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Frankenhand: An Intelligent Prosthetic

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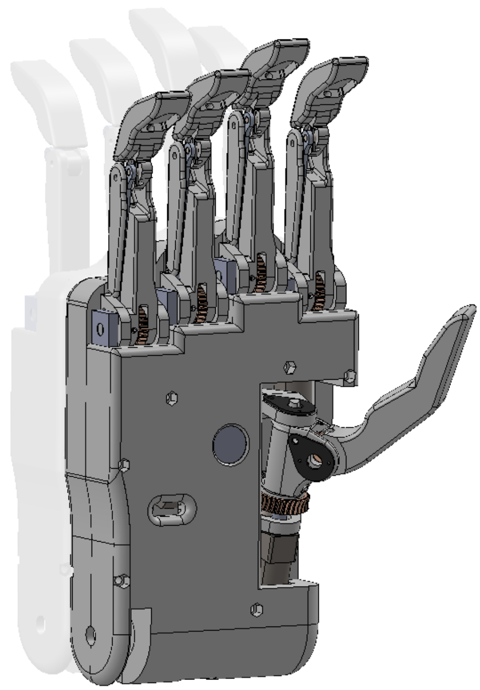

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Abstract

There are currently over 1.6 million patients in the United States who are missing limbs; this number is estimated to double by the year 2050 [19] . Over 1,000 of these cases are amputee patients from the armed forces (where over 20% of discharged service members and approximately 13% of active service members required upper body prostheses) [8] . There are multiple problems with current prosthetic devices for upper body amputations and limb loss. According to a 2011 study published by the Veteran's Affairs, approximately 44% to 45% percent of the upper body amputees felt that the use of a currently available prosthetics interfered with working properly in some form. Additionally, a staggering 70% believed they were limited with what types of activities they were able to perform due to the restrictions of having a prosthetic; More than 60% felt that they were restricted by their prosthetic with how much work they could complete [8] . Our project aims to rectify some of the problems encountered with the technology that is currently available. The goal of our project is to increase the usability of a prosthetic device and to increase the capabilities of the prostheses. Ultimately, our hand and forearm will be able to adjust the forces applied to an object to ensure a firm, but not insufficient grasp, as well as be self-aware in regards to its spatial orientation and distance from an object.

1 Introduction

Prosthetics is a rapidly-growing field of research. There is a constant movement towards smarter prosthetics that are progressively becoming more affordable and more advanced, with the hope that someday a prosthetic device will be created that can rival, or even surpass, the capabilities of human limbs. This progress is being driven by the increasing number of people who, due to amputations or birth defects, require a prosthetic device. Our project, in keeping with technological advancements, aims to create a working robotic, prosthetic hand and forearm that will look and act similarly to a human hand; improving on the advancements from the previous years. We aim to provide a solid platform with a basis to further extend its use as a prosthetic in years to come. In order to achieve this, we aim to integrate multiple systems, including an infrared sensor for proximity detection and IMU along with single-axis force sensors (used for tactile and pressure sensing), to make the prosthetic more interactive, while increasing its potential and minimizing costs in the process.

2 Background Research

2.1 Anatomy

The lower portion of the human arm is one of the most unique structures in the entire human body. The structures are delicate and coordinated enough to carry fragile items, while being strong enough to support heavy objects. Within the three main areas of the lower arm, the hand, wrist, and forearm, there are five (5) major components. These components (bone and joint, muscle, ligaments, nerves, and blood vessels) work together simultaneously, ensuring proper functionality at all times.

2.1.1 Hand

The hand is comprised of 19 smaller bones. These 19 bones are separated into two subdivisions: metacarpal bones and phalanges, as shown in Figure 1.

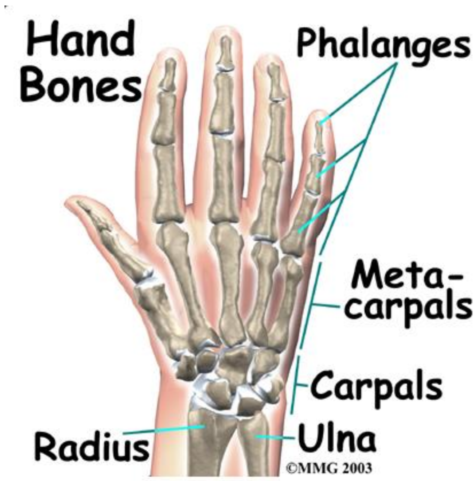


Figure 1: Bones of the Hands

The metacarpal bones connect the carpal bones of the wrist to the phalangeal bones of the fingers and thumb - making up the palm of the hand. There are three phalanges in each finger, with the exception of the thumb, which only has two. The joints between the metacarpals and phalanges are the metacarpophalangeal joints. Each joint is covered in cartilage, known as articular cartilage [14]. The multiple phalangeal bones connect at interphalangeal joints (closer to fingertip are proximal interphalangeal joints, closer to the metacarpals are the distal interphalangeal joints). These joints as well are covered by the same articular cartilage [14].

2.1.2 Wrist

The wrist consists of eight (8) carpal bones. These carpals connect to the ulna and radius, as well as the five (5) metacarpals found in the palm of the hand. The connection to the ulna and radius create the wrist joint which is responsible for the extension, flexion, and radial and ulnar deviations (waving). These motions are better depicted in the following figure.

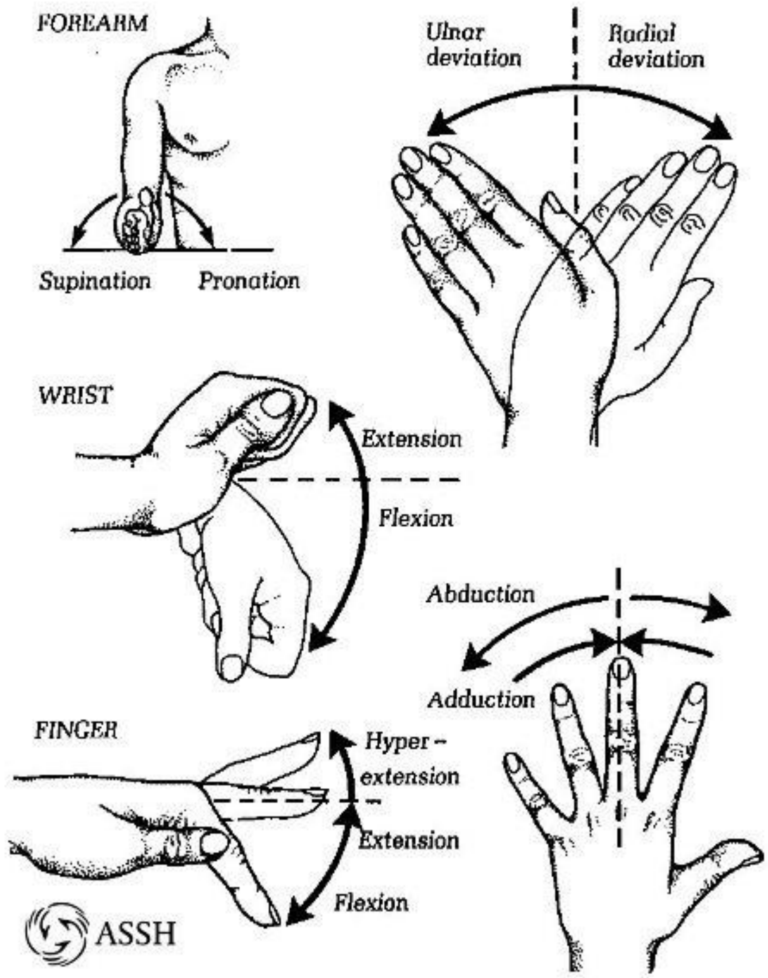


Figure 2: Motion of the Forearm, Wrist, and Fingers

2.1.3 Forearm

The forearm consists of two (2) bones: the ulna and the radius. The ulna comprises the outer half of the forearm while the radius is the internal bone. Rotation (pronation and supination are shown in Figure 2 above) and many of the other motions of the hand and wrist (such as bending of the wrist) are controlled by muscles that connect in the forearm. Some of these muscles connect at the elbow and extend across the hand, controlling motion of the fingers, others connect at the top of the forearm close to the wrist and control fine motor movements. The exception are the muscles that help control the motion of the pinky and thumb (for thumb opposition) start at the carpal bones [14]. The forearm is additionally responsible for housing the three main nerves for the hand sensation. The nerves: ulnar, medial, and radial - begin at the shoulder and each allow sensation in a different section of the hand. Figure 3 shows the areas associated with sensation controlled by each nerve.

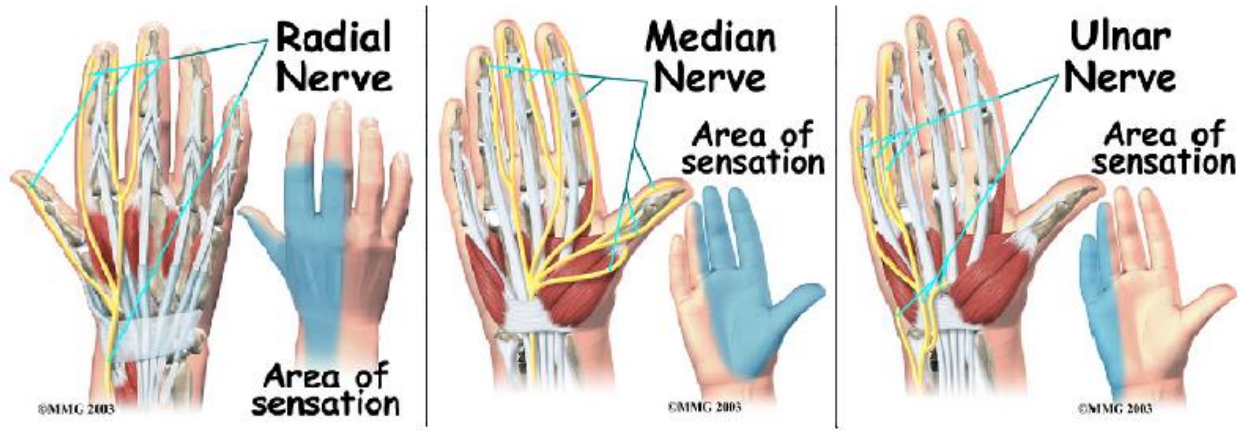


Figure 3: Sensational Areas of the Hand

2.2 Prosthetics

A prosthetic device is any type of assistive device or limb that is used to replace a missing limb or body part due to amputation or illness [18]. Prosthetics are designed to return functionality and use of the missing limb, as closely as possible to the original limb.

2.2.1 History

Prosthetic devices have existed for centuries throughout all cultures. Some of the earliest knows prosthetic pieces were found within the ancient Egyptian culture [12]. The complexity of prosthetics has increased as technology has advanced. Newer materials, such as carbon fibers and 3D printed prosthetics are allowing new age limbs to be built with the ability to incorporate more technology, replicate human anatomy and motion more closely, and also be more cost effective.

There are two primary categories of upper body prosthetics. Transradial prosthetics and transhumeral prosthetics are both replacement limbs for missing arms. Transradial prosthetic devices replace missing arms starting below the elbow, whereas transhumeral prosthetics replace missing arms from some point above the elbow. For both of these categories, the available prosthetic devices can be grouped as either a cable operated or myoelectric prosthetics [12].

2.2.2 Cable Operated Prosthetics

Cable operated prosthetics (also referred to as body-powered prosthetics) are devices which are controlled through the use of tensioned cables and pulley systems. The system is driven by the cables which are typically harnessed around the opposite, healthy shoulder, or occasionally for smaller amputations, controlled by cables connected to the wrist [3]. Cable-operated prostheses are controlled in one of two ways. The terminal device is either voluntary-opening or voluntary-closing. With the voluntary-opening devices, the cables are tensioned to open the prosthetic fingers when an elastic force is present [9]. For the voluntary-closing devices, the tensioning causes the fingers to close when the elastic force is presented [9]. The most common grip attached to the "hand" portion of the prosthetic is a hook, as shown below in Figure 4.

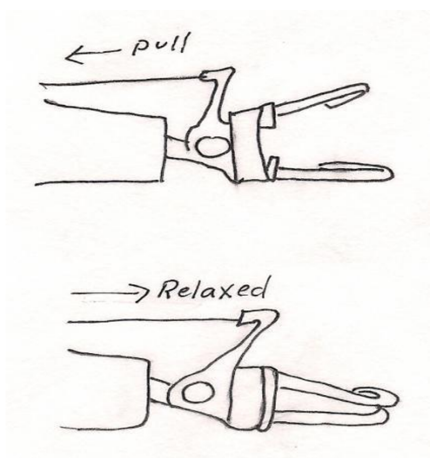


Figure 4: Hook "Hand" Cable Operated Prosthetic

Cable-operated systems have their drawbacks. The most prevalent drawback of these devices are centered on the need for a terminal device, or some form of artificial hand or hook. These termini restrict the usability of the prostheses as most ends are designed for a specific task. This requires the user to have multiple terminal devices (examples shown in the figure below) in order to obtain the same level of functionality as myoelectric prostheses [10]. However, there are multiple positives to the simple cable-operated prosthetic. Hook termini are smaller, and thus can be used to access smaller and narrower locations than the full-hand prostheses. Hooks are also extremely functional for occupations where the user is required to fulfill manual work [10].

Figure 5: Available Terminal Device Options [12]

2.2.3 Myoelectric and Combination Prosthetics

Myoelectric prosthetics are devices created using electronics to control the hand based on input sensed from muscle movement and impulse. The hand is moved typically by battery power which provide electricity to motors when stimuli are picked up by the sensors. Myoelectric devices tend to be more versatile and allow for more natural motion and actuation of the prosthetic device as well as looking more anatomically correct than some cable operated devices. However, due to their newer market status in comparison to the well-recognized hook prostheses, myoelectric arms can be very costly to the patient due to their status as "experimental" in some cases by insurance companies [1]. Additionally, myoelectric prosthetics require the remaining muscular activity to emit a minimum voltage threshold (typically on the magnitude of microvolts) [1] as well as typically requiring an external power supply charge for use. A cross-sectional diagram of an example myoelectric prosthetic is shown in Figure 7.

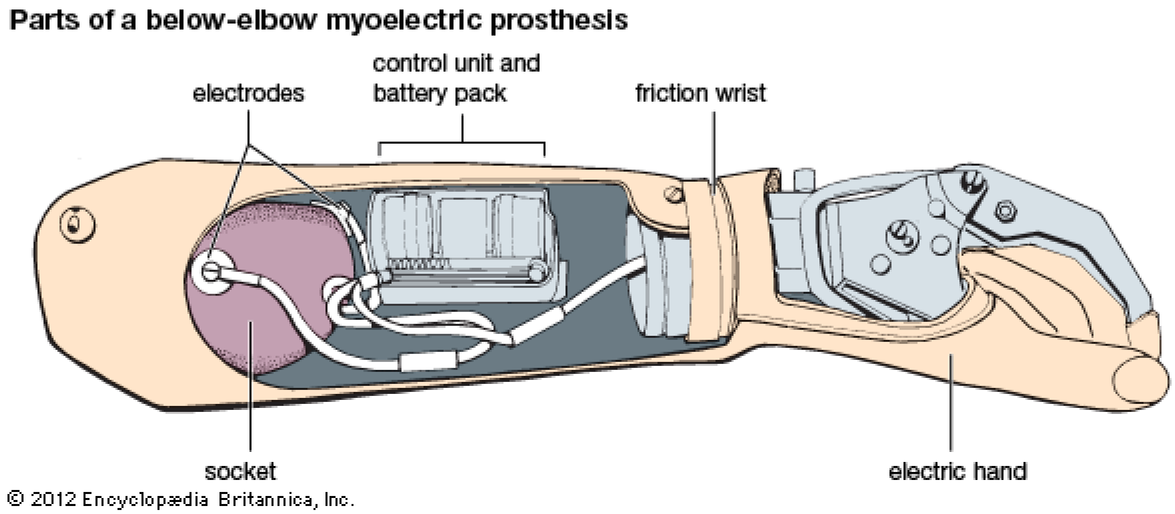


Figure 6: Myoelectric Prosthetic Cross-Section

There are also versions of prosthesis that combine features and functions from multiple categories of designs. One such device is the IRIS hand, designed in 2014. The design combined the cable aspect of user-powered devices, with the power aspect of motorized devices. The final design was a series elastic design, capable of moving on its own, requiring minimal input from the user, while simultaneously using minimal electronics [5]. A photograph of the IRIS hand follows. An image of the internal networking is shown in the following design section.

Figure 7: IRIS Cable Operated Prosthetic Device

3 Design and Specifications

3.1 Specifications

3.1.1 Task Specifications

The success of the hand is measured by how well it can function as a prosthetic. In the pursuit of that goal we have determined the following task specifications, detailing the full set of tasks that the hand should be able to demonstrate as a final product.

