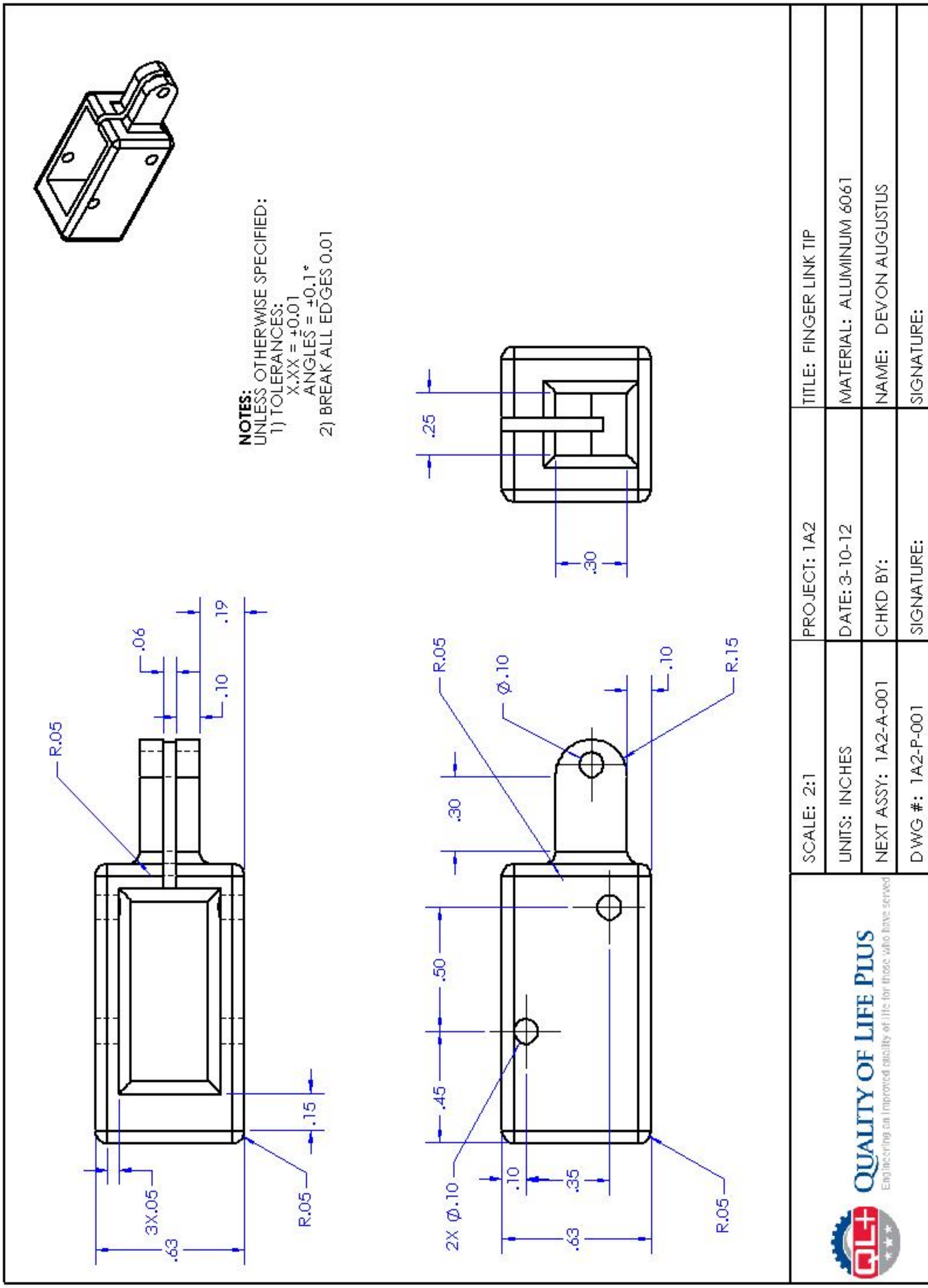
5 4 3 2 1

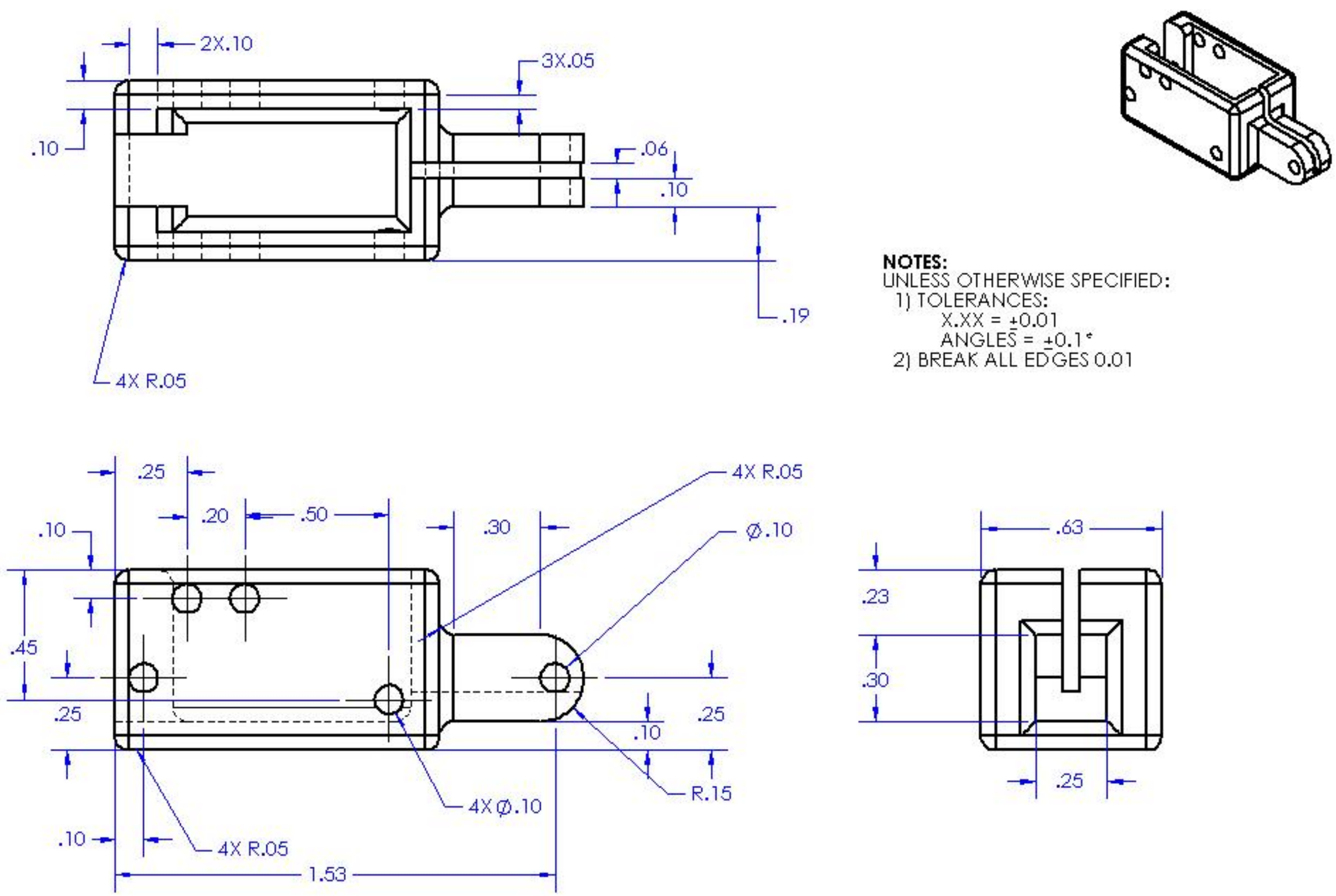
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1A2-P-012	THUMB BAR	1
2	1A2-P-014	THUMB SLIDER	1
3	THUMB PEG	STK .10 SHAFT .25 LONG	2
4	1A2-P-011	THUMB HOUSING	1
5	91251A144	#6-32 SOCKET SCREW MCMASTER-CARR	3
6	1A2-P-013	THUMB ATTACHEMENT TAB	1



Quality of Life Plus
Engineering an improved quality of life for those who have served

SCALE: 1:1.75	PROJECT: 1A2	TITLE: THUMB ASSEMBLY DRAWING
UNITS: INCHES	DATE: 05-23-2012	MATERIAL: N/A
NEXT ASSY: N/A	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-A-004	SIGNATURE:	SIGNATURE:

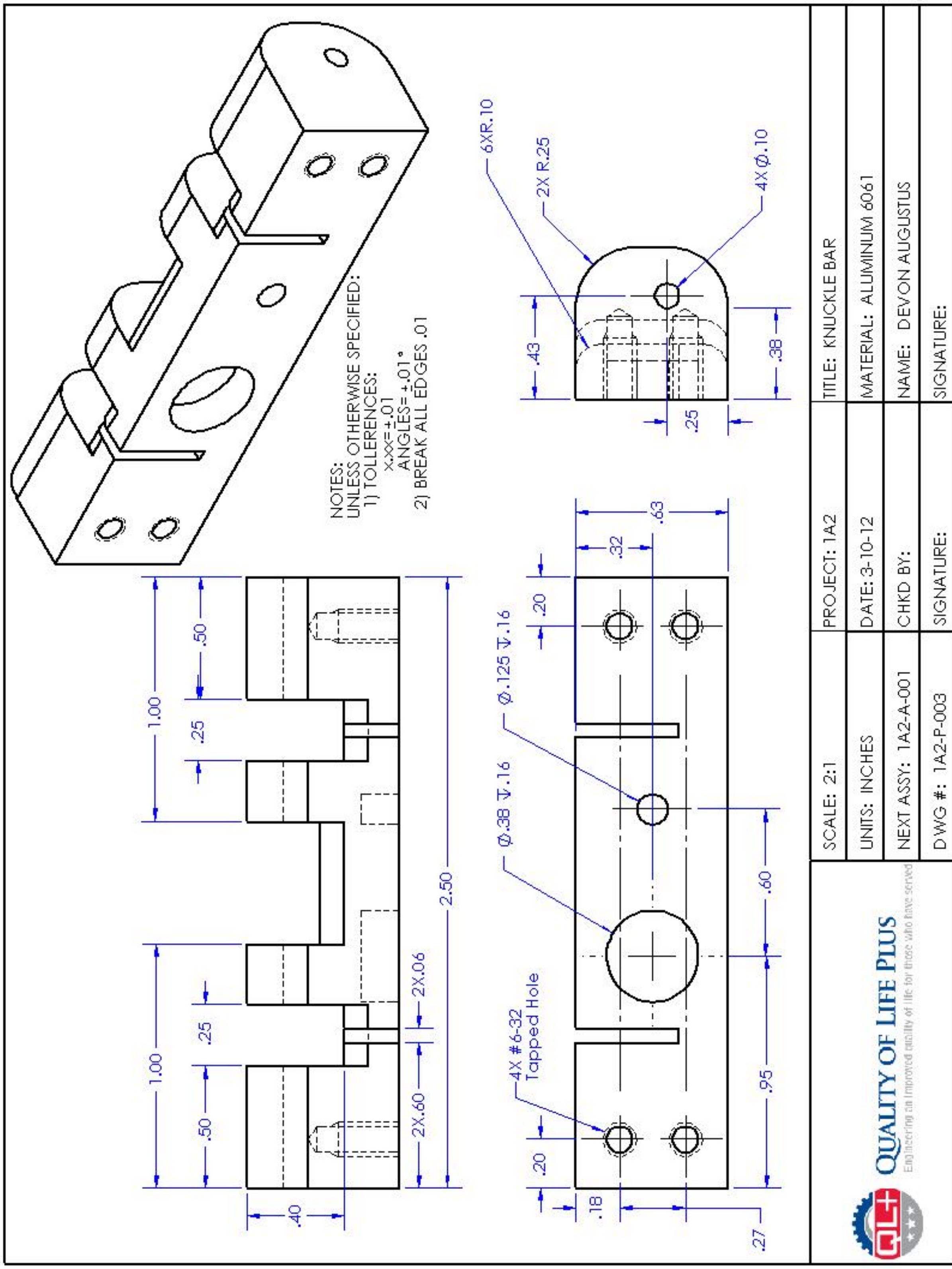

NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1°
2) BREAK ALL EDGES 0.01
R.05
.06
.19
.10
3X.05
.63
.15
R.05
.30
.50
.45
R.05
Ø.10
.10
R.15
2X Ø.10
.10
.35
.63
R.05
.25
.30
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served
SCALE: 2:1
UNITS: INCHES
NEXT ASSY: 1A2-A-001
DWG #: 1A2-P-001
PROJECT: 1A2
DATE: 3-10-12
CHKD BY:
SIGNATURE:
TITLE: FINGER LINK TIP
MATERIAL: ALUMINUM 6061
NAME: DEVON AUGUSTUS
SIGNATURE:

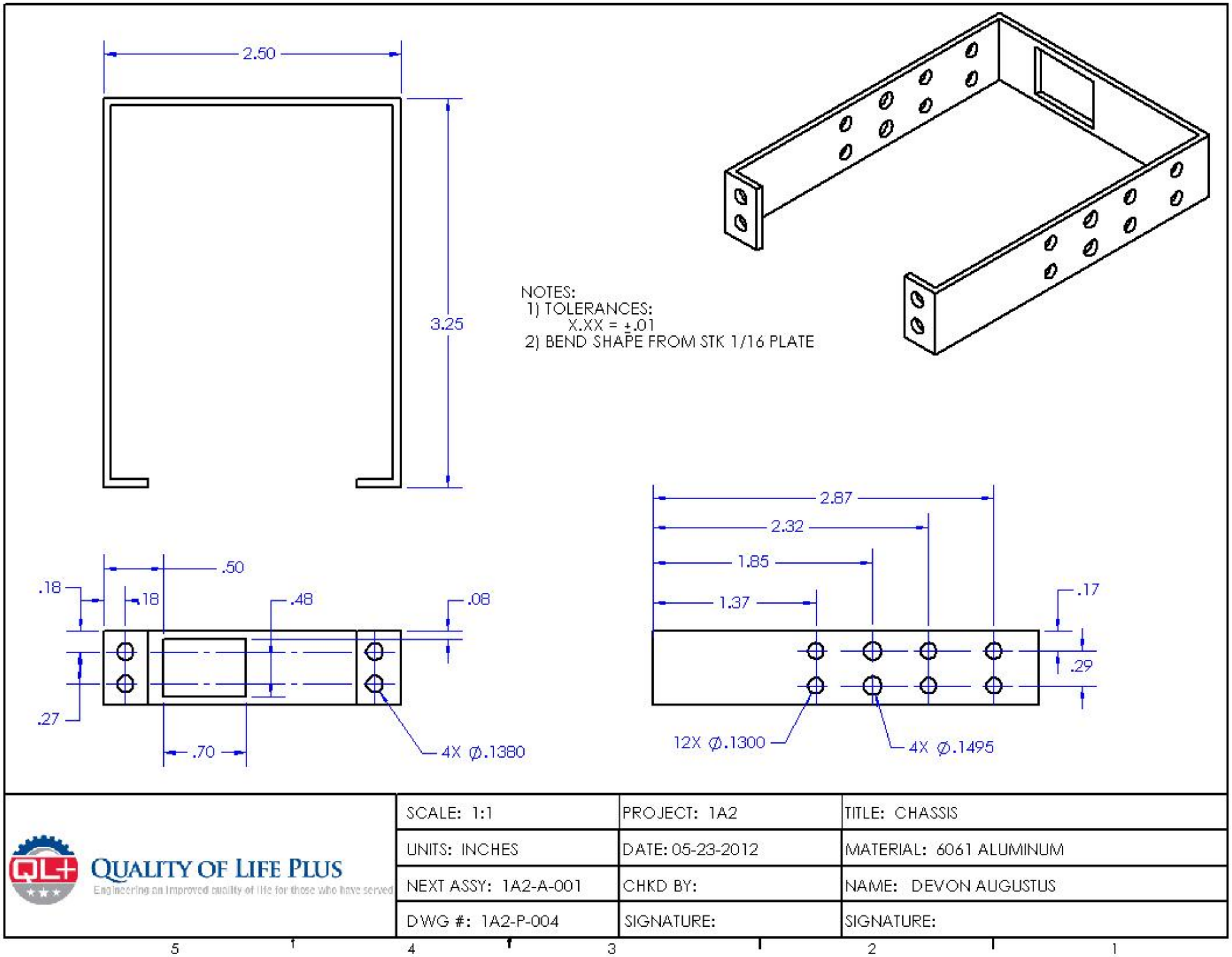


NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1°
2) BREAK ALL EDGES 0.01

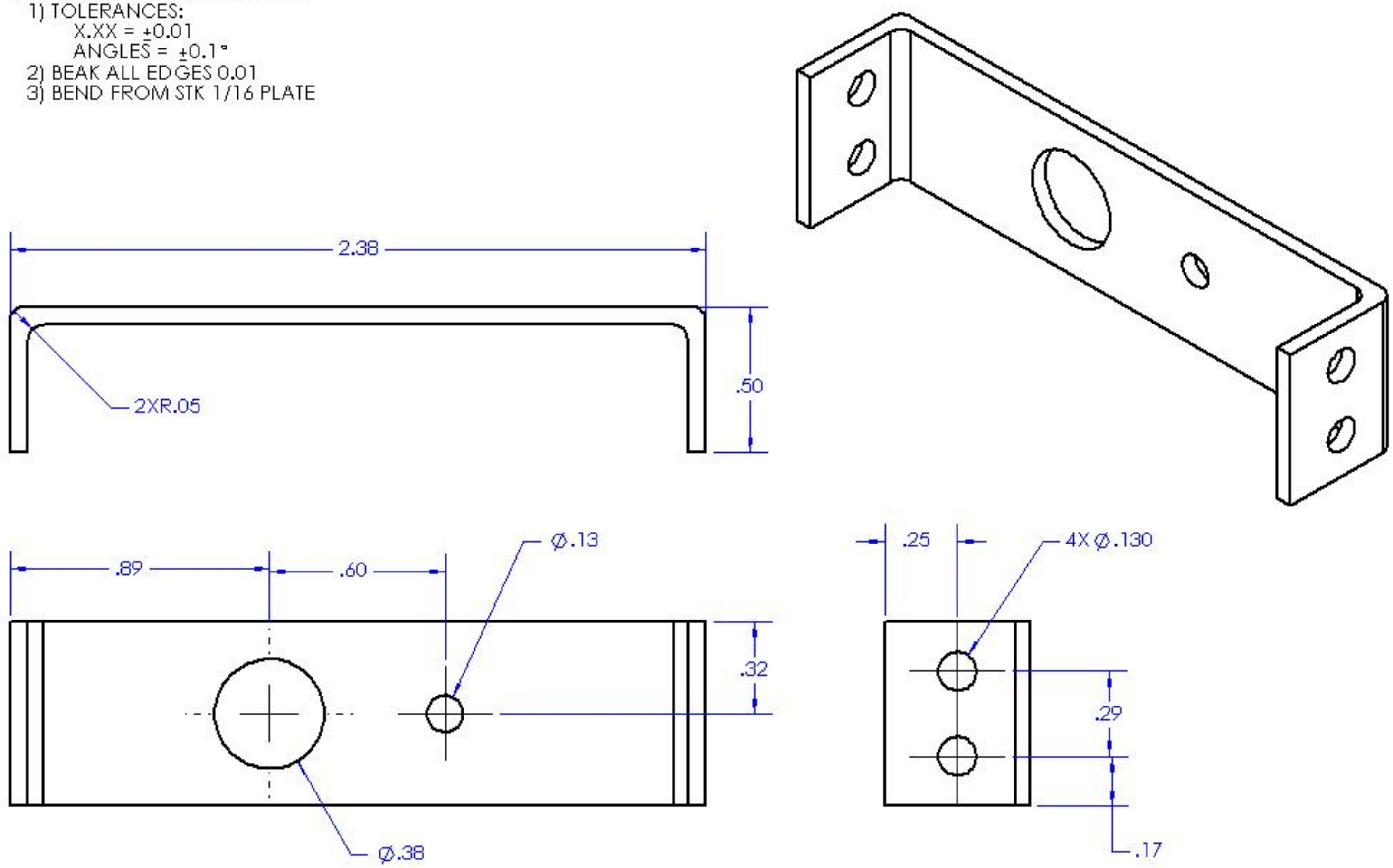
QUALITY OF LIFE PLUS — Engineering an improved quality of life for those who have served	SCALE: 2:1	PROJECT: 1A2	TITLE: FINGER LINK BASE
	UNITS: INCHES	DATE: 3-10-12	MATERIAL: ALUMINUM 6061
	NEXT ASSY: 1A2-A-001	CHKD BY:	NAME: DEVON AUGUSTUS
	DWG #: 1A2-P-002	SIGNATURE:	SIGNATURE:

5 4 3 2 1


NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLLERENCES:
X.XX=±.01
ANGLES=±.01°
2) BREAK ALL EDGES .01
6XR.10
2X R.25
4X Ø.10
.43
.38
.25
.63
.32
.20
Ø.125 ↧.16
Ø.38 ↧.16
4X #6-32
Tapped Hole
1.00
.50
.25
2.50
2X.06
2X.60
.40
.18
.27
.95
.60
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served
SCALE: 2:1
UNITS: INCHES
NEXT ASSY: 1A2-A-001
DWG #: 1A2-P-003
PROJECT: 1A2
DATE: 3-10-12
CHKD BY:
SIGNATURE:
TITLE: KNUCKLE BAR
MATERIAL: ALUMINUM 6061
NAME: DEVON AUGUSTUS
SIGNATURE:


2.50
3.25
NOTES:
1) TOLERANCES:
X.XX = ±.01
2) BEND SHAPE FROM STK 1/16 PLATE
2.87
2.32
1.85
1.37
.17
.29
12X Ø.1300
4X Ø.1495
.50
.18
.18
.48
.08
.27
.70
4X Ø.1380
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served
SCALE: 1:1
UNITS: INCHES
NEXT ASSY: 1A2-A-001
DWG #: 1A2-P-004
PROJECT: 1A2
DATE: 05-23-2012
CHKD BY:
SIGNATURE:
TITLE: CHASSIS
MATERIAL: 6061 ALUMINUM
NAME: DEVON AUGUSTUS
SIGNATURE:
5
4
3
2
1

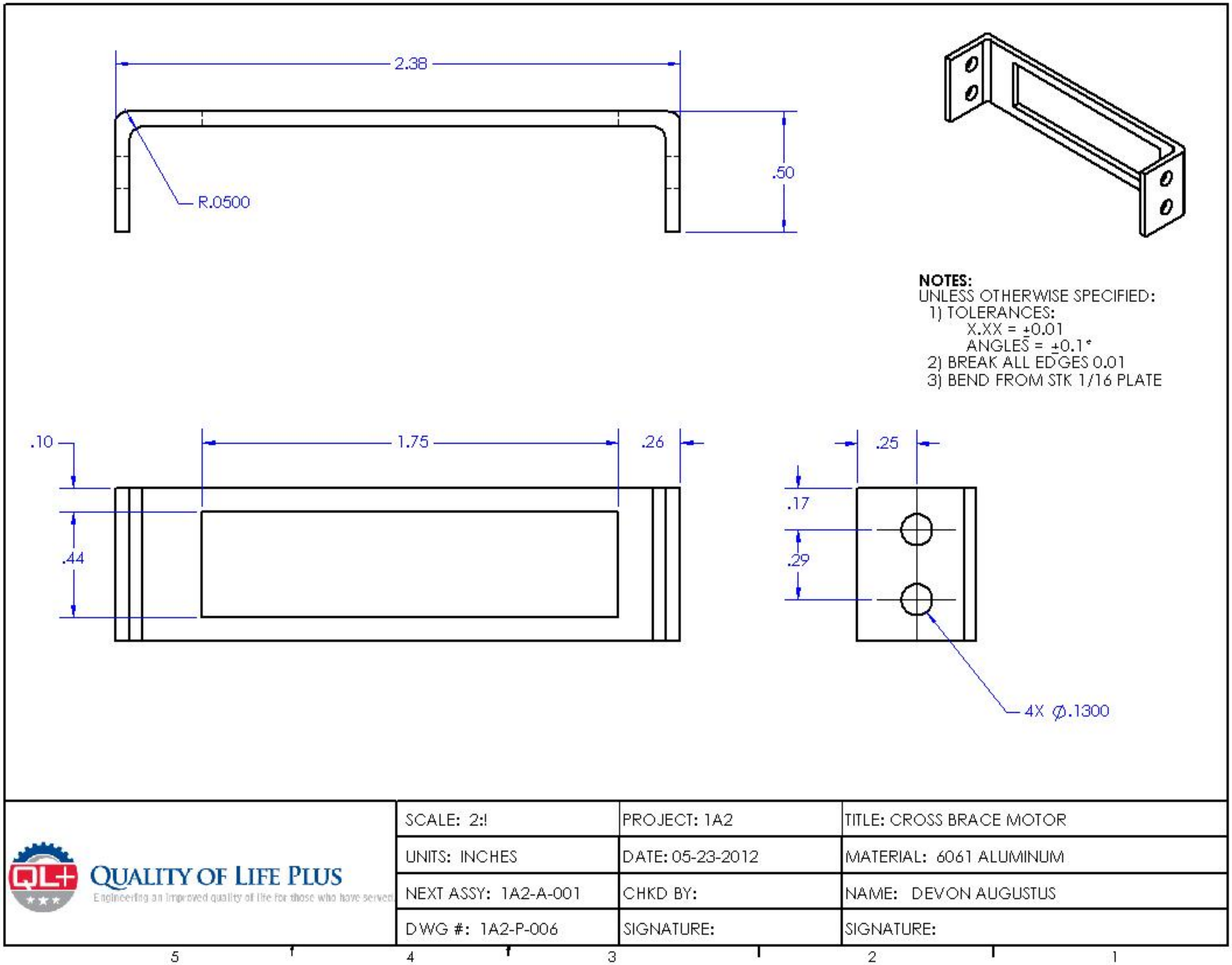
NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1°
2) BEAK ALL EDGES 0.01
3) BEND FROM STK 1/16 PLATE



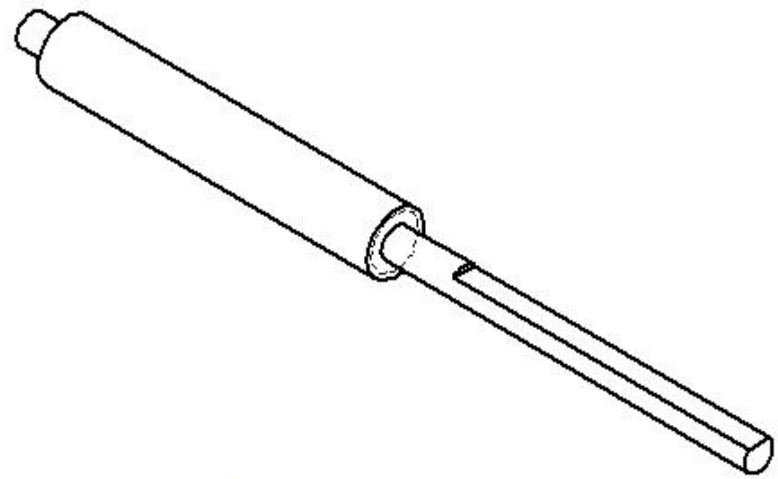
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served

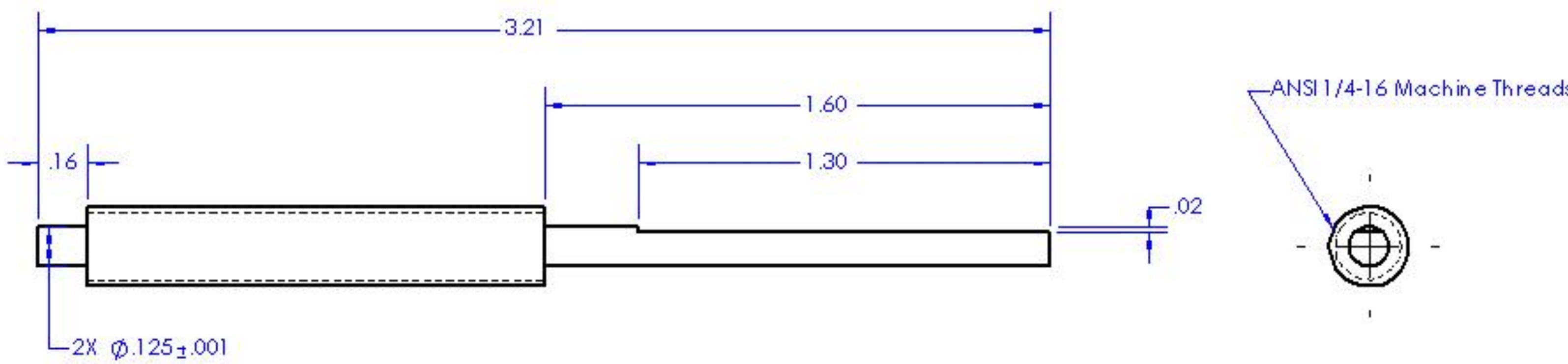
SCALE: 2:1	PROJECT: 1A2	TITLE: CROSS BRACE
UNITS: INCHES	DATE: 3-10-12	MATERIAL: ALUMINUM 6061
NEXT ASSY: 1A2-A-001	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-P-005	SIGNATURE:	SIGNATURE:

5 4 3 2 1


2.38
R.0500
.50
NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1°
2) BREAK ALL EDGES 0.01
3) BEND FROM STK 1/16 PLATE
.10
1.75
.26
.44
.25
.17
.29
4X Ø.1300
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served
SCALE: 2:!
UNITS: INCHES
NEXT ASSY: 1A2-A-001
DWG #: 1A2-P-006
PROJECT: 1A2
DATE: 05-23-2012
CHKD BY:
SIGNATURE:
TITLE: CROSS BRACE MOTOR
MATERIAL: 6061 ALUMINUM
NAME: DEVON AUGUSTUS
SIGNATURE:
5
4
3
2
1