Figure 8: Various Grips

- Prosthetic hand should know the current orientation of the palm within 5 degrees, using the IMU
- Hand should be able to perform all 3 basic grips
    - Precision (pinch) - hold pencil
    - Power - hold can/mug
    - (Support - grocery bags) - will not be tested
- Fingers must have enough grip strength to hold and carry an empty mug, or approximately 500 g.
- Hand should be able to move individual fingers independently of each other.
- Fingers should be able to register effective force to grip without breaking object by using integrated force sensors.
- Hand must be able to successfully hold an object using the following process:
    - Correctly identify an AR Tag corresponding to a specific object, or object shape, when camera is directed at it.
    - Send the appropriate signal to be processed based on AR Tag recognition.
    - Move fingers to the correct pre-grasp position using PD controller once an object is identified.
    - Identify when object is within reach of fingers, or within 2-3 cm from IMU/palm.
    - When object is within grasping range, close fingers on object and apply the appropriate amount of force to grip object.

    - Maintain a consistent and steady grip on object as it is being lifted.
        - Keep object orientation within 10 degrees - for testing with mug, this is to avoid any type of spilling of liquid.
        - Fingers' points of contact should not move on object once it is fully grasped by the hand, and should maintain appropriate force to grasp object.

3.1.2 Design Specifications

In order for our platform to support the above listed task specifications, we have identified the following as design requirements:

- Hand must contain a camera, IR sensor, IMU, and five (5) single-axis force sensors.
- Each finger must be able to measure the force it is applying to an object through the use of a sensor embedded in the fingertip.
- Wiring should be neat and take up as little space as possible
- The forearm needs to be able to contain all necessary electronics (other than what is in the hand) to control the arm
- Fingers must be strong enough to apply a consistent amount of force to objects
- Arm needs to be both lightweight and durable
- Electronics within the arm need to be easily accessible within five minutes

These are the core requirements to facilitate the completion of our objectives.

3.2 Design

3.2.1 Previous Designs

It was necessary to understand the design features of previous iterations in order to sufficiently make alterations. Previous hand designs started first with the "Design of a Human Hand Prosthesis," completed in 2012 as an MQP by Paul Ventimiglia. The design of this hand was comprised of multiple key aspects that would later be implemented into our own design. Primary key aspects were the finger design and the use of worm gears. The finger design consisted of two separate finger components, linked together with a single linkage. This linkage was connected at the knuckle and at the base of the fingertip pieces. As the motor rotated the gears, the metacarpal would begin to rotate on its axis as well. As this happened, the linkage would also rotate proportionally, effectively curling the fingertip. The figure below shows a three-stage depiction of this movement.

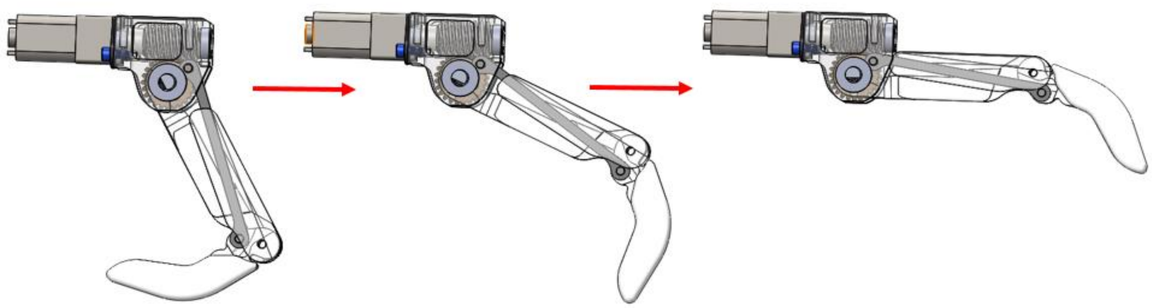


Figure 9: Progression of the Curling Finger

The worm gear was additionally critical to the design of the hand. These gears were able to ensure there was minimal to no back driving on the gears when the motors were not in use. Reducing the unnecessary movement of the gears reduces wear on the gears, maintains structural integrity, and elongating the life expectancy of the prosthesis.

The first iteration of this specific robotic hand project was the IRIS hand, which used a spring cable mechanism to control the fingers. This was an attempt to imitate the way a human hand uses tendons and muscles for its motion. Using a camera for object recognition, as a finger curled, the cable (nylon rope) would pull on the spring at the base of the fingers. As the springs expanded, tension would build in the system which would allow the fingers to return to starting position without additional electrical input. A diagram showing the spring and cable system has been taken from the IRIS hand report and is reproduced below.

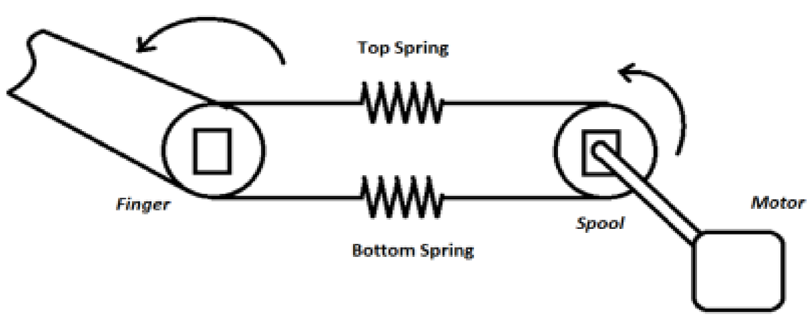


Figure 10: Spring and Cable Mechanics

Force identification was processed using the total deformation of the springs as they extended. While the hand was successful in grasping basic objects, the spring and cable mechanism required a lot of internal space in the arm to accommodate all ropes and springs, as depicted in the following image. In addition, the motor drivers had a tendency to burn out.

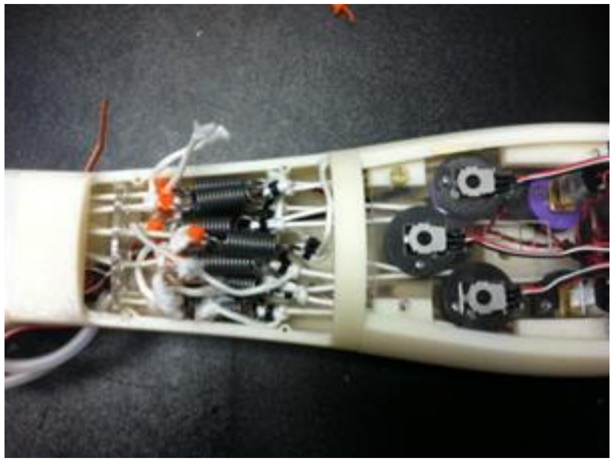


Figure 11: Spring and Cable Prosthetic System

The second iteration attempted to swap out the springs and cables of the IRIS hand for motors directly driving the fingers. This made more room in the palm and arm for electronics. Force recognition was conducted through measuring the current running through the motors driving the finger gears. The palm case was altered slightly from the IRIS hand to accommodate a larger thumb rotation base, as well as accommodating the addition of gears to rotate the wrist with motors. From this specific design, we decided to take the base design of the palm case, including the use of the camera, and the forearm for our project. Renderings and images of the final hand design hand are shown below.

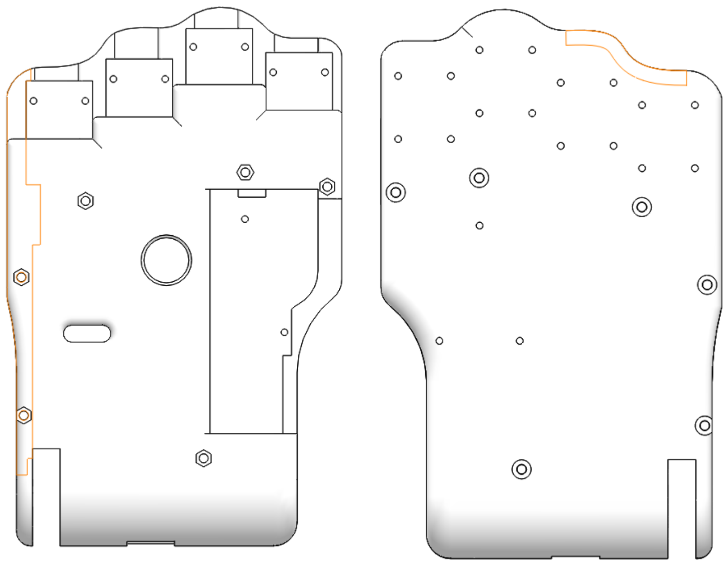


Figure 12: Frankenhand Palm Case Design, both halves fitted together

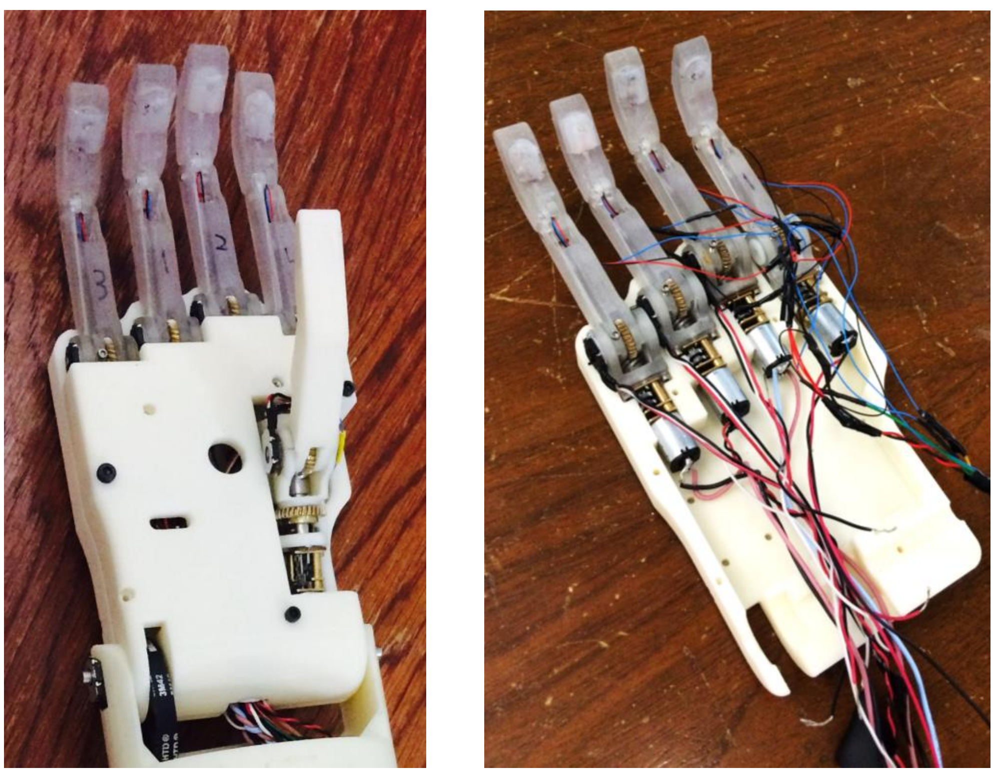


Figure 13: Constructed Prototype

3.2.2 Final Design

For the final design of this iteration, design aspects were taken in combination from previous projects. The primary design alterations from the most recent iteration (VIPER hand) were based around increasing the processing capabilities of the prosthetic. The palm case from the VIPER project was altered to include space for the addition of an inertial measurement unit (IMU) and an infrared sensor (IR). Both were intended to be used for spatial recognition and arm stabilization. The wire channel in the base of the palm case was made wider and deeper for easier closure of the case and to allow the addition of more wiring to the new components, while new wire channels were added on the back half of the case for wire management. Due to the alternate finger design selection, the knuckle slots in both halves of the palm care were re-designed. Previous designs were centered on the use of standard bevel gears. The new design made the use of the worm gears feasible. The palm case as redesigned can be seen below.

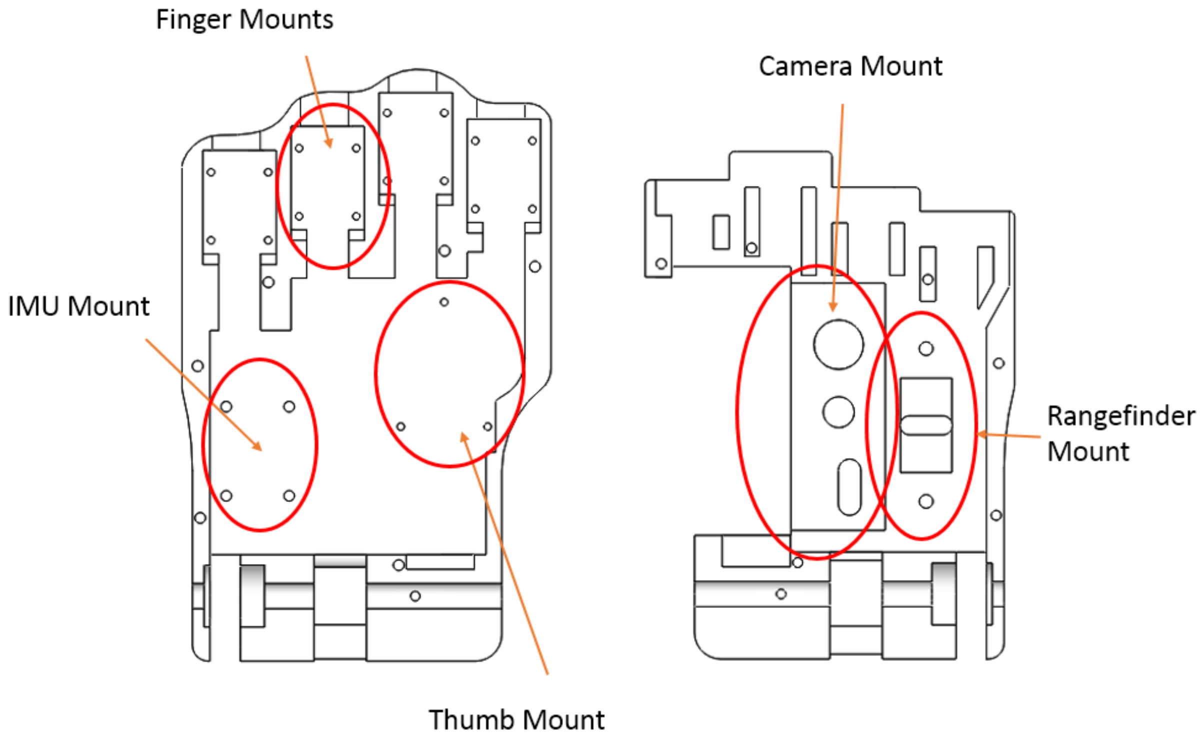


Figure 14: Redesigned Palm Case

Secondary changes to the previous design were centered on the fingers. As noted previously, the design for the fingers was adapted from the original prosthetic hand project. The new fingers were modified from the original design to include a slot in each fingertip for a silicone-covered, single-axis force sensor and cable channel through the phalanges. These force sensors were implemented to more accurately measure the changes in force between the time the fingers were not in contact with an object and the moment the maximum required force was reached.

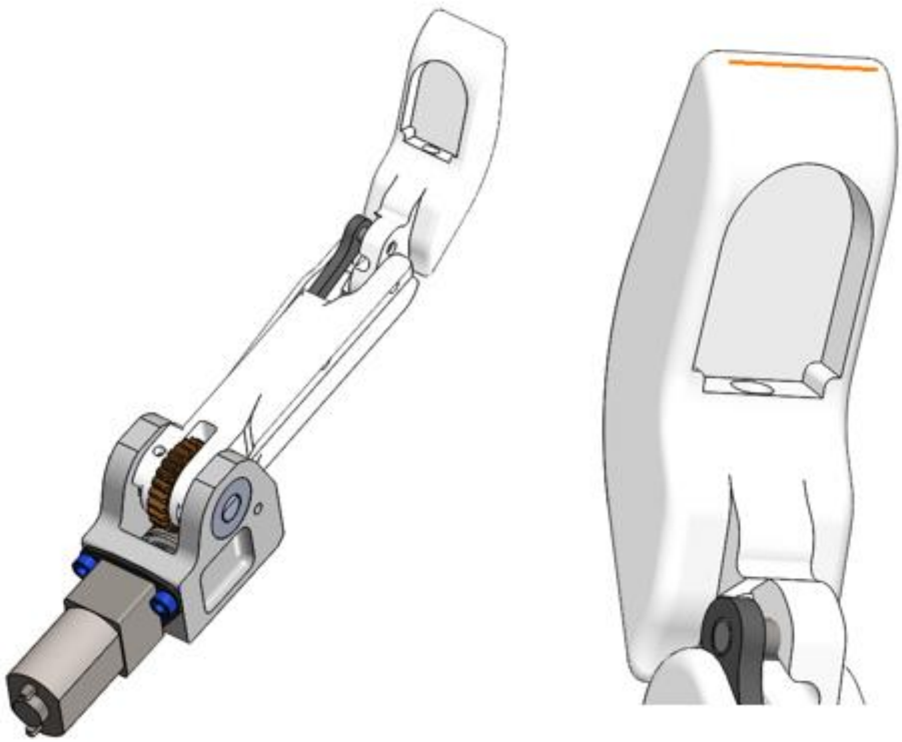


Figure 15: Finger Redesign with Sensor Slot and Wire Channel

The fingertips were widened laterally from 0.31” to 0.50” to allow sufficient space for the sensor slots and to be more anatomically correct.

Beyond the mechanical aspects of the redesign, the control process of grasping an object was altered as well. The closing of the grasp was intended to be automatic based on the combination of object recognition and proximity, dictated by the camera and IR respectively, as well as the fingertip sensors. The design inclusion of an IMU was intended to aid in prosthesis-object stabilization in the event that the user were to move their arm position significantly. The addition of the new sensors required a system upgrade from an Arduino Uno to the newer Arduino Due, since we now needed five inputs from force sensors, eight inputs from potentiometers, and two inputs each from the IMU, rangefinder, and camera, as well as 8 motor outputs. An I^2C breakout board was also purchased to accommodate the larger data input. Architectural diagrams of the electrical and coding components are laid out as follows:

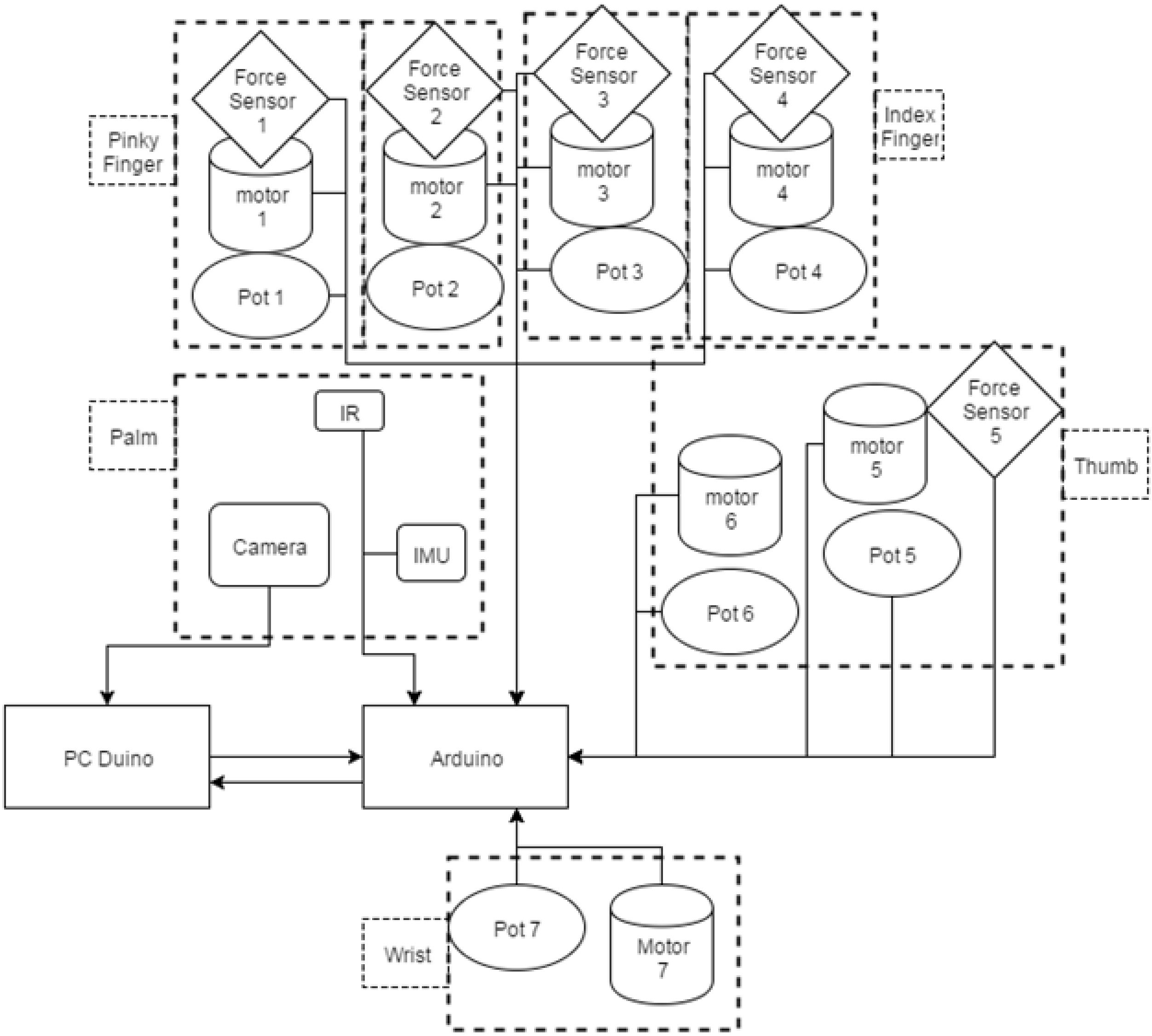


Figure 16: Rough Electrical Schematic

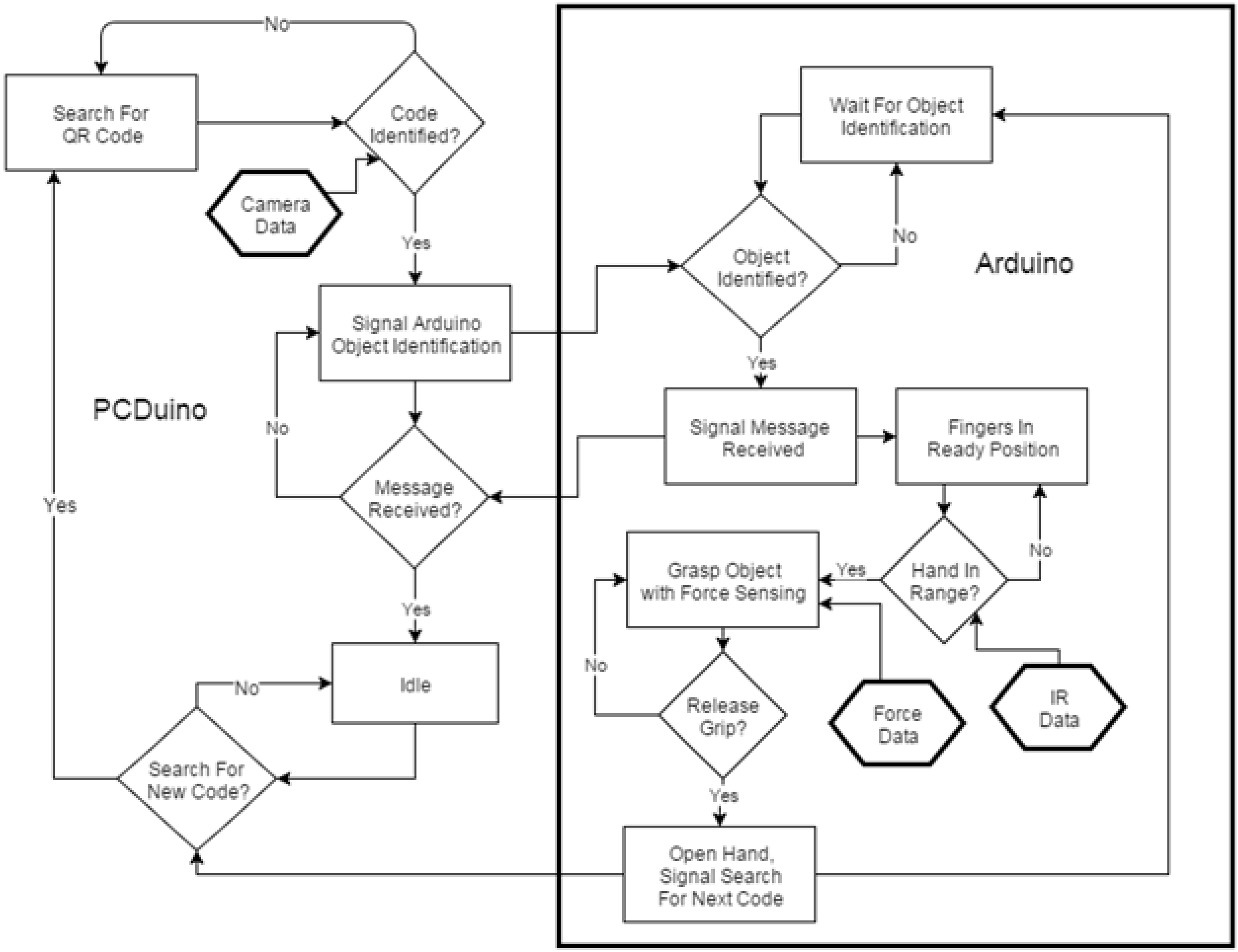


Figure 17: Code Flow Diagram

4 Performance and Evaluation

4.1 Design Evaluation

4.1.1 Finger Design and Evaluation

When it came to designing our fingers, we had several design specifications that we needed to balance and prioritize.

Priority	Feature
1	Able to interface with required components
2	Accurate and Precise control

3	Look and act like human fingers
4	Durable and able to withstand significant force
5	Simple and easy to make

First and foremost, the finger would be useless if it could not be implemented, so it needed to be constrained to fit within the palm of our hand. It also needed to house a functioning force sensor. Our next priority was to ensure that the fingers were able to move both accurately and precisely, since we wanted to allow the hand to grip a wide variety of things. Biological imitation was our third design consideration. Since it is a prosthetic, it needed to look and act similarly to a human hand. Then came durability. Since this is only a prototype, durability wasn't a huge concern. However, for a final product, durability should be a higher priority. Finally, we wanted simple and easy to make hands to reduce the number of failure points and pave the way to an affordable and reliable prosthetic.

The fingers were adapted primarily from the design used in the first model of the hand. The main fingers have two links and are actuated by a single motor. Each finger contains a linkage bar that curls the tip of the finger as the finger moves, to simulate how an organic hand works. The thumb has two degrees of freedom, one being the typical curling motion of a finger, the other allowing the thumb to rotate (how to describe the thumb motion. Use pictures)
All of the fingers were given slots in the tip to accommodate the force sensors. Each slot for the sensor has a wiring channel that leads back down through the finger segments and into the hand. Since finger precision was one of our most important objectives, we opted to use worm gears to drive the fingers. This prevented the fingers from being backdriven, as well as giving us a slightly slower and easier to control motion.

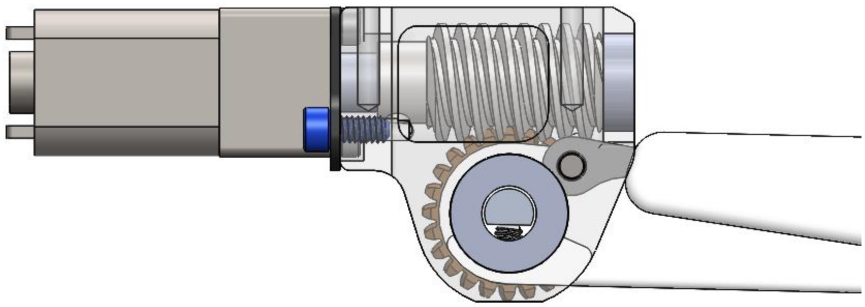


Figure 18: Worm Gear Driving Finger

The thumb was a little harder to design because it required two axes of rotation. Again. We were able to adapt a design from a previous year to our purposes. The first motor rotated the housing of the thumb laterally, while the second motor actually curls the thumb. This works because the housing of the thumb is rotationally independent from the motor and worm gear that curl the thumb.

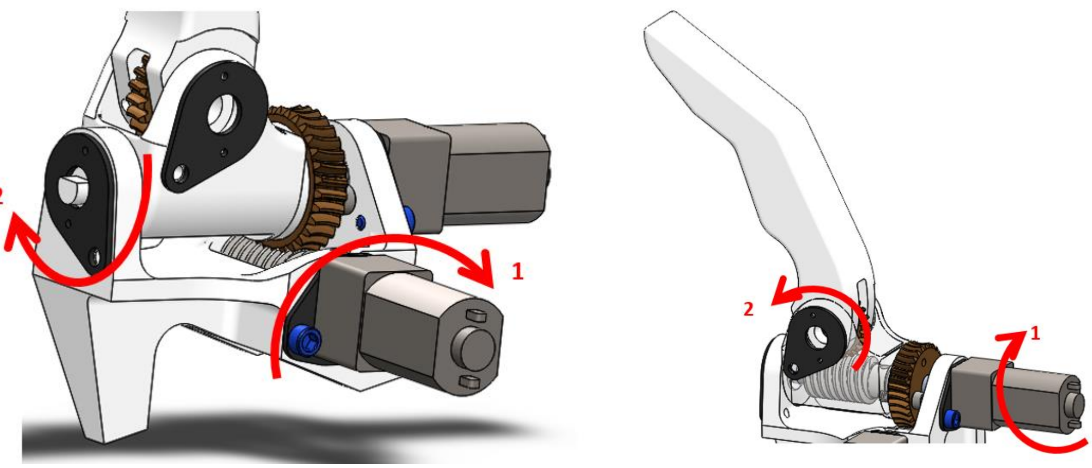


Figure 19: Rotational patterns of the Thumb

This allows our thumb to rotate in both axes normally seen in a thumb.

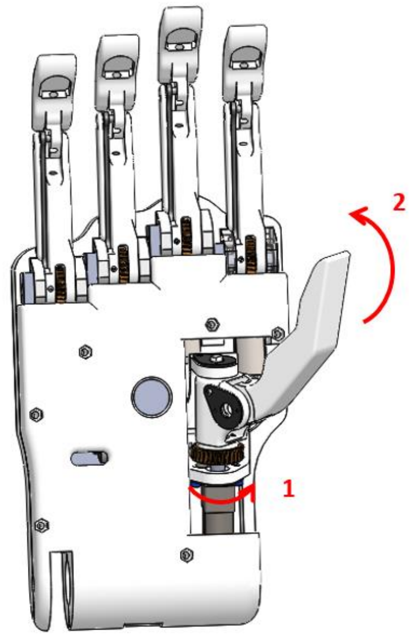


Figure 20: Range of Motion of the Thumb

We were then able to rate ourselves on how well we felt our fingers met their specifications.

Priority	Feature	Rating (out of 5)
1	Able to interface with required components	4
2	Accurate and Precise control	2
3	Look and act like human fingers	4
4	Durable and able to withstand significant force	2
5	Simple and easy to make	4

The fingers were able to interface with both the palm and the force sensors flawlessly. The only difficulty came in attaching the potentiometers. Unfortunately, the press fit planned for the potentiometers was not tight enough, so they had to be glued in place on the fingers. Despite that, the interface was sound. The fingers then lost some points in the accuracy and precision category. Partly due to the 3D printed material, the set screws that set the fingers to the shaft ended up stripping the threads from their holes. When the set screws failed there was no reliable method of fixing the rotation of the potentiometer to the curling of the finger, so the finger's motion was not accurately trackable.

The fingers looked quite similar to real fingers, and the range of motion is very similar to that of natural human fingers. Due to the second joint of the finger being kinematically linked to the first joint, the range of motion for the fingers are lacking in the ability for the second joint to move independently of the first. However, that was never a feature that we intended on implementing due to the size constraints of the hand and the complexity of such a mechanism on top of the existing hardware.

The fingers were also somewhat lacking on the durability side, but as stated above that was an acceptable result of the prototyping phase. Future iterations can focus on improving the materials used to make the fingers stronger and more resilient. One side effect of that would also likely be improved precision, since points of rotation will wear less over time. Finally, the fingers were fairly simple to assemble and did not require an overabundance of moving parts.

4.1.2 Palm Design and Evaluation

For the palm design, there were six main aspects the design needed to cover.

Priority	Feature
1	Knuckle slots needed to fit new knuckle design to hold fingers
2	Palm case needed to have sufficient space and designated spots for the camera, IR, and IMU
3	The case needed to have sufficient space for all wires
4	The width of the case at the wrist needed to fit within the dimensions of the forearm

5	Strong enough to hold heavier objects plus all electronics
6	Anatomically accurate

The most important aspect of the palm was the need to fit the knuckles. If the case did not accurately fit with the newer knuckle design, then the fingers could not be mounted. The palm also needed to have sufficient spacing to accommodate the addition of the IR and IMU. The camera slot needed to be adjusted to make this possible. With the addition of new electronics, there also needed to be extra space within the case to allow for all wiring. Insufficient space could lead to the inability to neatly wire all objects and/or the inability to secure the case closed. The fourth major priority when designing and evaluating the palm was the ability for the case to fit within the tolerances of the forearm. In the first prototyping run of our project, the wrist area of the casing was too wide, and thus the palm needed to be altered again.

While firmly grasping objects is important in consumer prosthetics, the strength was not a high priority. However, because the ideal goal of the project is to iterate the hand to a point where it could be consumer-ready, the durability and strength of the palm material needs to be considered. Finally, for aesthetic reasons, the case needed to be as close to anatomically correct in size to ensure a prosthetic that would be usable.