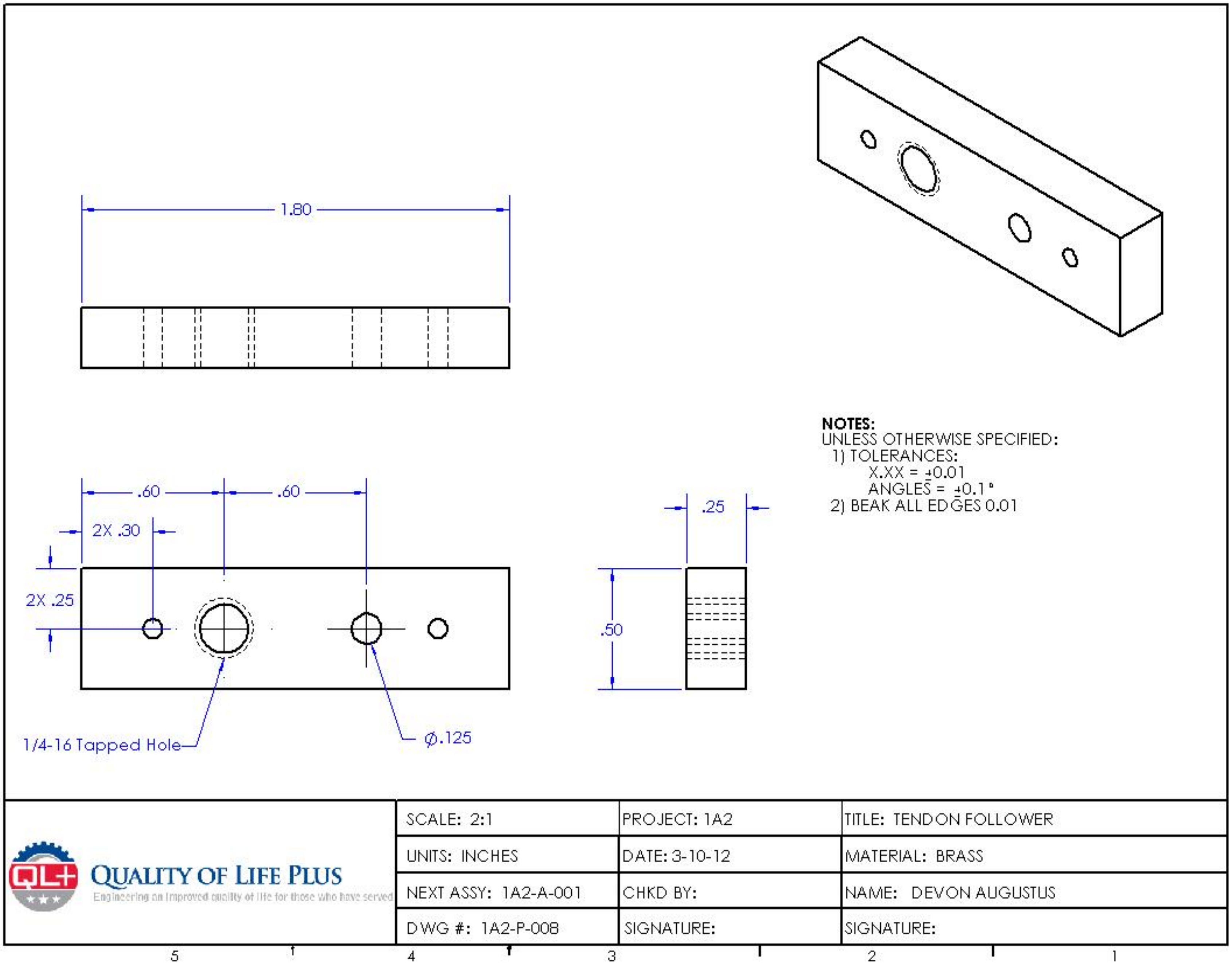
NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1 °
2) BEAK ALL EDGES 0.01
3) TURN SMALL DIAMETERS FROM STOCK 1/4-16 ACME SCREW



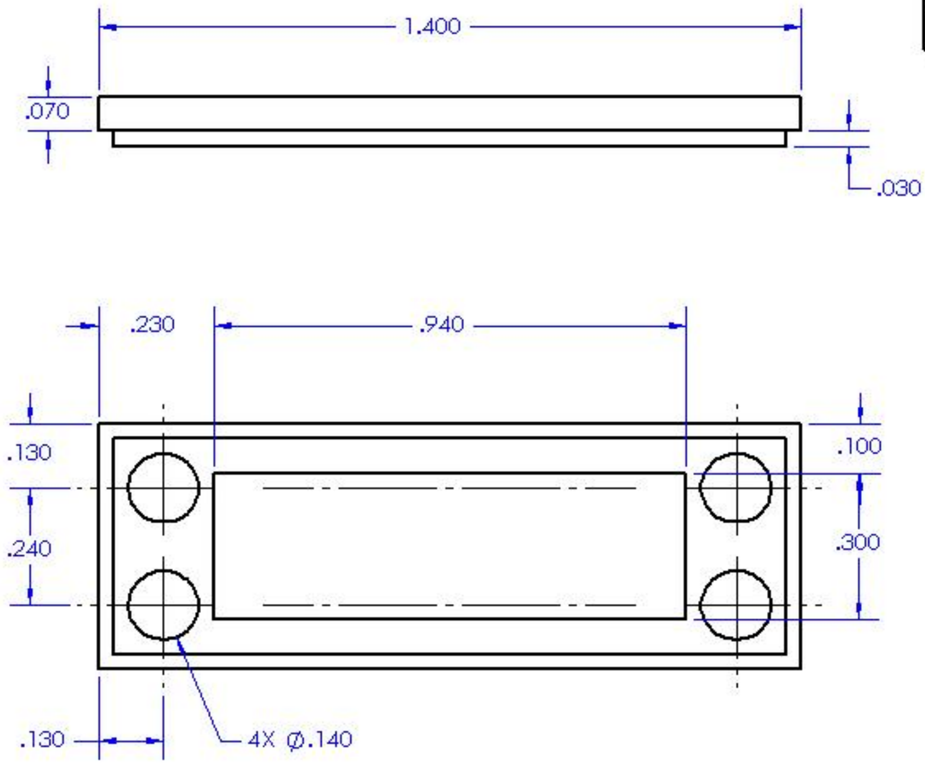


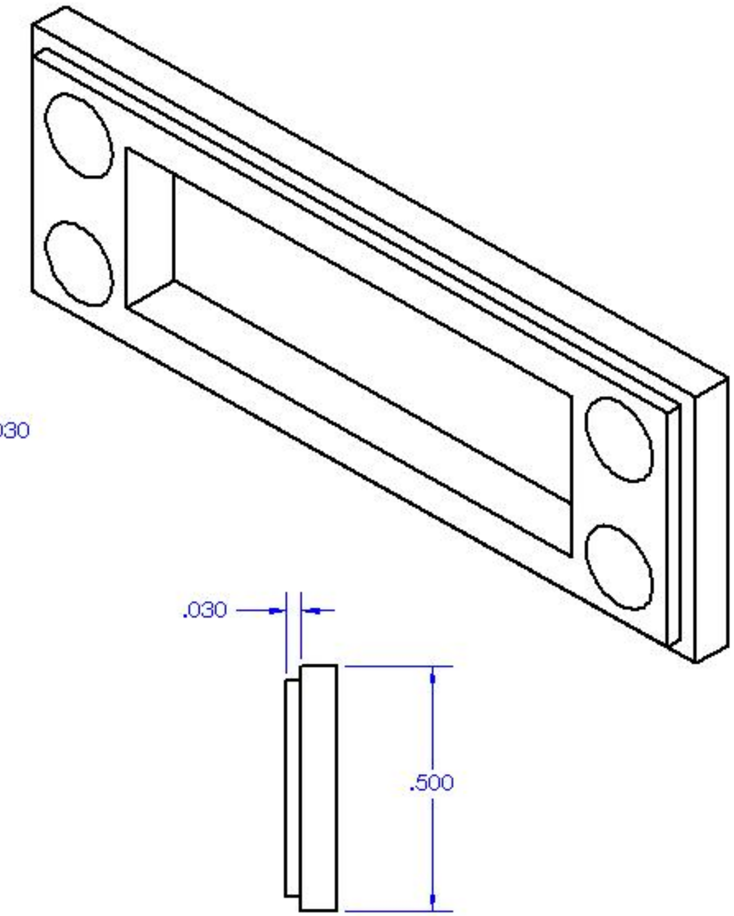
QUALITY OF LIFE PLUS Engineering an improved quality of life for those who have served	SCALE: 2:1	PROJECT: 1A2	TITLE: LEAD SCREW
	UNITS: INCHES	DATE: 03/06/12	MATERIAL: STEEL
	NEXT ASSY: 1A2-A-001	CHKD BY: I FRASER	NAME: DEVON AUGUSTUS
	DWG #: 1A2-P-007	SIGNATURE:	SIGNATURE:

5 4 3 2 1


1.80
.60
.60
2X .30
2X .25
1/4-16 Tapped Hole
ϕ.125
.25
.50
NOTES:
UNLESS OTHERWISE SPECIFIED:
1) TOLERANCES:
X.XX = ±0.01
ANGLES = ±0.1°
2) BEAK ALL EDGES 0.01
QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served
SCALE: 2:1
PROJECT: 1A2
TITLE: TENDON FOLLOWER
UNITS: INCHES
DATE: 3-10-12
MATERIAL: BRASS
NEXT ASSY: 1A2-A-001
CHKD BY:
NAME: DEVON AUGUSTUS
DWG #: 1A2-P-008
SIGNATURE:
SIGNATURE:
5
4
3
2
1