Evaluating the success of these main points was critical. Our rough evaluation of the completion of each criteria follows.

Priority	Feature	Rating (Out of 5)
1	Knuckle slots needed to fit new knuckle design to hold fingers	5
2	Palm case needed to have sufficient space and designated spots for the camera, IR, and IMU	3

3	The case needed to have sufficient space for all wires	2
4	The width of the case at the wrist needed to fit within the dimensions of the forearm	5
5	Strong enough to hold heavier objects plus all electronics	4
6	Anatomically accurate	3

Although the knuckles were able to stay in the case without excess movement, the palm case was not perfectly capable of fitting them. Areas of the slots were sanded down on both the bottom and top of the case to make the fit better for all knuckles. The spacing for the electronics, although adequate, was not ideal. The camera slot was shifted laterally to include spacing for the IR, and the IMU was given space on the back half of the palm case. However, the IMU location had to be altered from the center of the palm, to underneath the pinky finger, due to the overlap of the IMU with one of the thumb motors.

The palm fell short primarily in regards to adequate wire spacing. Once the fingers and motors were assembled in the palm case, the wire channel at the wrist needed to be sanded to allocate more space. Despite this, the wires still kept the case from securely closing shut, even when screwed together. The palm case did fit into the tolerances of the forearm, but only after a small dimensional modification and re-print of the case. With the re-printing, the material for the case was specified as such that it would have a high tensile strength to ensure the palm would be durable. Anatomically, the case ended up being slightly larger than an average adult male hand, pushing it towards the higher bounds of hand sizes. Ultimately, the hand should be closer to the size of an average adult, male or female, to ensure use.

4.2 Electronics

Unfortunately, due to time constraints we were not able to fully implement and combine all of our electronic components. However, we were able to interface with each electrical element and gather data from them independently.

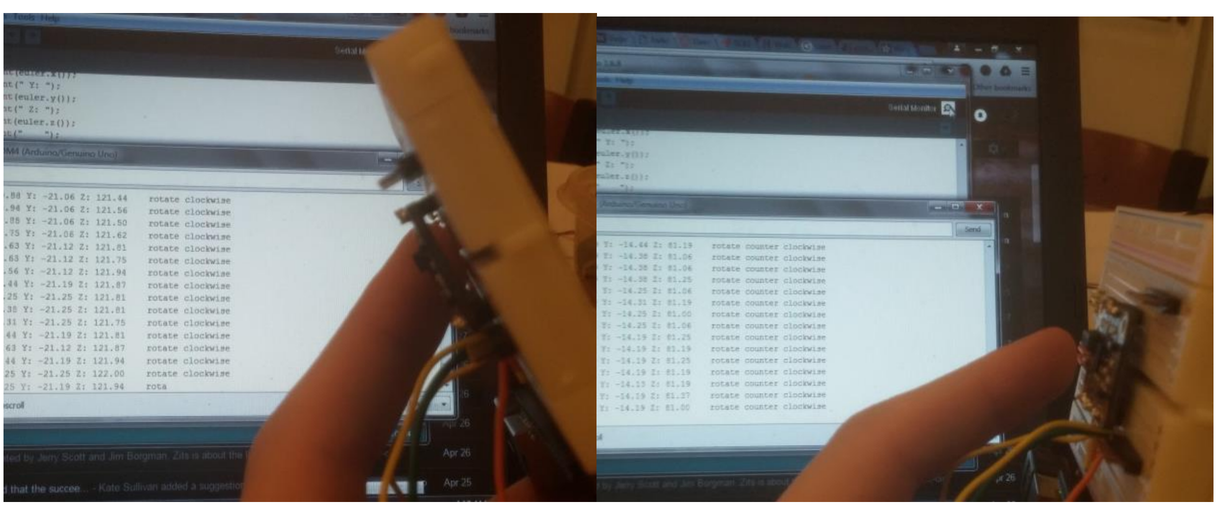
4.2.1 Camera:

Figure 21: Example of Camera Recognition

We were able to use the preexisting code for the camera to successfully identify the AR tag we tested with. The PCDuino then sent a confirmation signal to the Arduino board.

4.2.2 IMU:

The IMU came with a downloadable library that made implementation a breeze. It was able to directly output the Euler angles, as well as the data from the magnetometer, gyroscope, accelerometer, and gravitometer. Using the Euler angles we were able to demonstrate a simple loop where the Arduino output which direction to rotate the hand in order to make it upright. The IMU included drift correction in its programming.



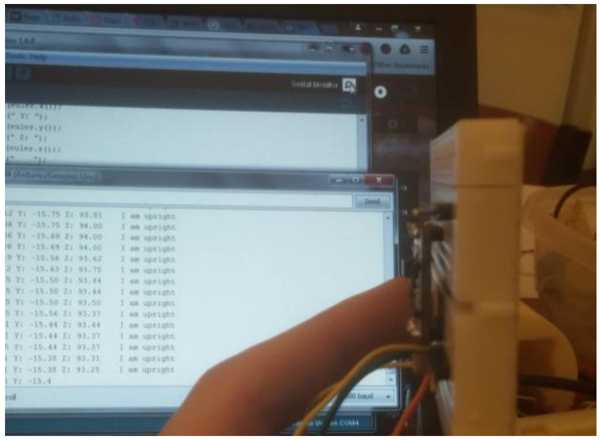


Figure 22: Sensing Orientation with the IMU

These pictures show the output of the Arduino with the IMU rotated in each direction and then upright. The screens output the direction in which the sensor needs to be turned to be in the right orientation.

4.2.3 IR Rangefinder:

The Infrared Rangefinder came with a downloadable library that, much like the IMU, output all of the data that was required for this project. However, it seemed likely that the walls of the slit that the rangefinder peeks through could skew its readings. To compensate we performed an accuracy evaluation on the rangefinder, measuring the output of the rangefinder reading a flat surface at ten millimeters from the surface of the palm.

Distance (from palm)	Trial 1	Trial 2	Trial 3	Average
0 mm	20	18	19	19.0
10 mm	29	26	25	26.7
20 mm	33	36	35	34.7
30mm	42	44	41	42.3
40mm	49	51	48	49.3
50mm	59	61	59	59.7
60mm	69	68	72	69.7
70mm	81	81	80	80.7

80mm	88	86	87	87.0
90mm	94	96	94	94.7
100 mm	104	101	103	102.7

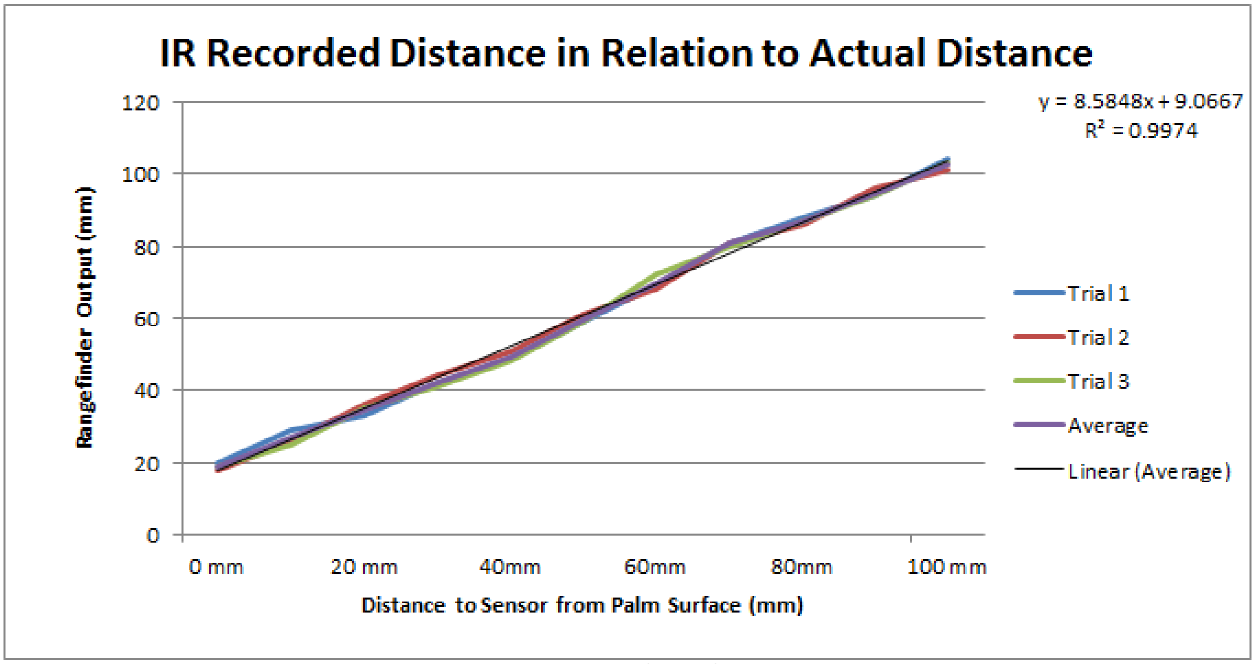


Figure 23: Linear Fit of Rangefinder Data

We took three readings at each distance between zero and one hundred millimeters from the hand. We were then able to evaluate a linear best fit, which had an R^2 value of 0.9974, meaning it fits the curve quite well.

4.2.4 Force Sensors:

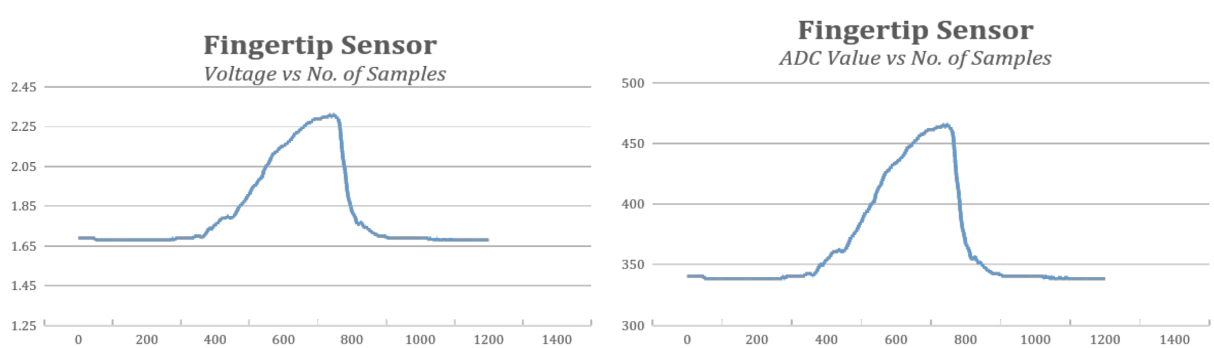


Figure 24: Fingertip Force Sensor Readings

The force sensors were effective at recording force, but they were not terribly accurate in their measurements.

4.3 Specification Review

Specification	Was it met?
Prosthetic hand should know the current orientation of the palm within 5 degrees, using the IMU.	Yes. IMU is accurate at sensing well within that level of accuracy
Hand should be able to perform all 3 basic grips.	Partial success
● Precision (pinch) - hold pencil	The hand had some difficulty performing this
● Power - hold can/mug	Yes, the hand was able to perform a power grip
Fingers must have enough grip strength to hold and carry an empty mug, or approximately 500 grams.	Yes, fingers were successful in holding a coffee pot well over 500 grams
Fingers should be able to register effective force to grip without breaking object by using integrated force sensors.	Possibly. Not enough testing was done to see if the force sensors readings could be refined enough for accurate force measurements.
Hand must be able to successfully hold an object using the following process:	Partial success
● Correctly identify an AR Tag corresponding to a specific object, or object shape, when camera is directed at it.	Yes, the robot is able to identify an AR tag.
● Send the appropriate signal to be processed based on AR Tag recognition.	Yes, upon identifying an AR tag it sends the appropriate signal to the Arduino.
● Move fingers to the correct pre-grasp position using PD controller once an object is identified.	No. Testing did not progress far enough fot this step to be implemented.
● Identify when object is within reach of fingers, or within 2-3 cm from IMU/palm.	In theory, yes. However, this was never tested with the full hand assembly grasping an object. Only with the rangefinder by itself.

• When object is within grasping range, close fingers on object and apply the appropriate amount of force to grip object.	No. It can definitely close the grip, but the appropriate force is reliant further refinement of the force sensor data.
• Maintain a consistent and steady grip on object as it is being lifted.	No. again, this is requires further analysis of readings from the force sensors.
• Keep object orientation within 10 degrees - for testing with mug, this is to avoid any type of spilling of liquid.	In theory, yes. The IMU proved proficient at determining orientation, but it was never tested on the full hand assembly.
• Fingers' points of contact should not move on object once it is fully grasped by the hand, and should maintain appropriate force to grasp object.	No. The full code structure was not implemented, so this could not be evaluated.

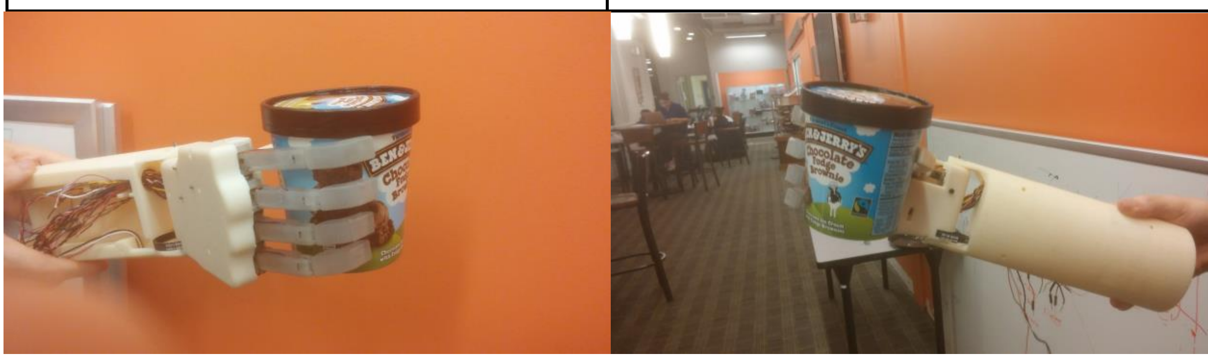


Figure 25: Hand Holding Ice Cream

Figure 26: Holding the Heavier and Harder to Grip Paper Towel Roll

Figure 27: Testing a New Grip on a Coffee Pot

Figure 28: Robot vs Human Grip on the Coffee Pot

5 Recommendations for Future Work

Based on the completion of our project, we recommend the continuation of this project for a minimum of another year. The biggest priorities for continuation of this project surrounds the coding of all electronics to fully integrate all systems. Additionally, within the electronic systems, expansion of the camera capabilities would be beneficial. Being able to identify basic objects without the use of an AR tag would be integral to making this hand a viable prosthetic.

In terms of physical suggestions, we recommend the following project(s) look for additional ways to make the prosthetic more life-sized, as in its current design, it is larger than a normal adult hand. Structurally, the shafts pinning the fingers to the knuckles should be replaced with slightly thicker shafts, as well as including a drilled hole of 3/16" through the shaft to secure the movement of the finger rotation to the potentiometers.

In order to control the organization of the wiring, it is also recommended that the wire channel through the wrist is both deepened and widened. This will create the additional space needed to connect wiring to the IR, IMU, and camera. The extra clearance will make closing the palm case easier.

Overall, with a few minor mechanical updates this hand will provide a strong platform for an innovative and intelligent prosthetic hand. Once the electronics can be fully implemented the hand can be coded to identify and grasp a wide variety of objects, as the original project had strived for.

6 References

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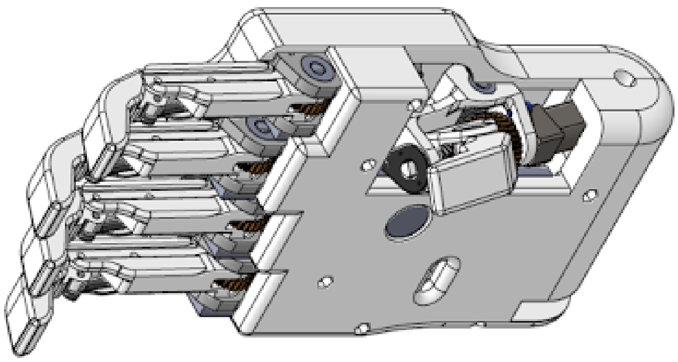
7 Appendix A: Bill of Materials and Associated Cost

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Palm		1
2	Metacarpal Phalanx		4
3	Finger Tip	FINGER TIP	4
4	Linkage		4
5	Knuckle		4
6	98381A434		8
7	Motor Mount Plate		6
8	91290A021		12
9	98511A113		12
10	Worm Gear		6
11	Spur Gear, 24 Tooth		5
12	Finger Shaft		4
13	Motor		6
14	Finger Spur Washer		8
15	Shaft, Extended		4
16	94355A080		4
17	spur finger rot lock shaft		8
18	Worm Washer		6
19	Backhand		1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
20	IMU		1
21	Part2^Full Hand		1
22	potblock		4
23	Thumb Roller Knuckle		1
24	Spur Gear, 30 Tooth		1
25	Thumb Roller		1
26	Thumb		1
27	Shaft, Extended		1
28	90128A044		2
29	Shaft, Extended		1
30	Potentiometer Mount, Thumb Roller		2
31	Camera		1



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THREE PLACE DECIMAL ± 0.001
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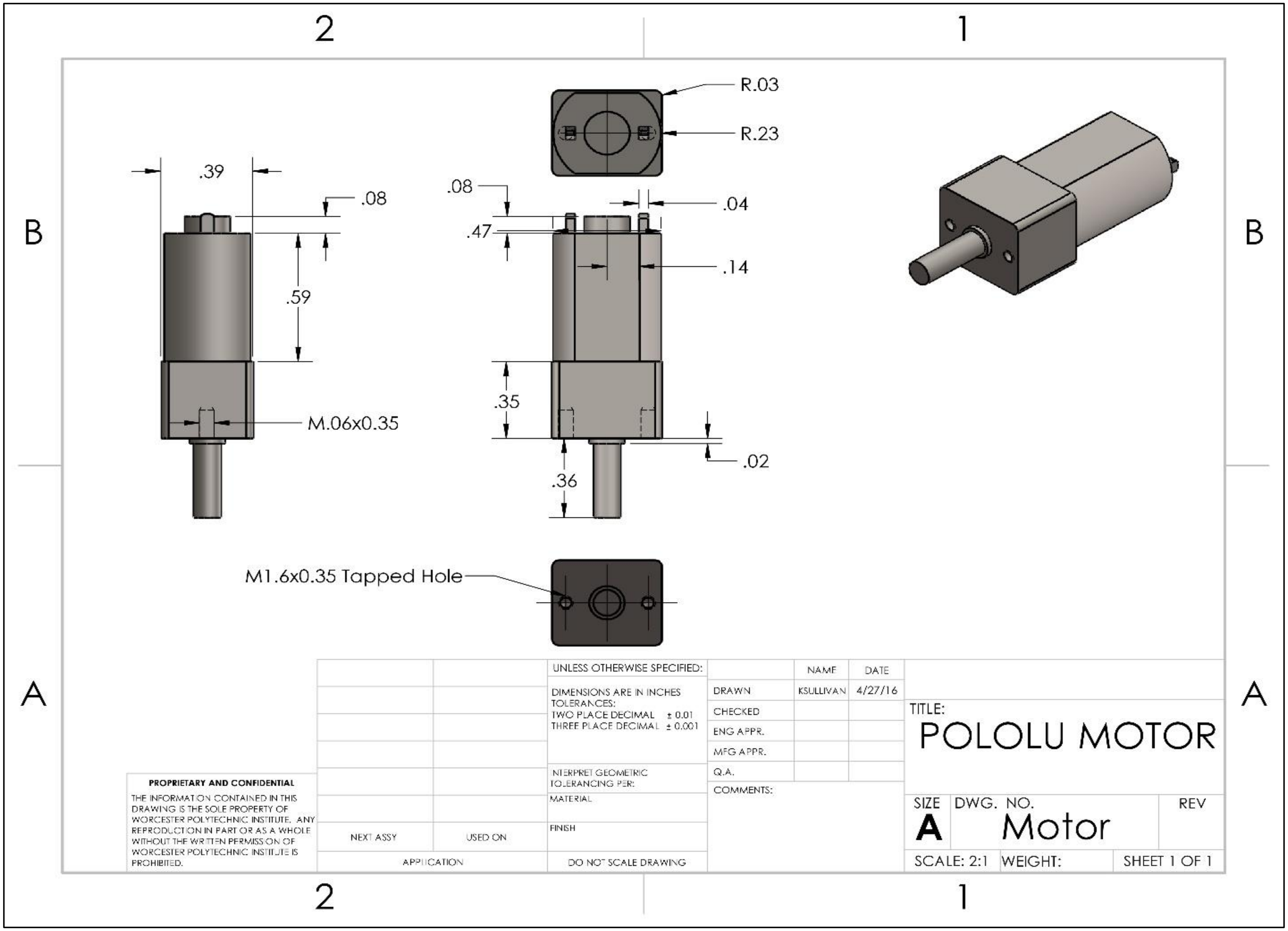
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: FULL HAND
SIZE A
DWG. NO. Full Hand Assy
REV
SCALE: 1:4
WEIGHT:
SHEET 2 OF 2

ITEM NO.	PART	QTY	$/UNIT*	$/1000
1	PALM	1	$ 22.04	$ 22,040.00
2	BACKHAND	1	$ 22.04	$ 22,040.00
3	METACARPAL PHALANX	4	$ 50.64	$ 50,640.00
4	FINGER TIP	4	$ 50.64	$ 50,640.00
5	THUMB	1	$ 14.67	$ 14,670.00
6	KNUCKLE	4	$ 50.64	$ 50,640.00
7	THUMB ROLLER KNUCKLE	1	$ 14.67	$ 14,670.00
8	THUMB ROLLER	1	$ 14.67	$ 14,670.00
9	CAMERA	1	$ 39.99	$ 39,990.00
10	IMU	1	$ 34.95	$ 34,950.00
11	IR	1	$ 24.95	$ 24,950.00
12	WORM GEAR	6	$ 109.98	$ 109,980.00
13	SPUR GEAR, 24 TOOTH	5	$ 70.50	$ 70,500.00
14	SPUR GEAR, 30 TOOTH	1	$ 14.15	$ 14,150.00
15	MOTOR	6	$ 95.70	$ 95,700.00
16	LINKAGE	4	$ -	$ -
17	MOTOR MOUNT PLATE	6	$ -	$ -
18	POTENTIOMETER MOUNT	2	$ -	$ -
19	SHAFT, FINGER	4	$ 2.90	$ 2,900.00
20	SHAFT, EXTENDED	3	$ 1.70	$ 1,695.00
21	WORM WASHER/COLLAR	6	$ 0.02	$ 17.00
22	SPUR WASHER/COLLAR	8	$ 1.04	$ 1,040.00
23	SHAFT, FINGER ROTATION LOCK	8	$ -	$ -
24	MISC. SCREWS	30	$ -	$ -
25	ARDUINO	1	$ 49.95	$ 49,950.00
TOTAL COST			**$635.88**	**$635,882.00**
*A **UNIT** is classified as parts for 1 complete hand; Some parts were obtained from previous project material so no cost was associated.				

8 Appendix B: Technical Data Sheet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.08
.08
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.02
.36
M1.6x0.35 Tapped Hole
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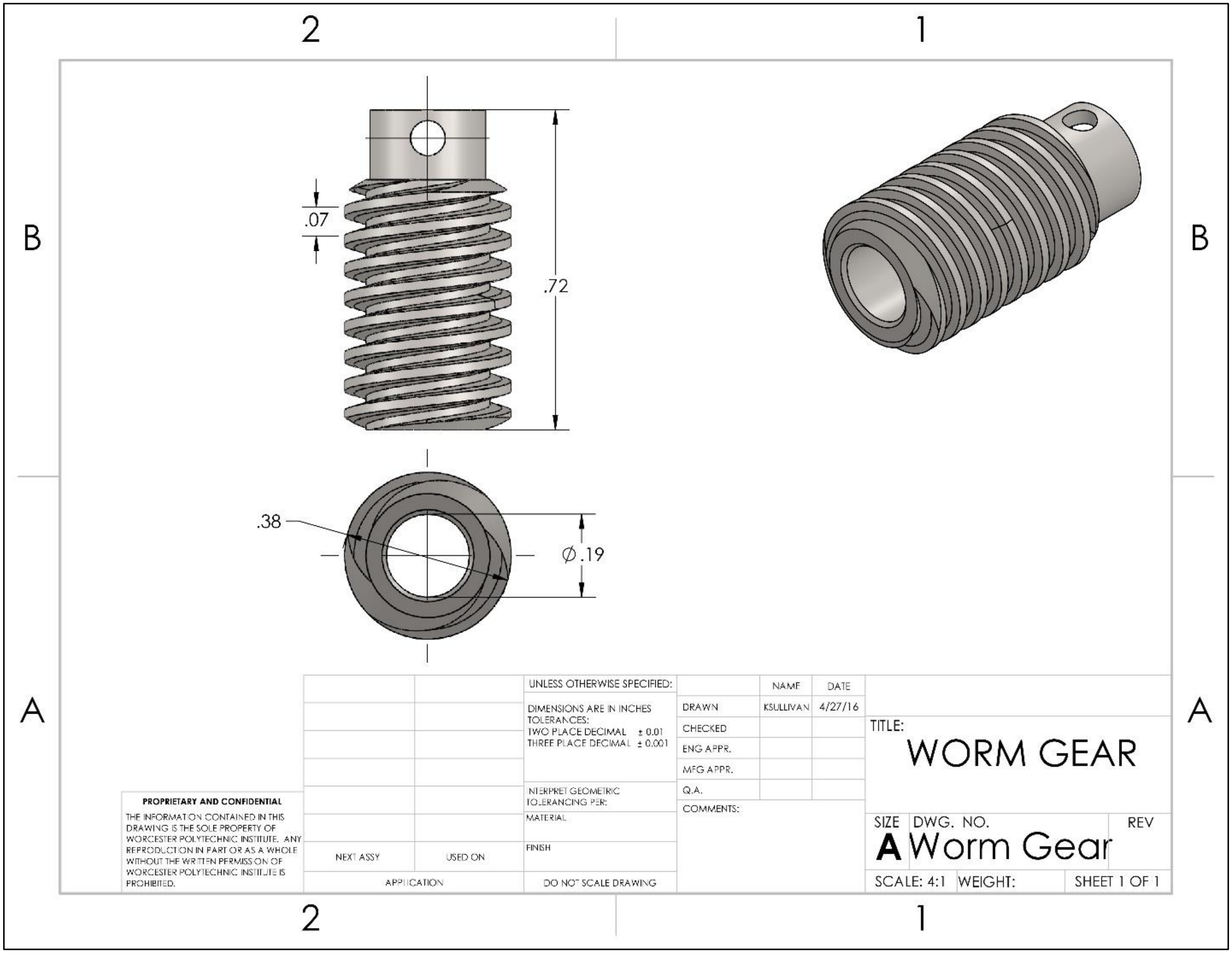
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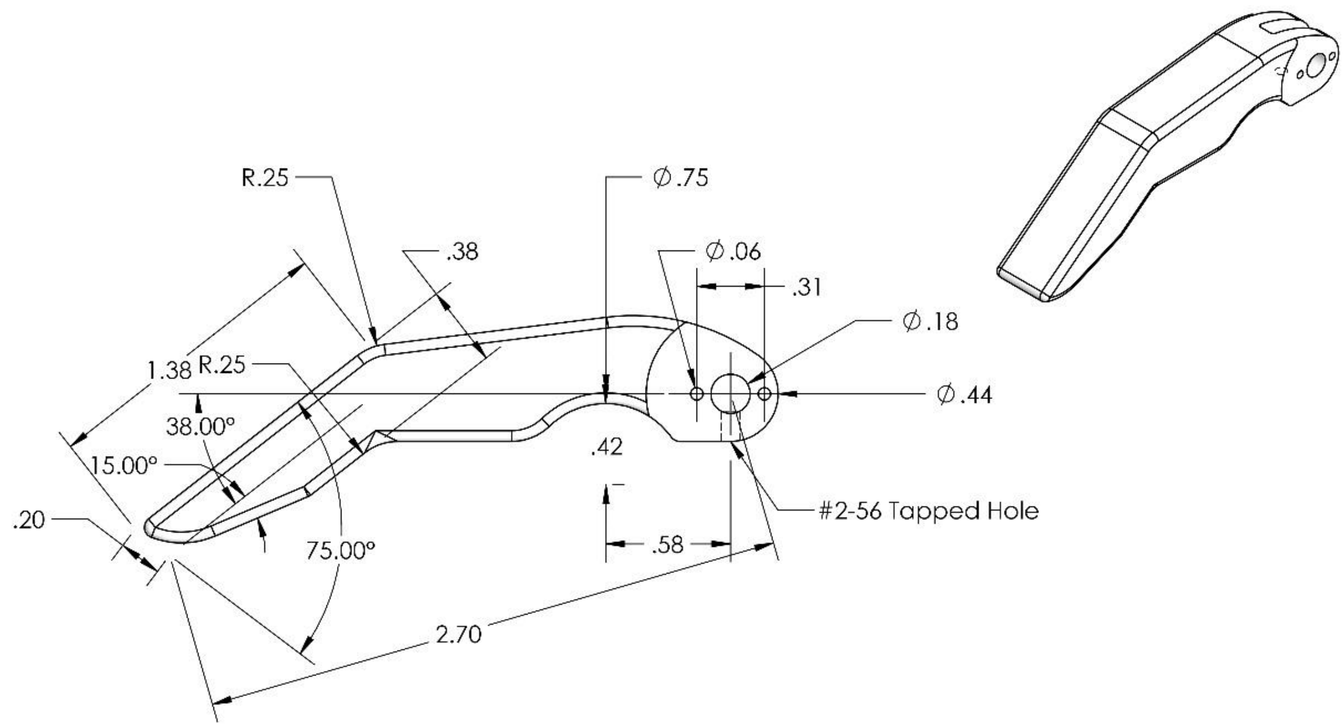

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TITLE: **THUMB**

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A	Thumb	

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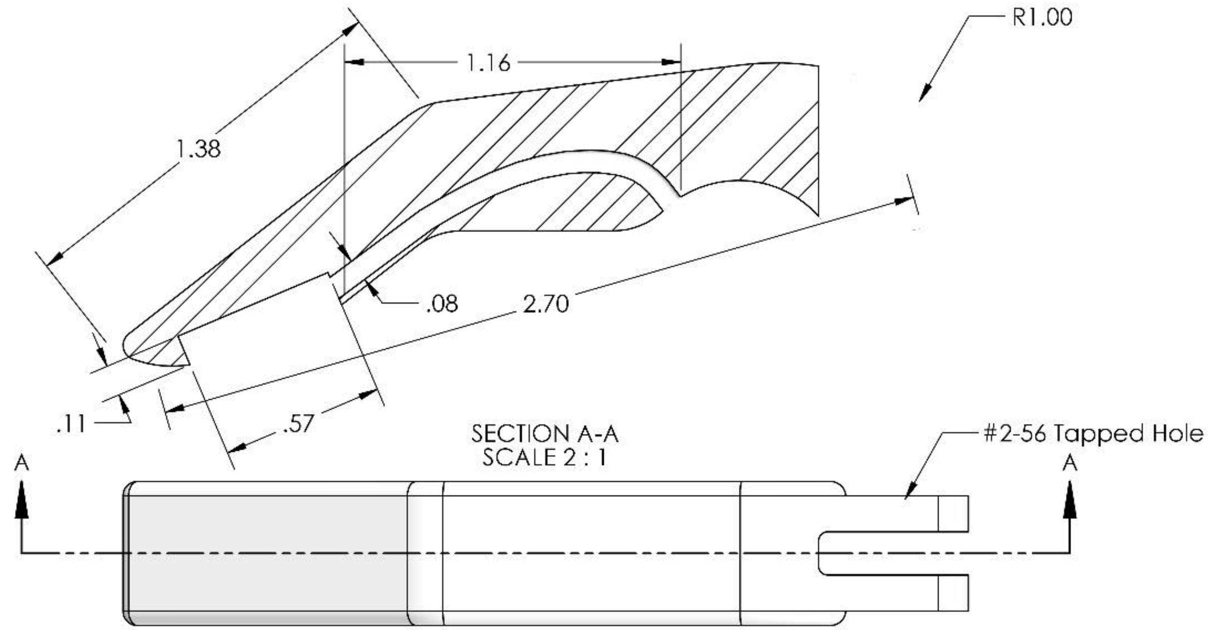