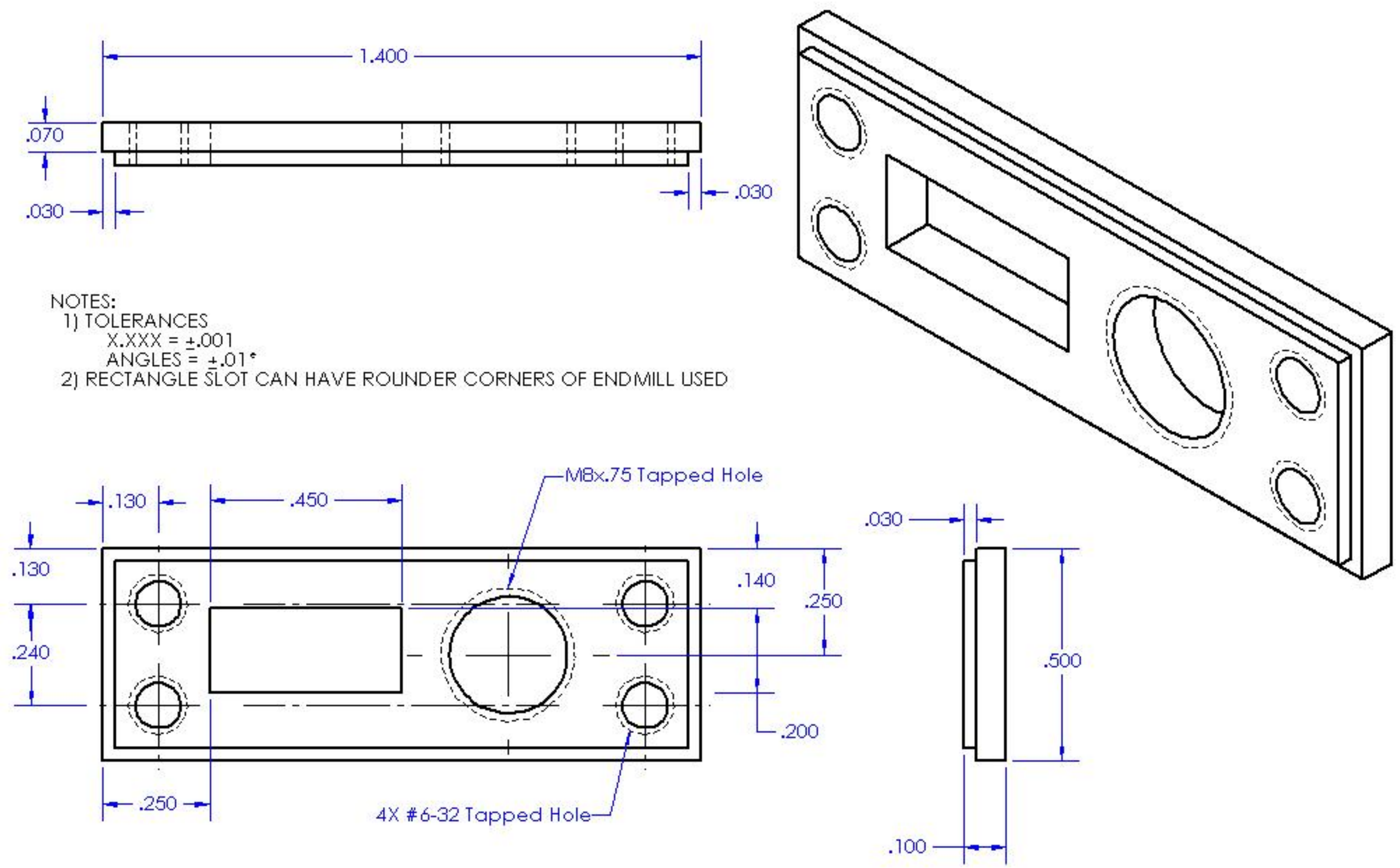
NOTES:
1) TOLERANCES
X.XXX = ±.001
ANGLES = ±.01°
2) RECTANGLE SLOT CAN HAVE ROUNDER CORNERS OF ENDMILL USED





QUALITY OF LIFE PLUS — Engineering an improved quality of life for those who have served	SCALE: 3:1	PROJECT: 1A2	TITLE: MOTOR SUPPORT NO THREADS
	UNITS: INCHES	DATE: 5-9-12	MATERIAL: BRASS
	NEXT ASSY: 1A2-A-001	CHKD BY:	NAME: DEVON AUGUSTUS
	DWG #: 1A2-P-009	SIGNATURE:	SIGNATURE:

5 4 3 2 1

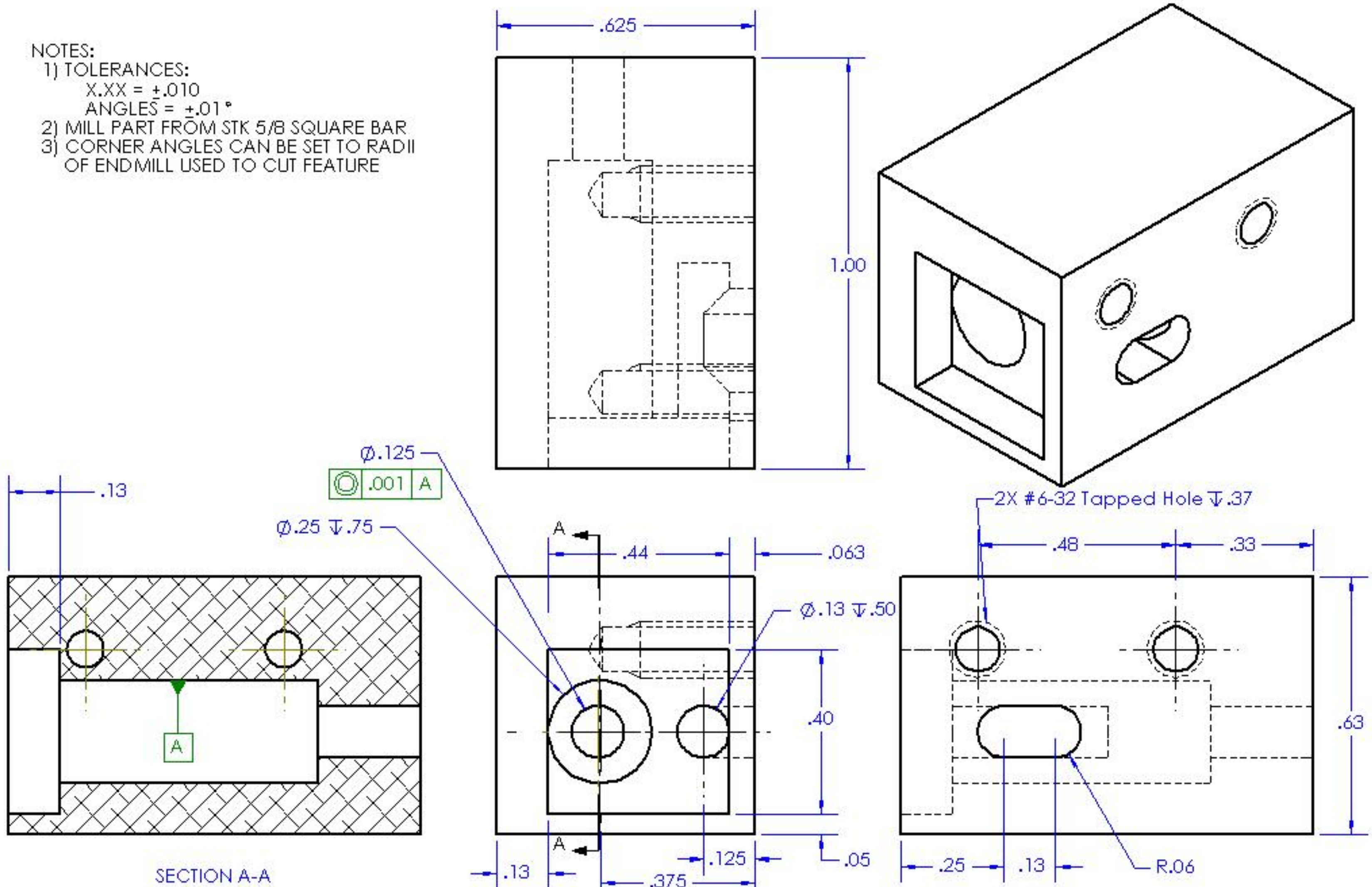


NOTES:
1) TOLERANCES
X.XXX = ±.001
ANGLES = ±.01°
2) RECTANGLE SLOT CAN HAVE ROUNDER CORNERS OF ENDMILL USED

QUALITY OF LIFE PLUS — Engineering an improved quality of life for those who have served	SCALE: 3:1	PROJECT: 1A2	TITLE: MOTOR SUPPORT THREADED
	UNITS: INCHES	DATE: 5/9/12	MATERIAL: BRASS
	NEXT ASSY: 1A2-A-001	CHKD BY:	NAME: DEVON AUGUSTUS
	DWG #: 1A2-P-010	SIGNATURE:	SIGNATURE:

5 4 3 2 1

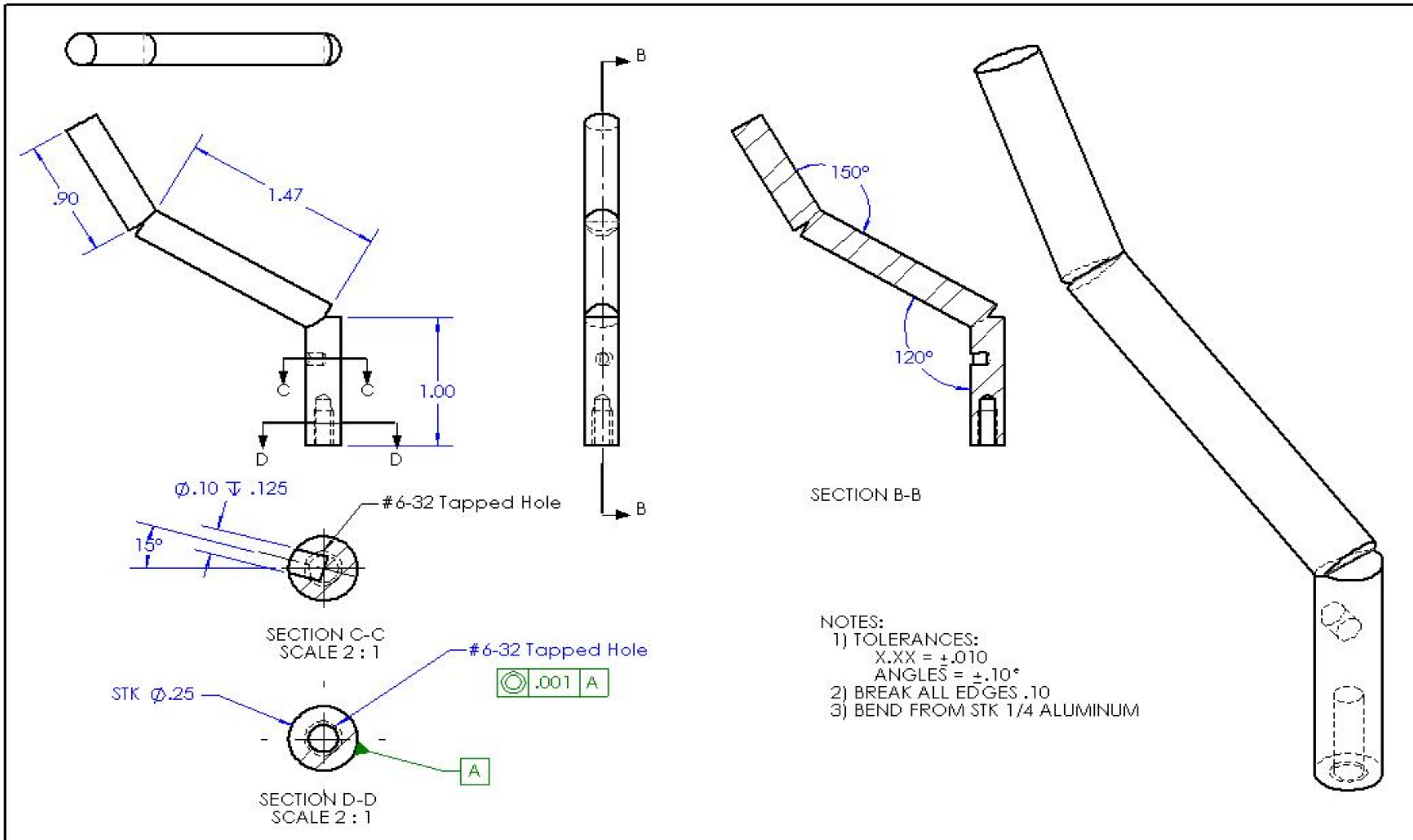
NOTES:
1) TOLERANCES:
X.XX = ±.010
ANGLES = ±.01°
2) MILL PART FROM STK 5/8 SQUARE BAR
3) CORNER ANGLES CAN BE SET TO RADII
OF ENDMILL USED TO CUT FEATURE



QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served

SCALE: 3:1	PROJECT: 1A2	TITLE: THUMB HOUSING
UNITS: INCHES	DATE: 5-11-2012	MATERIAL: 6061 ALUMINUM
NEXT ASSY: 1A2-A-004	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-P-011	SIGNATURE:	SIGNATURE:

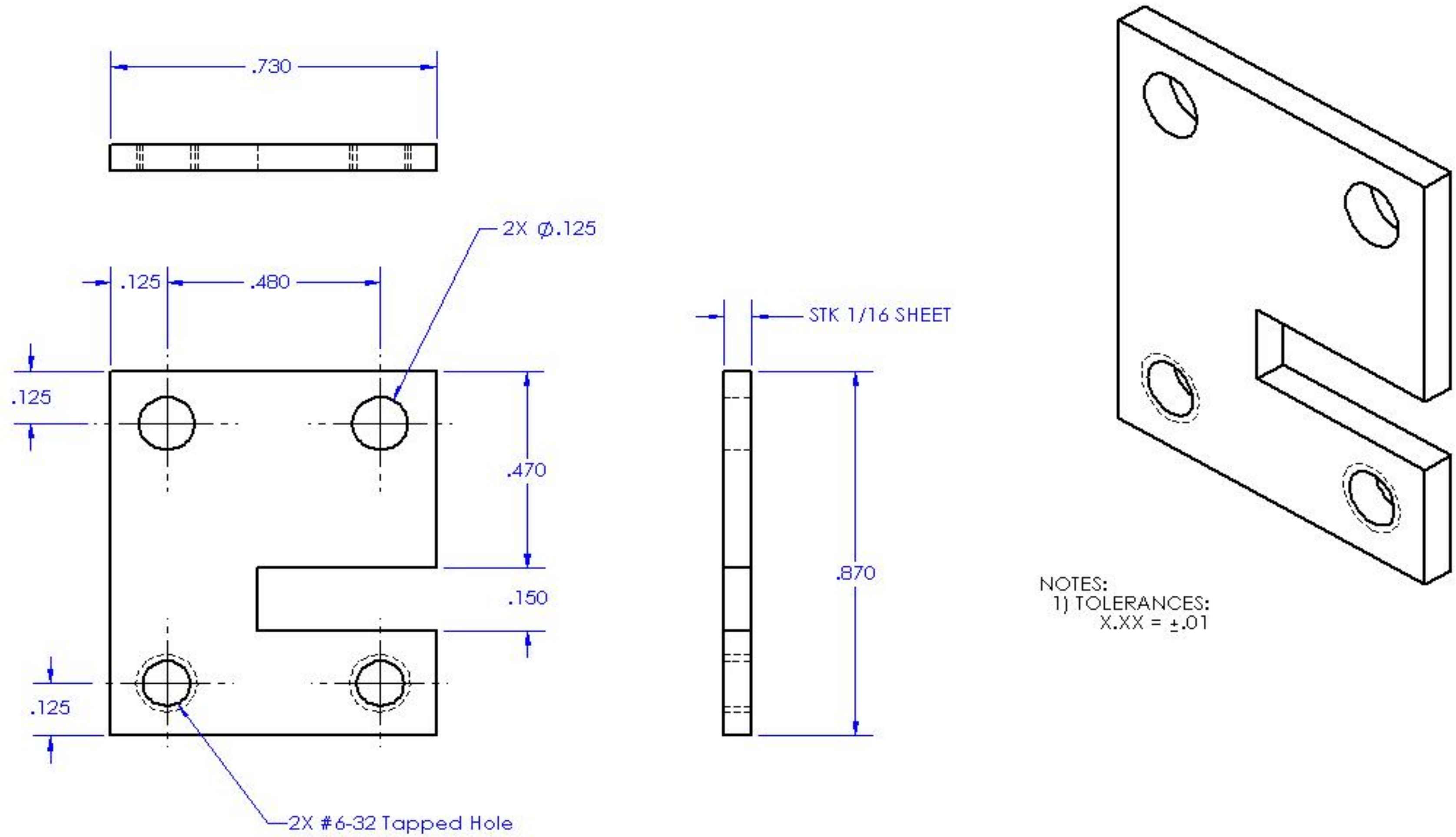
5 4 3 2 1



QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served

SCALE: 1:1	PROJECT: 1A2	TITLE: THUMB BAR
UNITS: INCHES	DATE: 05-22-2012	MATERIAL: ALUMINUM
NEXT ASSY: 1A2-A-004	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-P-012	SIGNATURE:	SIGNATURE:

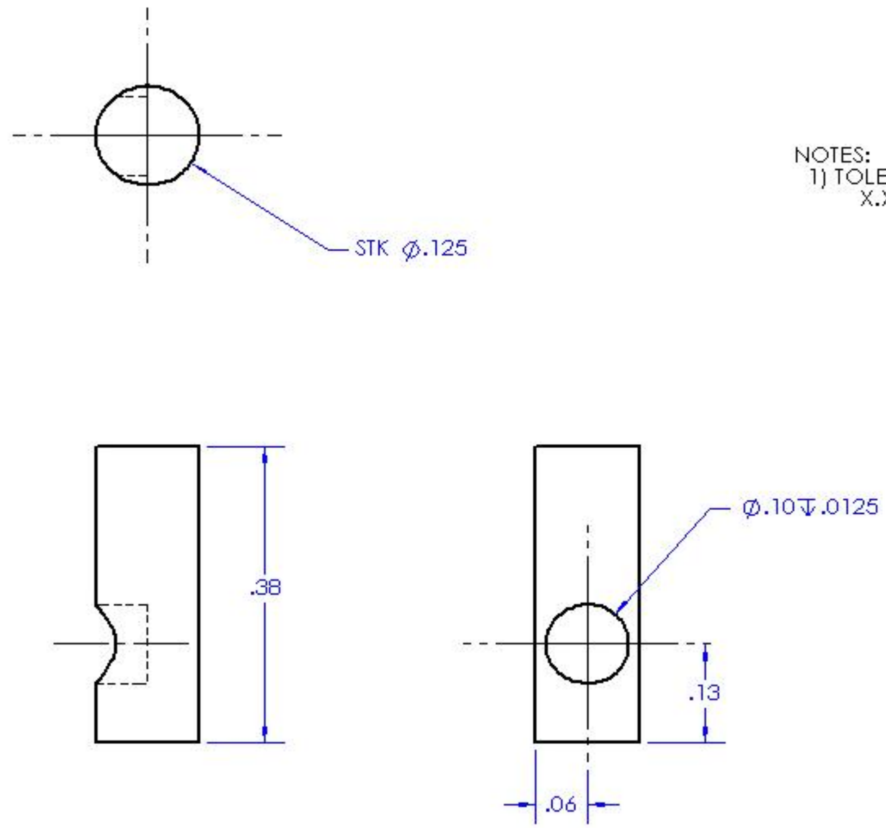
5 4 3 2 1



QUALITY OF LIFE PLUS
Engineering an improved quality of life for those who have served

SCALE: 3:1	PROJECT: 1A2	TITLE: THUMB ATTACHMENT TAB
UNITS: INCHES	DATE: 5-10-2012	MATERIAL: 6061 ALUMINUM
NEXT ASSY: 1A2-A-004	CHKD BY:	NAME: DEVON AUGUSTUS
DWG #: 1A2-P-013	SIGNATURE:	SIGNATURE:

5 4 3 2 1



NOTES:
1) TOLERANCES:
X.XX = ±.01

QUALITY OF LIFE PLUS Engineering an improved quality of life for those who have served	SCALE: 5:1	PROJECT: 1A2	TITLE: THUMB SLIDER PIN
	UNITS: INCHES	DATE: 5-11-2012	MATERIAL: STEEL
	NEXT ASSY: 1A2-A-004	CHKD BY:	NAME: DEVON AUGUSTUS
	DWG #: 1A2-P-014	SIGNATURE:	SIGNATURE:

Appendix E: Sample Calculations

EES Code Formatted Equations and Optimization Results

$$F_{grip} = 20$$

$$z_2 = 34.5$$

$$z_1 = 34.5$$

$$\theta_1 = 90$$

$$n_2^2 = m_2^2 + y_2^2 - 2 \cdot m_2 \cdot y_2 \cdot \cos(\psi_2)$$

$$n_2 = \sqrt{(a_2 - e_2)^2 + (f_2 - b_2)^2}$$

$$m_2 = \sqrt{(a_2 - d_2)^2 + (c_2 - b_2)^2}$$

$$y_2 = \sqrt{(f_2 - c_2)^2 + (e_2 - d_2)^2}$$

$$x_2 = \sqrt{b_3^2 + (a_3 - e_2)^2}$$

$$\frac{\sin(\alpha_2)}{x_2} = \frac{\sin(\beta_2)}{y_2}$$

$$\zeta_2 + \beta_2 + \alpha_2 = 180$$

$$\zeta_2 = \zeta_{20} - \theta_2$$

$$\zeta_{20} = 90 + \arctan\left[\frac{a_3 - e_2}{b_2}\right] + \arctan\left[\frac{f_2 - c_2}{e_2 - d_2}\right]$$

$$z_3^2 = z_1^2 + z_2^2 - 2 \cdot z_1 \cdot z_2 \cdot \cos(180 - \theta_1)$$

$$\frac{\sin(180 - \theta_1)}{z_3} = \frac{\sin(\xi)}{z_2}$$

$$0 = \frac{-F_{grip} \cdot z_3 \cdot \sin(90 - \xi) \cdot \cos(-\theta_2 + \zeta_{20} + \beta_2)}{y_2 \cdot (\sin(-\theta_2 + \zeta_{20} + \beta_2) - \sin(\psi_2))^2}$$

$$T_{mid} = \frac{F_{grip} \cdot z_3 \cdot \sin(90 - \xi)}{(\sin(-\theta_2 + \zeta_{20} + \beta_2) - \sin(\psi_2)) \cdot y_2}$$

$$T_{02} = \frac{F_{grip} \cdot z_3 \cdot \sin(90 - \xi)}{(\sin(0 + \zeta_{20} + \beta_{20}) - \sin(\psi_2)) \cdot y_2}$$

$$\frac{\sin(\alpha_{20})}{x_2} = \frac{\sin(\beta_{20})}{y_2}$$

$$\zeta_{20} + \beta_{20} + \alpha_{20} = 180$$

$$\frac{\sin(\alpha_{2max})}{x_2} = \frac{\sin(\beta_{2max})}{y_2}$$

$$\zeta_{2max} + \beta_{2max} + \alpha_{2max} = 180$$

$$\zeta_{2max} = \zeta_{20} - 90$$

$$T_{max2} = \frac{F_{grip} \cdot z_3 \cdot \sin(90 - \xi)}{(\sin(-90 + \zeta_{20} + \beta_{2max}) - \sin(\psi_2)) \cdot y_2}$$

$$T = \mathbf{Max}(T_{02}, T_{mid}, T_{max2})$$

$$\frac{Lmax}{\sin(\zeta_{2max})} = \frac{y_2}{\sin(\beta_{2max})}$$

$$\frac{L0}{\sin(\zeta_{20})} = \frac{y_2}{\sin(\beta_{20})}$$

$$Pull = 2 \cdot (L0 - Lmax)$$

Omptimization Results

$a_2 = 12.7$

$b_2 = 21$

$c_2 = 15$

$d_2 = 2$

$e_2 = 12.7$

$f_2 = 34.5$

$a_3 = 0$

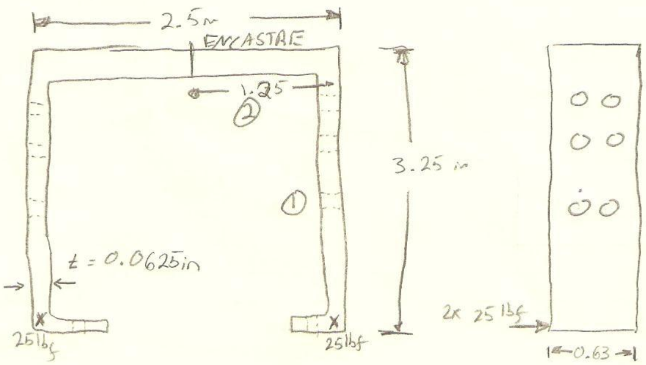
$b_3 = 21$

NOTE: All values above are in SI units. Conversion to Imperial units was undertaken for the purpose of dimensioning and ordering of parts.

The tension in the tendon was calculated for the first finger link fully actuated. The equations used are shown above. The equations were entered into EES and the program's optimization process was used to determine the necessary lengths of each dimension to minimize the tension necessary in the cable.

Chassis Deflection Hand Calculations

Prosthetic Hand Chassis	ME 404-02	Devon Augustus	1/2

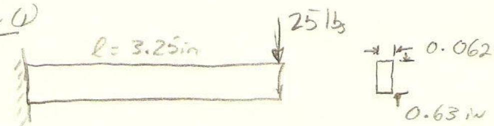


MATERIAL:
ALUMINUM
$E = 10 \times 10^6$ psi
$G = 3.7 \times 10^6$ psi
↳ Beer 5th Ed

to simplify this model for verification, remove holes & apply force at the nuetral axis of the long side.

Can be modeled with 2 cantilever beams & 1 torsion

Section ①



From Shigly's TABLE A-9-1

$$\delta_{max} = \frac{Fl^3}{3EI}$$

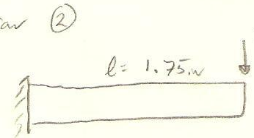
$$I = \frac{1}{12}(0.0625in)(0.63in)^3$$

$$I = 0.001302 in^4$$

$$\therefore \delta_{max①} = \frac{(25lb)(3.25in)^3}{3(10 \times 10^6 lb/in^2)(0.001302 in^4)}$$

$$\delta_{max①} = 0.02197 \text{ in}$$

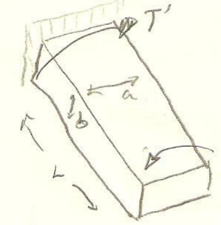
Section ②



$$\delta_{max②} = \frac{(25lb)(1.75in)^3}{3(10 \times 10^6 psi)(0.001302 in^4)}$$

$$\delta_{max②} = 0.00343$$

torsion of section 2:



for this bar, $a = 0.0625$ in
$b = 0.63$ in

From Beer & Johnson Mechanics of Materials 5th Edition
↳ Cal Poly Supplinent Binder Ed.

$$\theta = \frac{TL}{c_2 a b^3 G} \quad \text{(EQ 3.44)}$$

$G_{AL} = 3.7\times10^9$ psi (Appendix B)

$$a/b = \frac{0.63}{0.0625} = 10.08$$

↳ $C_2 = 0.312$ (TABLE 3.1)

$$\therefore \theta = \frac{(25\text{lb})(3.25\text{in})(1.25\text{in})}{(0.312)(0.63)(0.0625)^3(3.7\times10^6\text{psi})}$$

$\theta = 0.572$ rad

$\therefore \delta_{Torsion} = (0.572\text{ rad})(3.25\text{in})$

$\delta_{Tor} = 1.859$ in

$\delta_{Tot} = \delta_{max①} + \delta_{max②} + \delta_{TOR}$

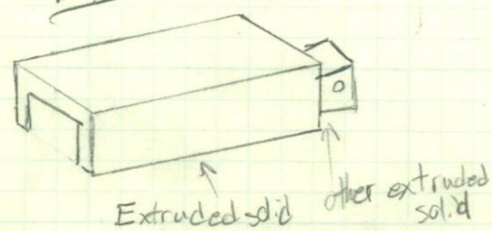
$= 0.02197$ in $+ 0.00343$ in $+ 1.859$ in

$\delta_{tot} = 1.8844$ in

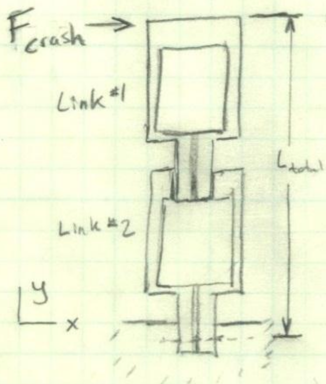
NOTE: Since a point encastre on the wrist is somewhat unrealistic, FE Model may have the boundry condition set as fixed for the whole back plate. In this case, compare model resuts to δ_{max} ① since section ② will no longer add noticably to the deformation.

Finger Link Impulse Shear Hand Calculations

Finger Part



Finger Joint



$w = 5/8" = 0.625$ in
$L = 1" = 1.0$ in
$l_{hinge} = 0.1$ in
$t_{lip} = 0.2$ in
$t = 0.1$ in

$t_{slot} = 1/16" = 0.0625$ in
$d_{tongue} = 0.3$ in
$w_{tongue} = 0.25$ in
$t_{tongue} = 0.1$ in

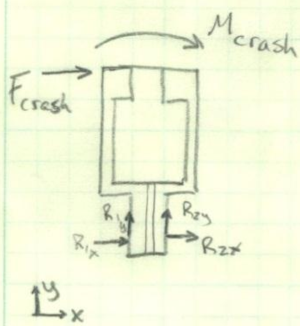
$L_{total} = 2L - t_{lip} - l_{hinge}$
$= 1.7$ in

Aluminum 2014, $S_{uy} = 58$ ksi [Mechanics of Materials, Beer, Johnston, DeWolf]

Objective: - Reactions at knuckle pin & stress
- Stress at Link #2/knuckle joint in tongue

Assume: - Link #1 is rigid (conservative estimate)
- Steel pin Ø 0.1 in

Analysis:



$$\Sigma F_x: F_{crash} + R_{1x} + R_{2x} = 0 \quad (1)$$

$$\Sigma F_y: R_{1y} + R_{2y} = 0 \quad (2)$$

$$\Sigma M_1: -M_{crash} - F_{crash}(L - l_{hinge}) + R_{2y} w_{tongue} = 0$$

$$-F_{crash}([L - l_{hinge}] + [L - t_{lip}]) + R_{2y} w_{tongue} = 0 \quad (3)$$

$$\Sigma M_F: -M_{crash} + (R_{1x} + R_{2x})(L - l_{hinge}) + R_{1y}\left(\frac{w - w_{tongue}}{2}\right) + R_{2y}\left(\frac{w - w_{tongue}}{2} + w_{tongue}\right) = 0$$

$$-F_{crash}(L-t_{lip}) + (R_{1x}+R_{2x})(L-l_{hinge}) + R_{1y}\left(\frac{W-W_{tong}}{2}\right) + R_{2y}\left(\frac{W+W_{tong}}{2}\right) = 0 \quad (4)$$