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TITLE: THUMB

SIZE	DWG. NO.	REV
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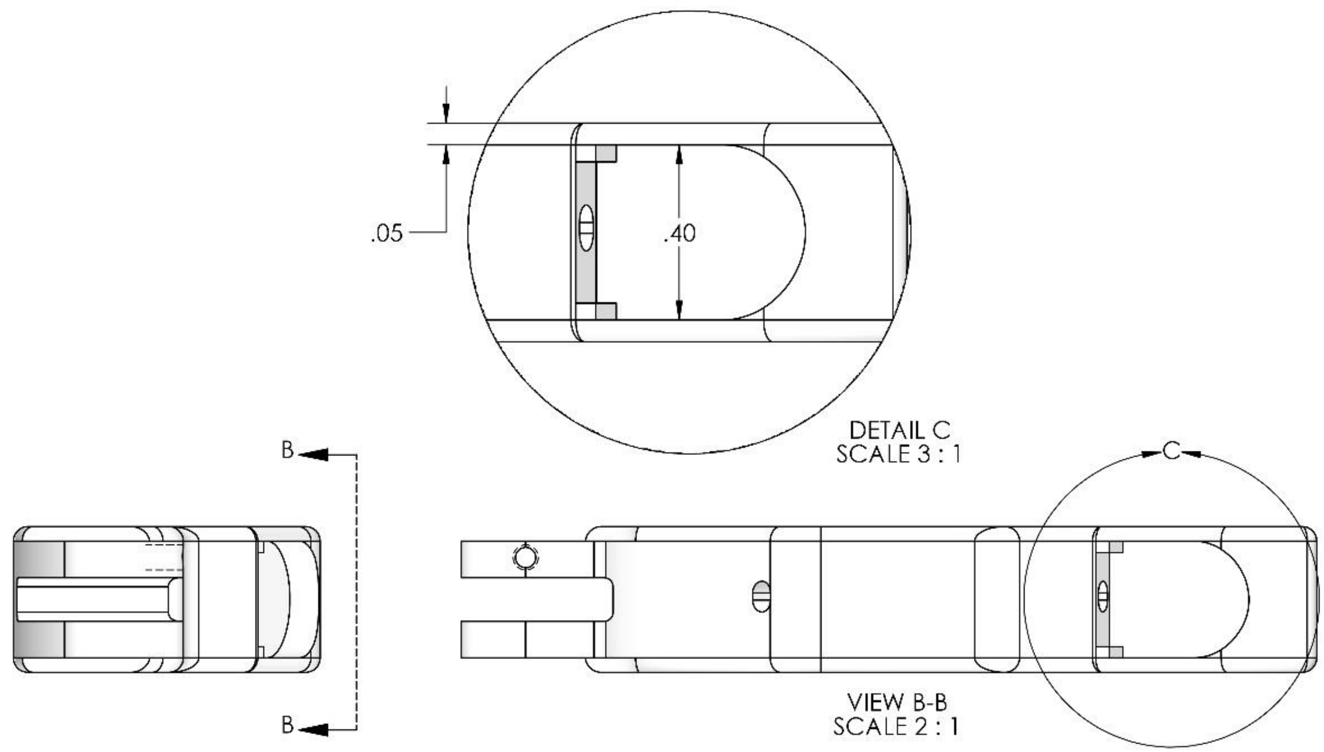

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TITLE:

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A	Thumb	

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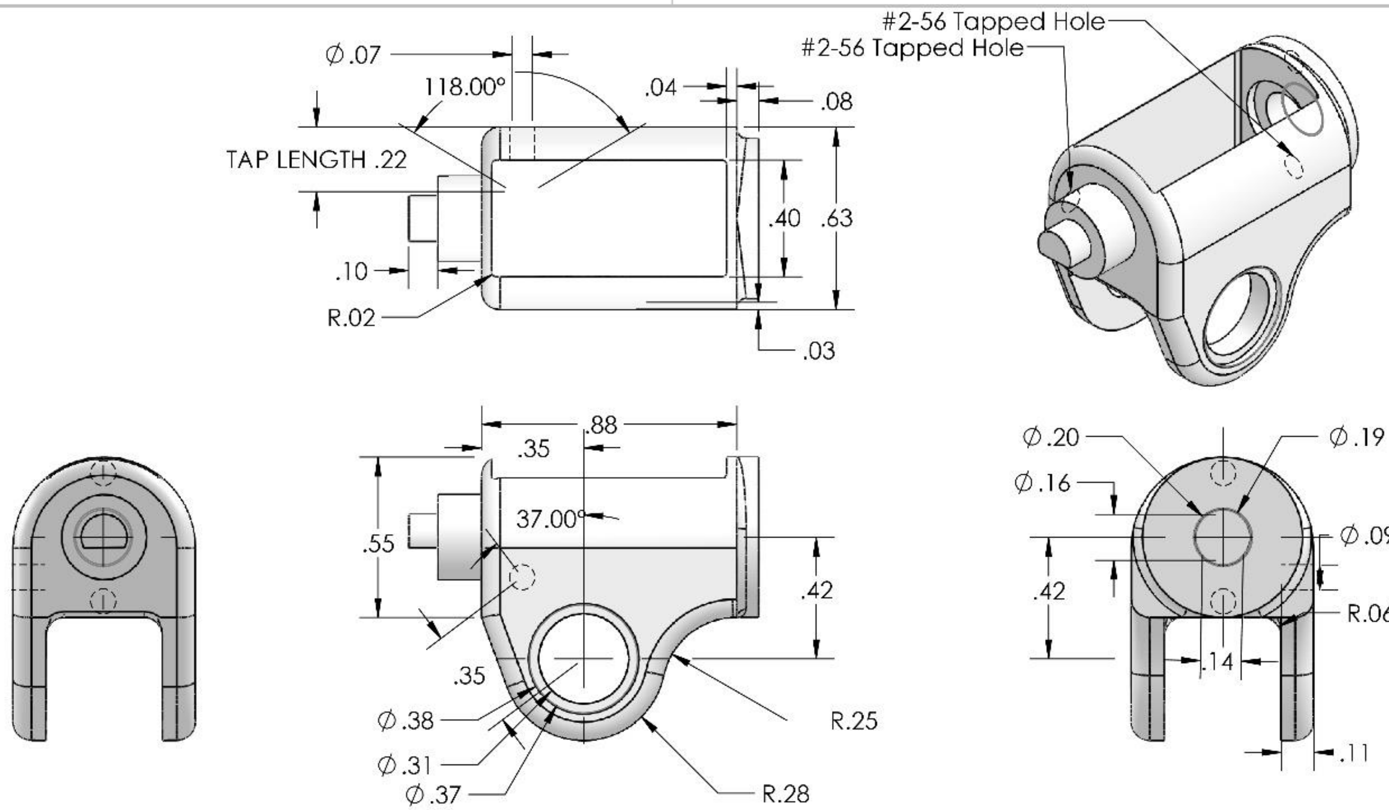

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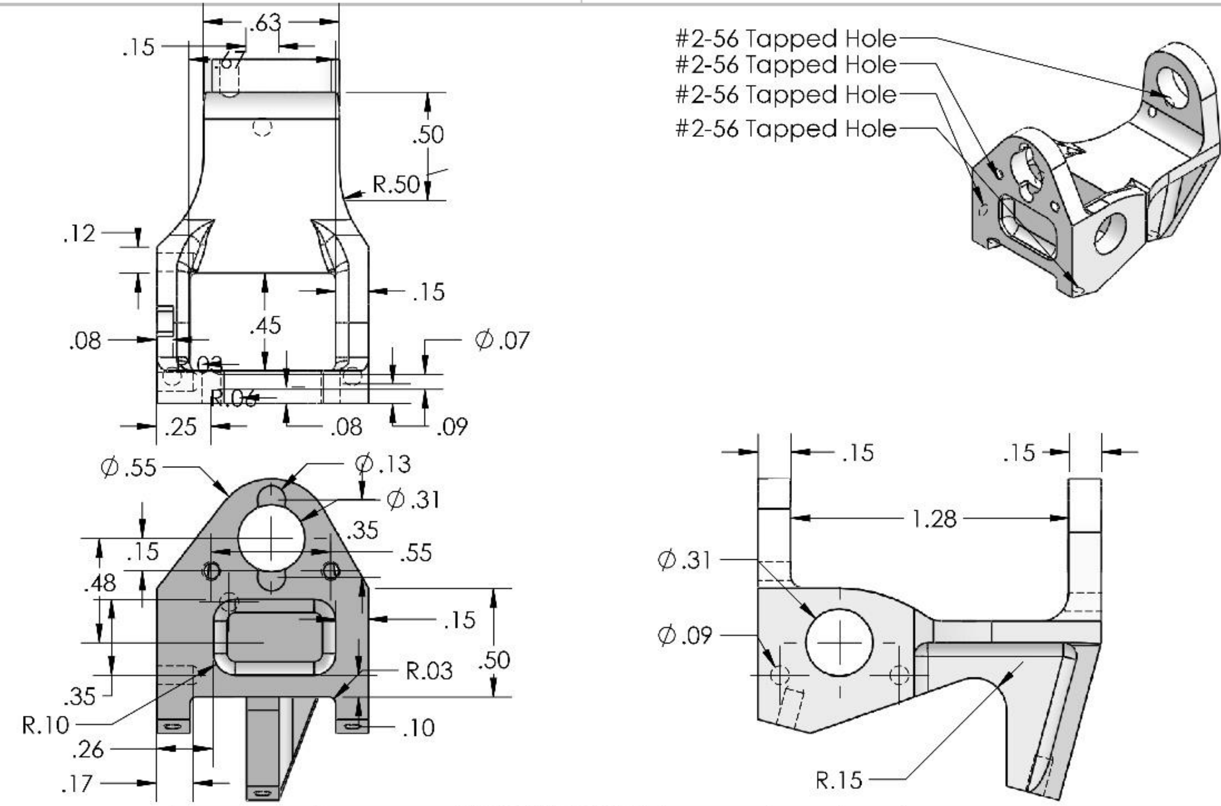

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MATERIAL: ABS

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
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MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

THUMB KNUCKLE

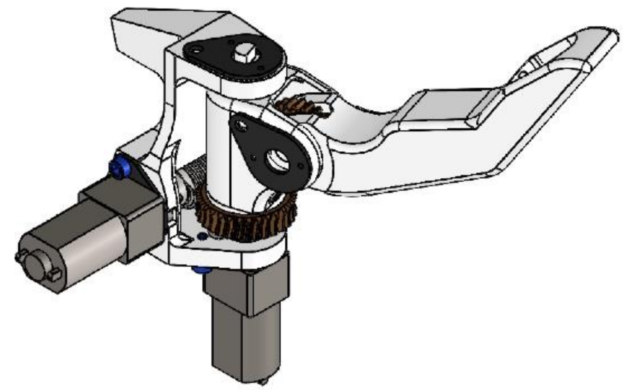
SIZE: A | DWG. NO. Thumb Roller Knuckle | REV

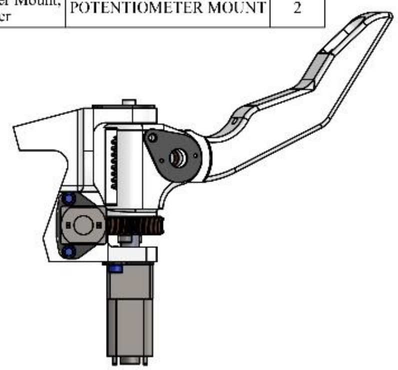
SCALE: 1:1 | WEIGHT: | SHEET 1 OF 1

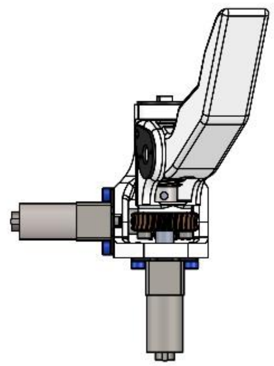
NEXT ASSY | USED ON

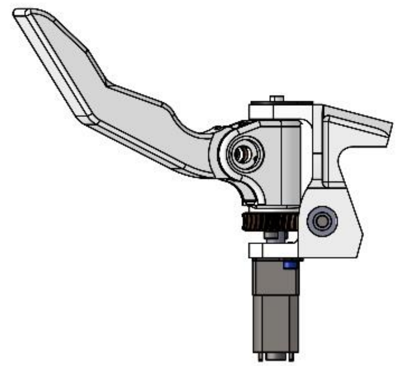
APPLICATION

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Thumb Roller Knuckle	THUMB KNUCKLE	1
2	Motor Mount Plate	MOTOR MOUNT PLATE	2
3	Worm Washer		2
4	Spur Gear, 30 Tooth		1
5	91290A021		4
6	98511A113		4
7	Motor	POLOLU MOTOR	2
8	Thumb Roller	THUMB ROLLER	1
9	Thumb	THUMB	1
10	Worm Gear	WORM GEAR	2
11	Shaft, Extended		1
12	90128A044		2
13	Spur Gear, 24 Tooth		1
14	Shaft, Extended		1
15	Potentiometer Mount, Thumb Roller	POTENTIOMETER MOUNT	2









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MATERIAL

FINISH

DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
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COMMENTS:

TITLE:

THUMB SUB-ASSEMBLY

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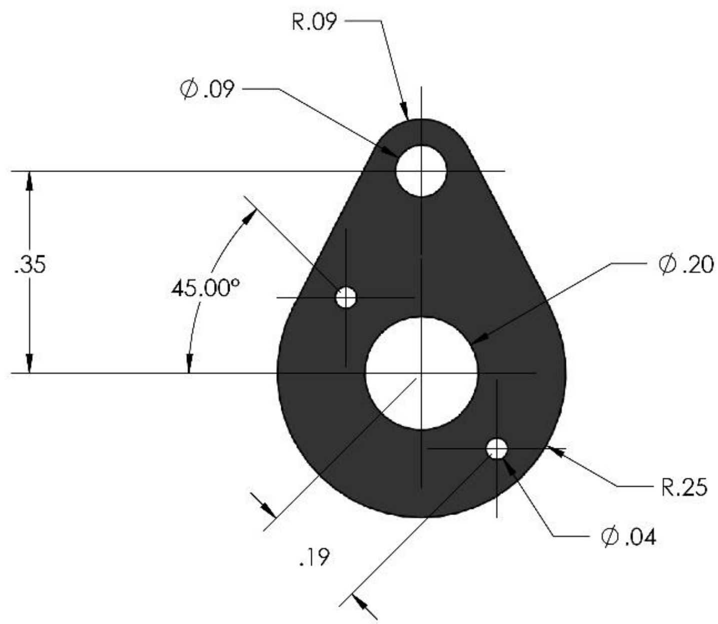
NEXT ASSY | USED ON

APPLICATION

2 1

B B



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MFG APPR.		
Q.A.		
COMMENTS:		

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
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THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
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FINISH

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NEXT ASSY | USED ON

APPLICATION

PROPRIETARY AND CONFIDENTIAL

TITLE:
POTENTIOMETER MOUNT

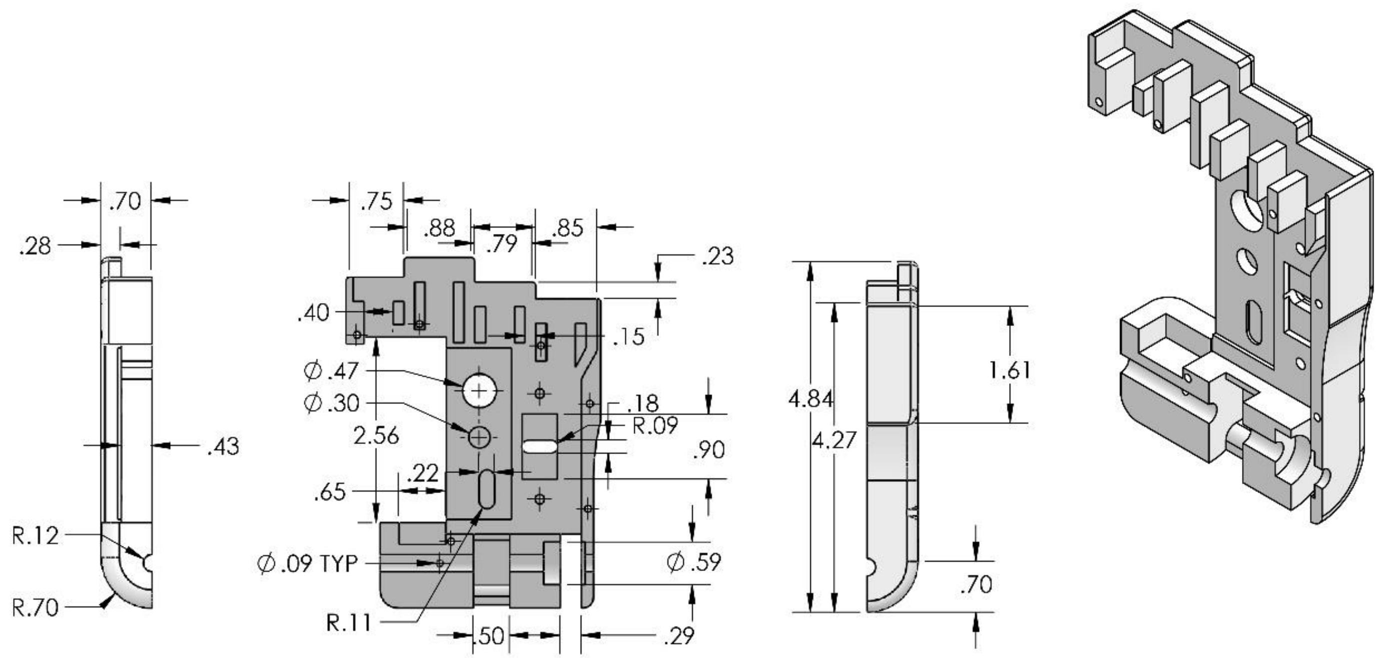
SIZE **A** | DWG. NO. Potentiometer Mount | REV

SCALE: 4:1 | WEIGHT: | SHEET 1 OF 1

2 1

2 1

B



B

A A

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			CHECKED			TITLE:
			ENG APPR.			HAND CASE, PALM
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL ABS	COMMENTS:			SIZE A · DWG. NO. Palm · REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 · WEIGHT: · SHEET 1 OF 1

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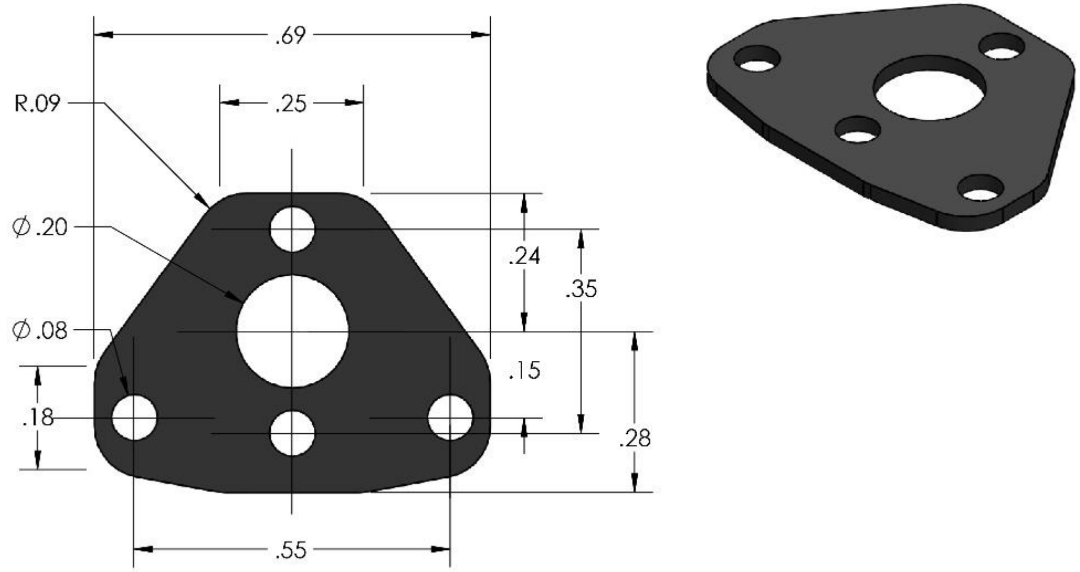
2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Acrylic

FINISH:

DO NOT SCALE DRAWING

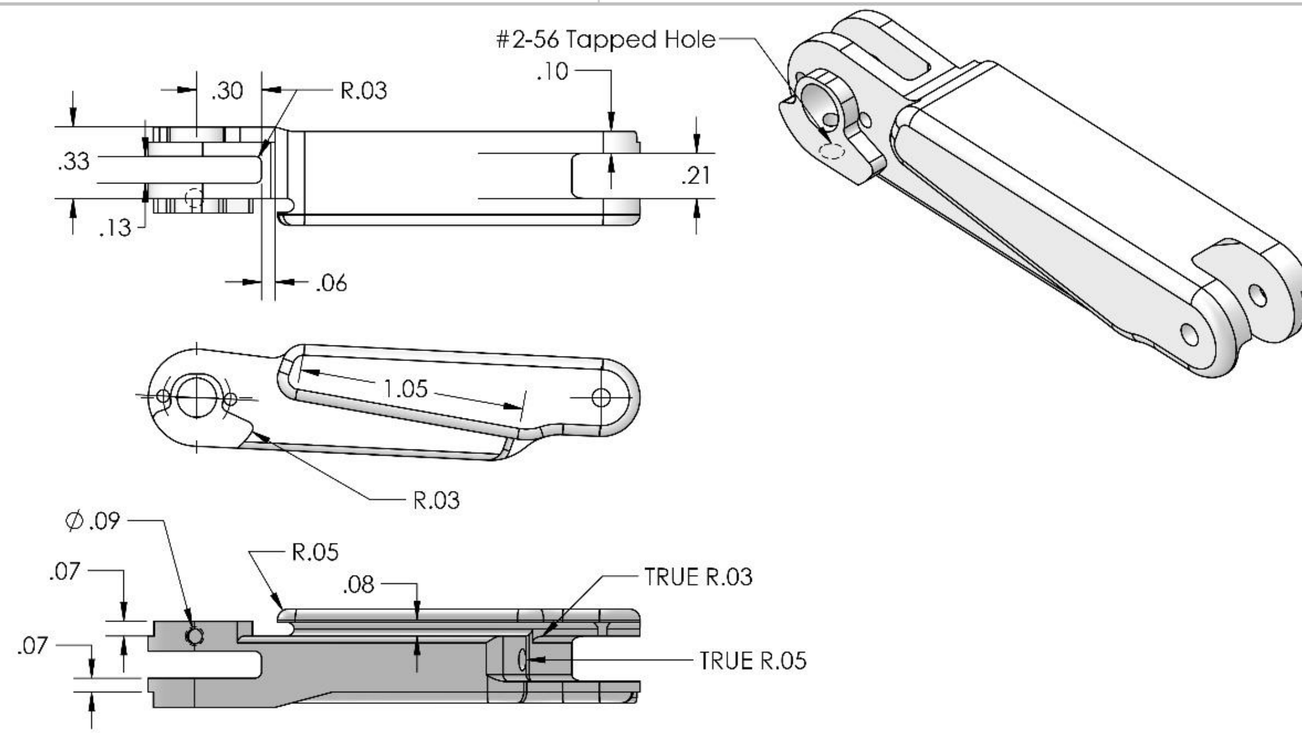
	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
MOTOR MOUNT PLATE

SIZE	DWG. NO.	REV
A	Motor Mount Plate	

SCALE: 4:1 WEIGHT: SHEET 1 OF 1



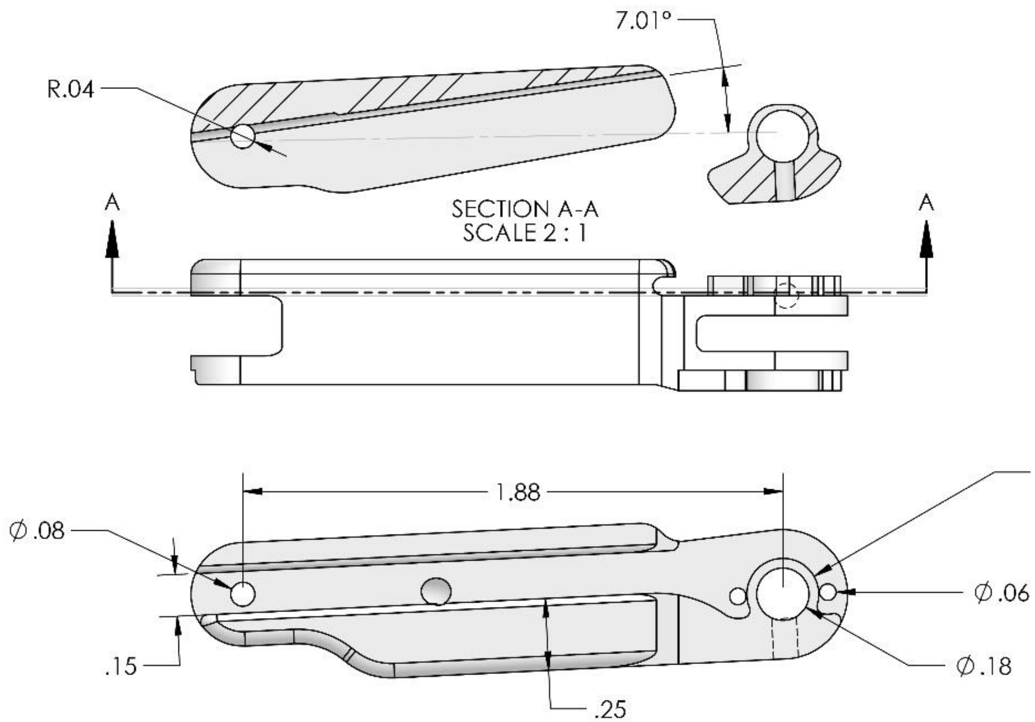
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.001	DRAWN	KSULLIVAN	4/27/16
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL Polyethylene, Crosslinked	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

METACARPAL PHALANX

SIZE **A** | DWG. NO. Metacarpal Phalanx | REV

SCALE: 1:1 | WEIGHT: | SHEET 1 OF 2



2 1

B B

A A

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NEXT ASSY | USED ON

APPLICATION

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polyethylene, Crosslinked

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

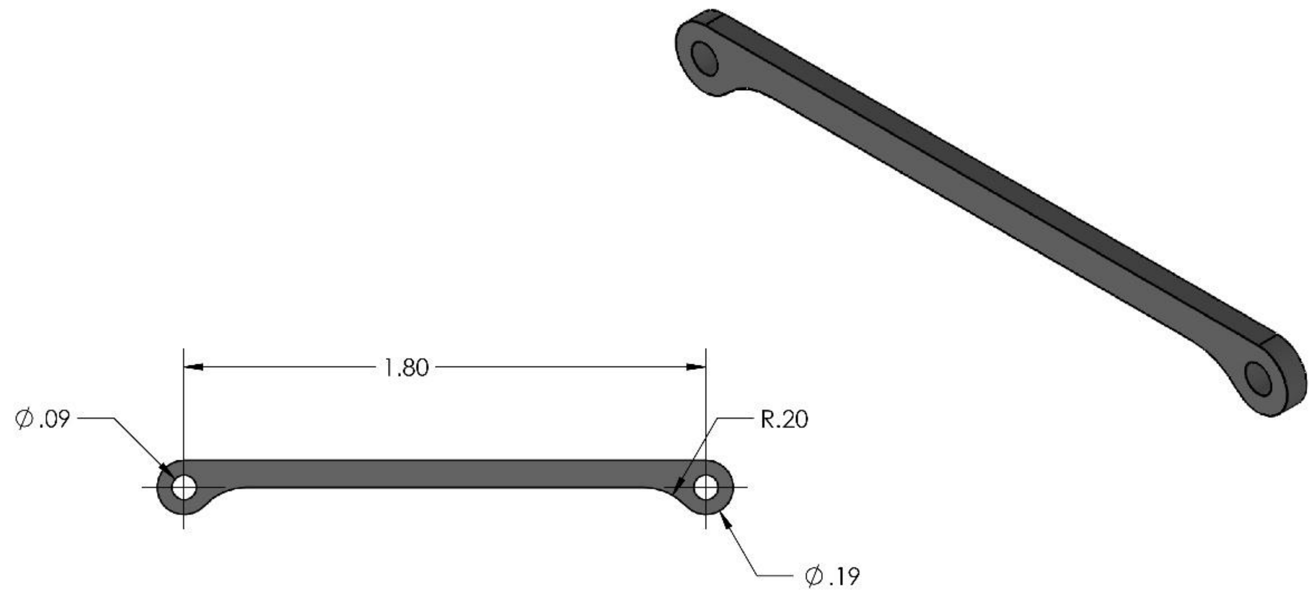
COMMENTS:

TITLE:
METACARPAL PHALANX

SIZE A | DWG. NO. Metacarpal Phalanx | REV

SCALE: 1:1 | WEIGHT: | SHEET 2 OF 2

2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.001	DRAWN	KSULLIVAN	4/27/16	
	CHECKED			TITLE:
	ENG APPR.			LINKAGE
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL Acrylic	COMMENTS:			SIZE A DWG. NO. Linkage REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

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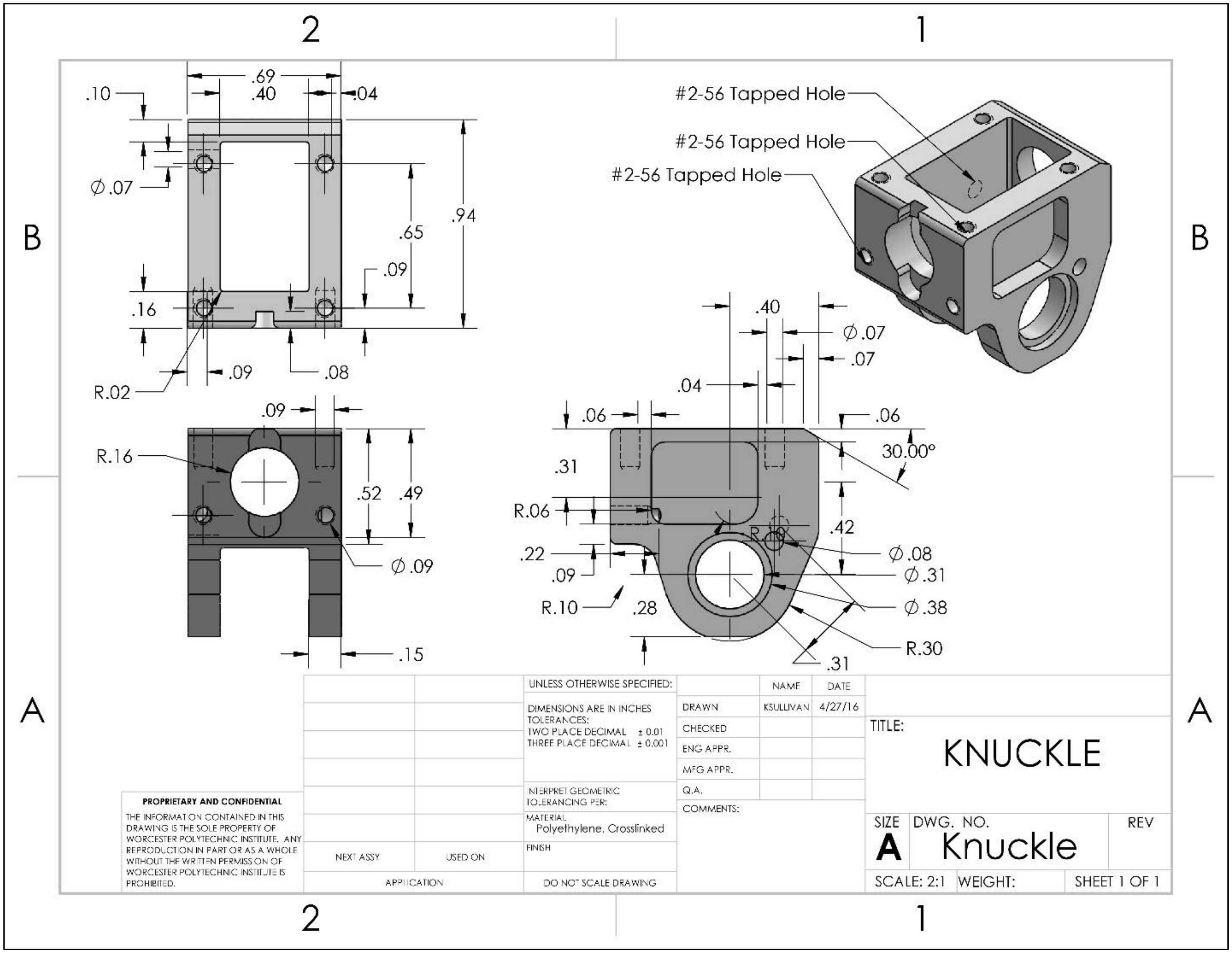
#2-56 Tapped Hole
#2-56 Tapped Hole
#2-56 Tapped Hole
.69
.40
.04
.10
∅.07
.65
.94
.09
.16
R.02
.09
.08
.09
R.16
.52
.49
∅.09
.15
.40
∅.07
.07
.04
.06
.06
30.00°
.31
R.06
.42
R.10
∅.08
.22
∅.31
.09
∅.38
R.10
.28
R.30
.31
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Polyethylene, Crosslinked
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
KSULLIVAN
4/27/16
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
KNUCKLE
SIZE
A
DWG. NO.
Knuckle
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
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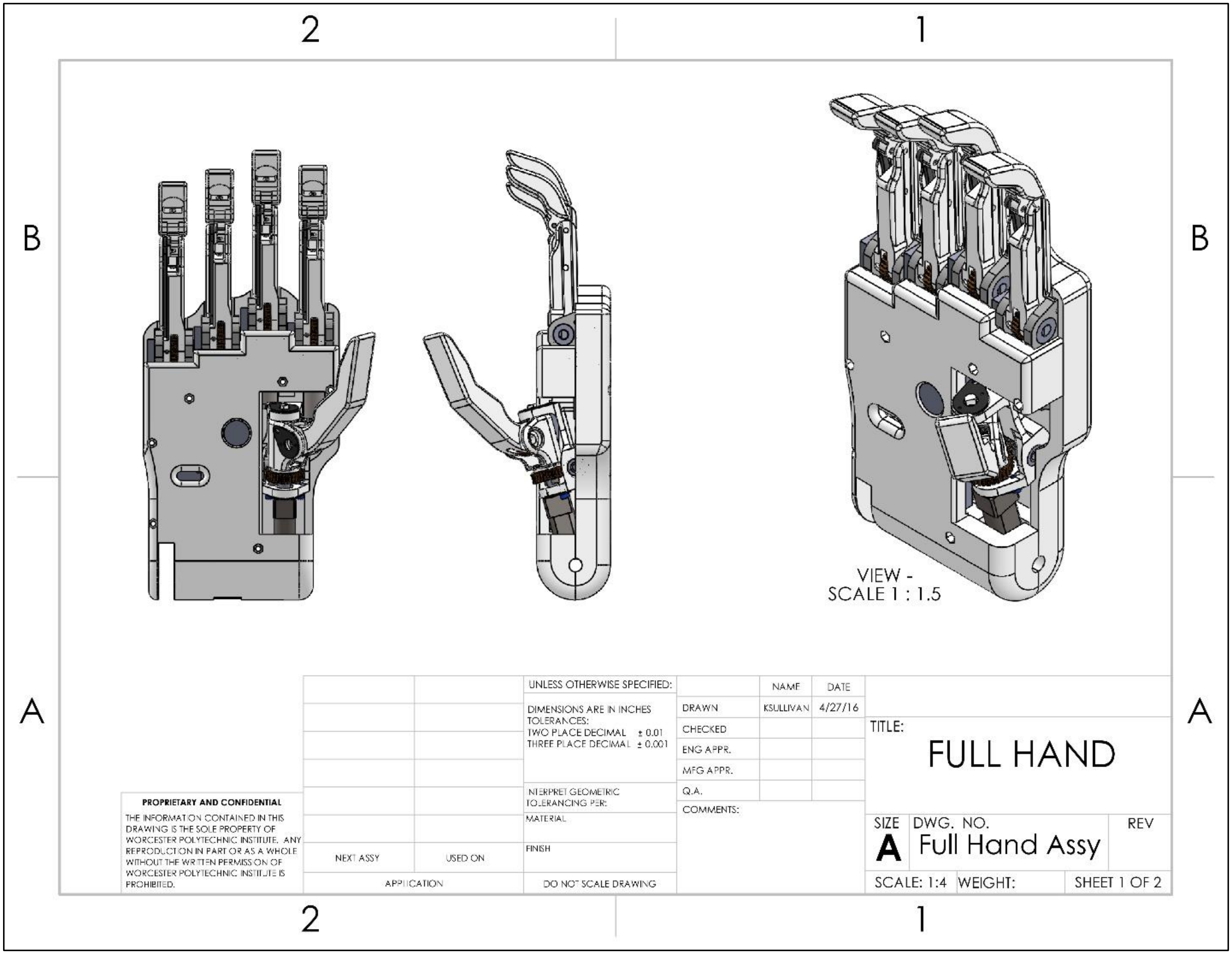
2
1
B
B
A
A
VIEW -
SCALE 1 : 1.5
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
KSULLIVAN
4/27/16
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
FULL HAND
SIZE
A
DWG. NO.
Full Hand Assy
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 2
NEXT ASSY
USED ON
APPLICATION
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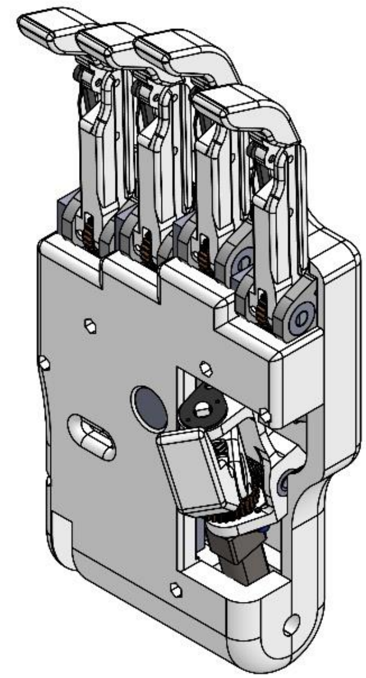
2
1