(1) & (2) into (4)

$$-F_{crash}(L-t_{lip}) - F_{crash}(L-l_{hinge}) + R_{1y}\left(\frac{W-W_{tong}}{2}\right) + R_{1y}\left(\frac{W+W_{tong}}{2}\right) = 0$$

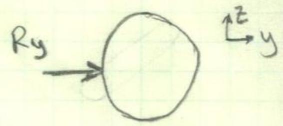
$$-F_{crash}(2L-t_{lip}-l_{hinge}) + R_{1y}W = 0 \quad \text{[This is just (3)]}$$

$$\boxed{R_{1y} = \frac{2L-t_{lip}-l_{hinge}}{W} F_{crash}} \qquad R_{1y}(F_{crash})$$

(2)
$$\boxed{R_{2y} = -\frac{2L-t_{lip}-l_{hinge}}{W} F_{crash}} \qquad R_{2y}(F_{crash})$$

Slider Joint

$\therefore R_{1x} = R_{2x} = 0$



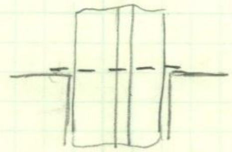
$$\tau = \frac{F}{A}$$

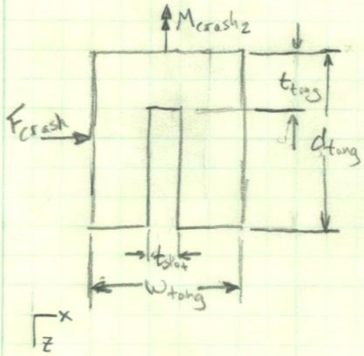
$$\tau_{crash} = \frac{R_y}{\frac{\pi}{4}D^2}$$

$$\boxed{\tau_{crash} = \frac{4(2L-t_{lip}-l_{hinge})}{\pi D^2 W} F_{crash}} \qquad \tau_{crash}(F_{crash})$$

$S_y = 57$ kpsi [Shigley's 1020 CD steel]

– Stress in tongue –





$$I_{zz} = I_{tong} - I_{slot}$$

$$I_{zz} = \frac{1}{12} d_{tong} w_{tong}^3 - \frac{1}{12}(d_{tong} - t_{tong}) t_{slot}^3$$

$$\sigma = \frac{Mc}{I}$$

$$= \frac{M_{crash} \, w_{tong}/2}{I_{zz}}$$

$$\boxed{\sigma_{max} = \frac{F_{crash}(L_{total})\, w_{tong}/2}{\frac{1}{12}\left(d_{tong} w_{tong}^3 - (d_{tong} - t_{tong}) t_{slot}^3\right)}} \quad \sigma_{max}$$

– Numerical –

$$\tau_{crash} = \frac{4(2L - t_{lip} - l_{hinge})}{\pi D^2 w} F_{crash}$$

$$57000\,psi = \frac{4(2[1\,in] - [0.2\,in] - [0.1\,in])}{\pi (0.1\,in)^2 (0.625\,in)} F_{crash,max}$$

$$\boxed{F_{crash,max} = 164.57\#} \quad F_{crash,max,\tau}$$

$$\sigma_{max} = \frac{6 L_{total} w_{tong}}{d_{tong} w_{tong}^3 - (d_{tong} - t_{tong}) t_{slot}^3} F_{crash}$$

$$58000\,psi = \frac{6(1.7\,in)(0.625\,in)}{(0.3\,in)(0.25\,in)^3 - (0.3\,in - 0.1\,in)(0.0625\,in)^3} F_{crash}$$

$$\boxed{F_{crash} = 42.203\#} \quad F_{crash,max,\sigma}$$

@ $F_{crash} = 40\#$: $\boxed{\tau_{crash} = 13852.8\,psi \quad \sigma_{crash} = 54972.6\,psi}$ $\tau_{crash}, \sigma_{crash}$

Motor Specification Analysis

The length of tendon that needs to be pulled is 30 mm.

We want to close the hand in 1 second.

The follower block must move at $\frac{30\,mm}{1\,second}\left(\frac{1\,in}{25.4\,mm}\right)$

$1.18\ in/sec$

We will use 1/4" – 16 threaded acme rod

$$\frac{1.18\,in}{sec}\cdot\left(\frac{16\ thread}{in}\right)\left(\frac{1\,rev}{1\ thread}\right)\left(\frac{60\,sec}{1\,min}\right)$$

The screw mus spin at least $\underline{1133\ rpm}$

The maximum force that the tendon will hold is estimated to be 80 lb.

The torque required to raise this force is:

$$T_{raise} = \frac{F\,d_m}{2}\left[\frac{l + \pi\mu d_m \sec(\alpha)}{\pi d_m - \mu l \sec(\alpha)}\right]$$

$F = 80\ lb$

$l = 1/16\ in$

$d_m = 1/4\ in$

$\alpha = 29/2\ deg$

μ (dry steel, brass nut) $= 0.15 - 0.19$

We will use 0.19

$$T_{raise} = \frac{80\,lb\cdot 1/4\,in}{2}\left[\frac{1/16 + \pi\cdot 0.19\cdot 1/4\cdot \sec(29/2)}{\pi\cdot 1/4 - 0.19\cdot 1/16\,\sec(29/2)}\right]$$

The torque to the lead screw must be at least

2.80 lb in.

Appendix F: Cost Break Down

General Cost Breakdown					
Part/Service	Price/unit	#	Total Cost	Part Number	Source
18-8 Blind Rivet 1/8" Diameter Pack of 100	$9.12	1	$9.12	97525A410	McMaster Carr
ACME Threaded Rod Alloy Steel 1/4"-16 Thread 1'L	$10.00	1	$10.00	93410A904	McMaster Carr
#39 High-Speed Steel Hardened Rod 2-3/8 Length	$2.07	15	$31.05	3009A904	McMaster Carr
Steel Ball Bearing-ABEC-1 Double Shielded, NO. R2 for 1/8" Shaft Diameter	$5.60	6	$33.60	60355K41	McMaster Carr
#6-32 Zinc Plated Allen Screws (Bag of 100)	$6.94	1	$6.94	90128A144	McMaster Carr
1/8" Diameter Aluminum Alloy 6061 6" Length	$2.11	1	$2.11	8974K14	McMaster Carr
1/16" 6" x 48" Aluminum 6061 Plate	$27.75	1	$27.75	89015K77	McMaster Carr
1/4 x 1/2 x 12 Brass Alloy 360	$11.42	1	$11.42	8954K405	McMaster Carr
Steel Cable for Tendons	$0.57	50	$28.50	8930T28	McMaster Carr
48 D.P., 40 Teeth, 20° Pressure. Angle, 303 Stainless Steel Gear	$15.09	2	$30.18	S1063Z-048S040	SDP-SI
48 D.P., 20 Teeth, 20° Pressure. Angle, 303 Stainless Steel Gear	$13.86	2	$27.72	S1166Z-048S020	SDP-SI
Metric High-Speed Steel Hand Tap Taper, 8 X .75mm, D5 Pitch Dia, 4 Flute	$30.04	1	$30.04	26015A171	McMaster Carr
ACME Thread Tap 1/4"-16, Straight Flute, Right-Hand Thread	$69.70	1	$69.70	25345A41	McMaster Carr
Copper Oval Compression Sleeve for 1/16" Rope Diameter, 3/8" Sleeve Length, Packs of 50	$7.59	1	$7.59	3897T22	McMaster Carr
Commercial Grade Nylon-Coated Wire Rope SS, 7X7, 3/64"-1/16", 270# Break Strength, Orange (Same as 8923T314)	$0.32	25	$8.00	8923T316	McMaster Carr
Metric Black&Gold Oxide HSS Jobbers Drill Bit 2.0mm, 51mm Oal, 22.2mm Drill Depth, 135 De g Point	$1.49	4	$5.96	30565A233	McMaster Carr
Shaft Adapter 2mm to 1/8"	$3.72	1	$3.72	BRB253-2	Ondrives Ltd
EC 10 Ø10 mm, brushless, 8 Watt, sensorless	$231.21	1	$231.21	315174	Maxon Motors
Planetary Gearhead GP 10 A Ø10 mm, 0.01 - 0.15 Nm, Metal Version	$108.70	1	$108.70	332424	Maxon Motors
Multipurpose 6061 Aluminum Alloy, 5/8 Square Inch 3' Length	$13.19	1	$13.19	9008K113	McMaster Carr
Music Wire Torsion Spring, 180 Degree Angle, .130 OD, .150" Left Hand, Pack of 6	$5.63	1	$5.63	9271K79	McMaster Carr
Werker WKA6-3.3F	$20.00	1	$20.00	WKA6-3.3F	Batteries Plus

TOTAL COST:	$722.13

Electronics Cost Breakdown			
Component	Price/Unit	Quantity	Component Cost ($)
2.0 Kohm Resistor	$0.02	20	$0.40
1.0 Kohms Resistor	$0.02	20	$0.40
10.0 Kohm Resistor	$0.02	10	$0.20
20.0 Kohm Resistor	$0.02	10	$0.20
2.55 Kohm Resistor	$0.04	10	$0.40
510 ohm Resistor	$0.02	10	$0.20
IC Op Amp	$0.67	4	$2.68
75V Diode	$0.33	3	$0.99
4.7 uF Capacitor	$0.33	3	$0.99
10000 pF Capacitor	$0.04	10	$0.40
Proto Board	$2.16	4	$8.64
Arduino Nano	34.99	1	$34.99
Pressure Sensor (DigiKey MPX5500D-ND)	$16.10	2	$32.20
Medical Leads (3)	$10.79	1	$10.79

TOTAL COST:	**$93.48**

NOTE: Bill of Materials is still under development. Costs listed in this section do not include tax or shipping and are subject to frequent change.

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