2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Palm		1
2	Metacarpal Phalanx		4
3	Finger Tip	FINGER TIP	4
4	Linkage		4
5	Knuckle		4
6	98381A434		8
7	Motor Mount Plate		6
8	91290A021		12
9	98511A113		12
10	Worm Gear		6
11	Spur Gear, 24 Tooth		5
12	Finger Shaft		4
13	Motor		6
14	Finger Spur Washer		8
15	Shaft, Extended		4
16	94355A080		4
17	spur finger rot lock shaft		8
18	Worm Washer		6
19	Backhand		1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
20	IMU		1
21	Part2^Full Hand		1
22	potblock		4
23	Thumb Roller Knuckle		1
24	Spur Gear, 30 Tooth		1
25	Thumb Roller		1
26	Thumb		1
27	Shaft, Extended		1
28	90128A044		2
29	Shaft, Extended		1
30	Potentiometer Mount, Thumb Roller		2
31	Camera		1



B B

A A

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

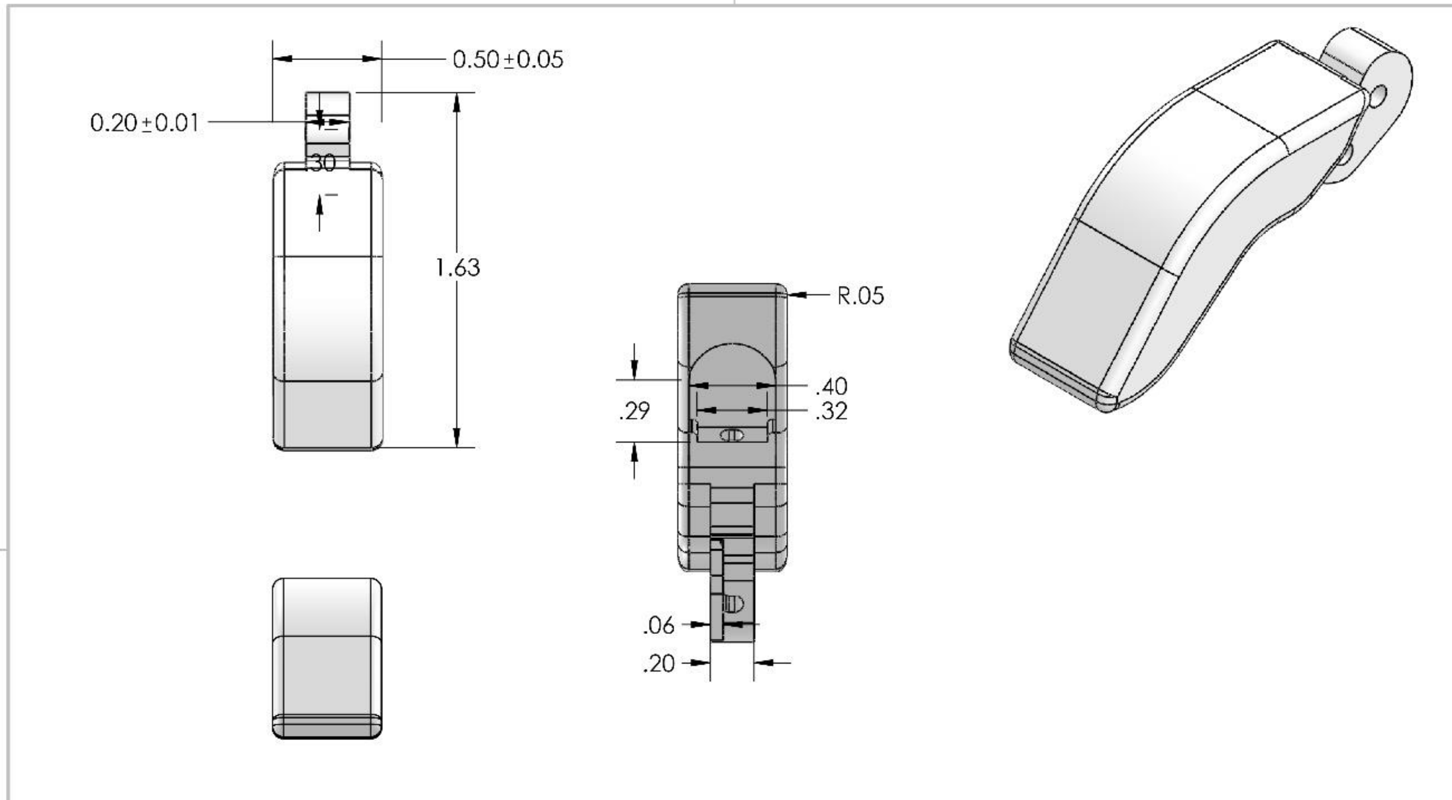
TITLE:

FULL HAND

SIZE A | DWG. NO. Full Hand Assy | REV

SCALE: 1:4 | WEIGHT: | SHEET 2 OF 2

2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: Polyethylene Cross-Linked

FINISH: GLOSSY

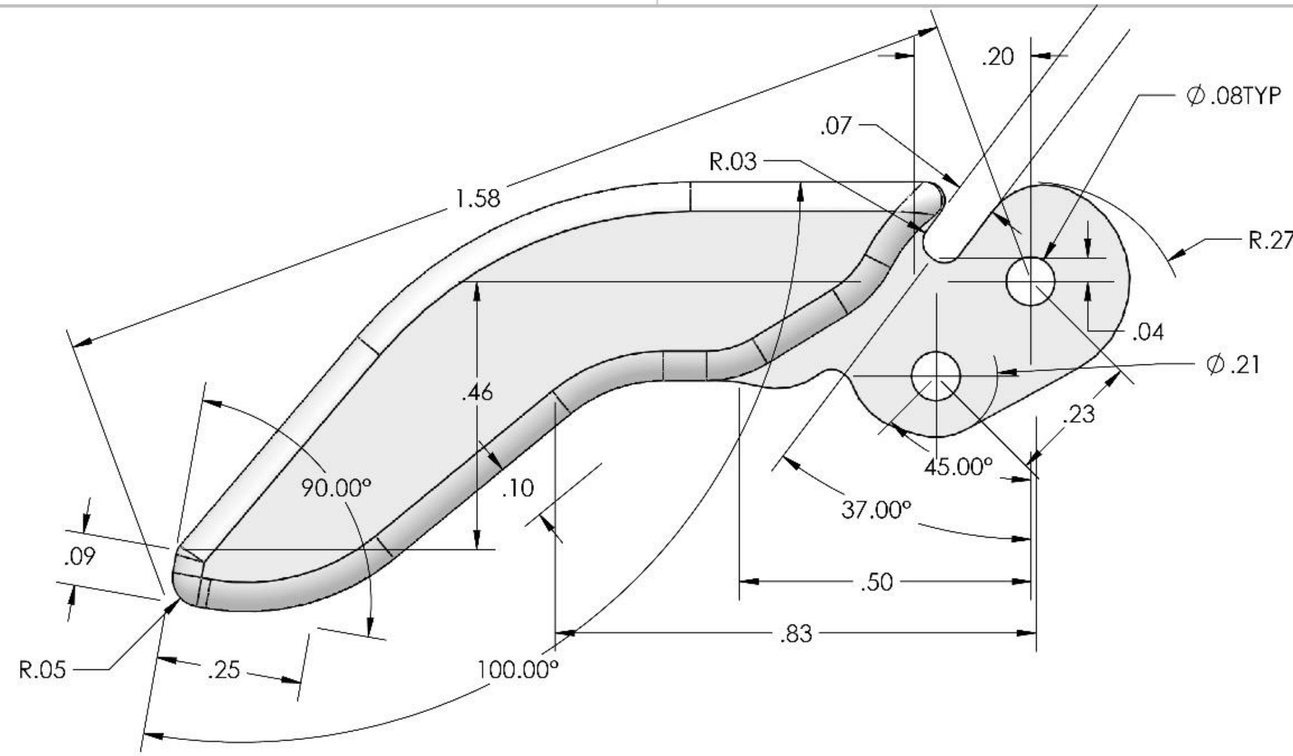
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: FINGER TIP

SIZE	DWG. NO.	REV
A	Finger Tip	

SCALE: 1:1 WEIGHT: SHEET 1 OF 2



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.001	DRAWN	KSULLIVAN	4/27/16	
			CHECKED			TITLE:
			ENG APPR.			FINGER TIP
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Polyethylene Cross-Linked	COMMENTS:			SIZE A DWG. NO. Finger Tip REV
NEXT ASSY	USED ON	FINISH GLOSSY				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 2 OF 2

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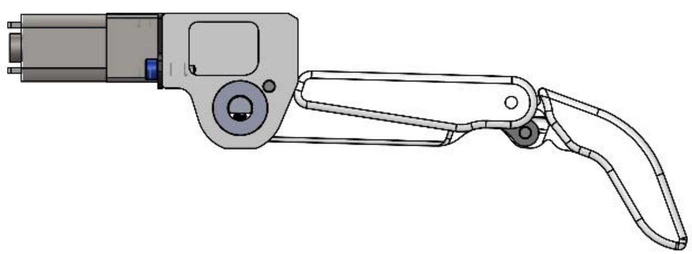
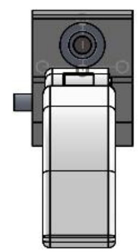
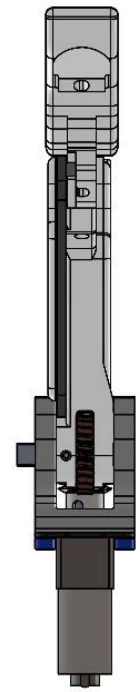
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Metacarpal Phalanx	METACARPAL PHALANX	1
2	Finger Tip	FINGER TIP	1
3	Linkage	LINKAGE	1
4	Knuckle	KNUCKLE	1
5	98381A434		2
6	Motor Mount Plate	MOTOR MOUNT PLATE	1
7	91290A021		2
8	98511A113		2
9	Worm Gear	WORM GEAR	1
10	Spur Gear, 24 Tooth		1
11	Finger Shaft		1
12	Motor	POLOLU MOTOR	1
13	Finger Spur Washer		2
14	Shaft, Extended		1
15	94355A080		1
16	spur finger rot lock shaft		2
17	Worm Washer		1







UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

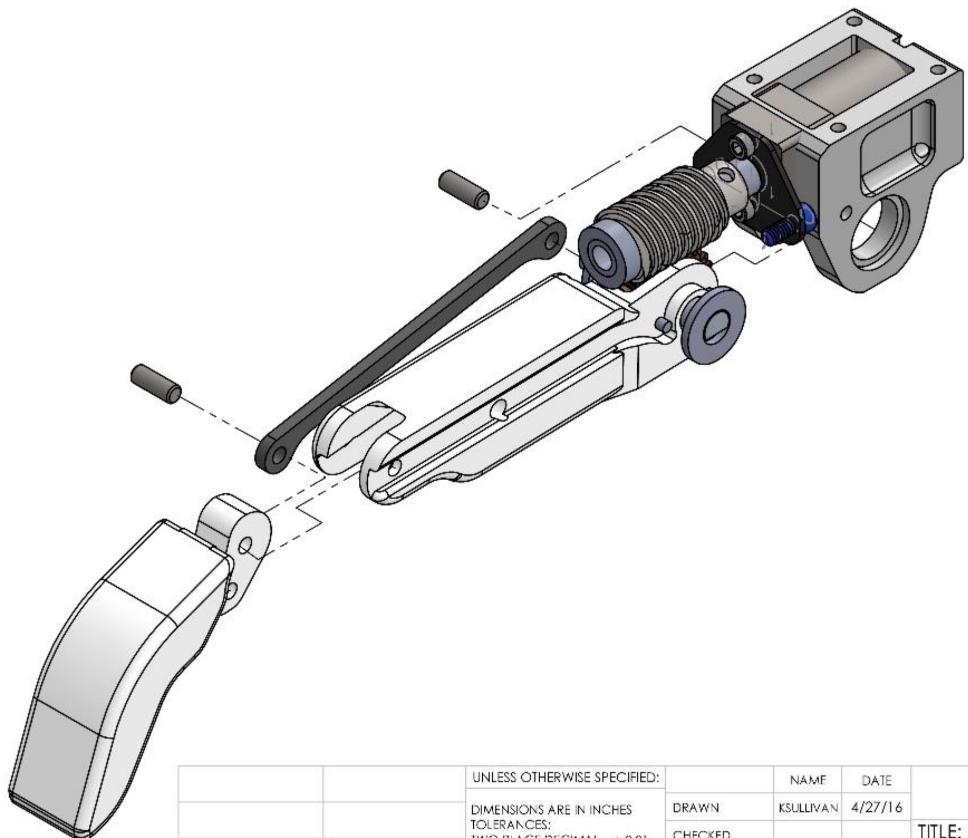
COMMENTS:

TITLE:

FINGER SUB-ASSEMBLY

SIZE **A** DWG. NO. Finger Assembly REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 2



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APPLICATION		

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DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ± 0.01
THREE PLACE DECIMAL ± 0.001

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	KSULLIVAN	4/27/16
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

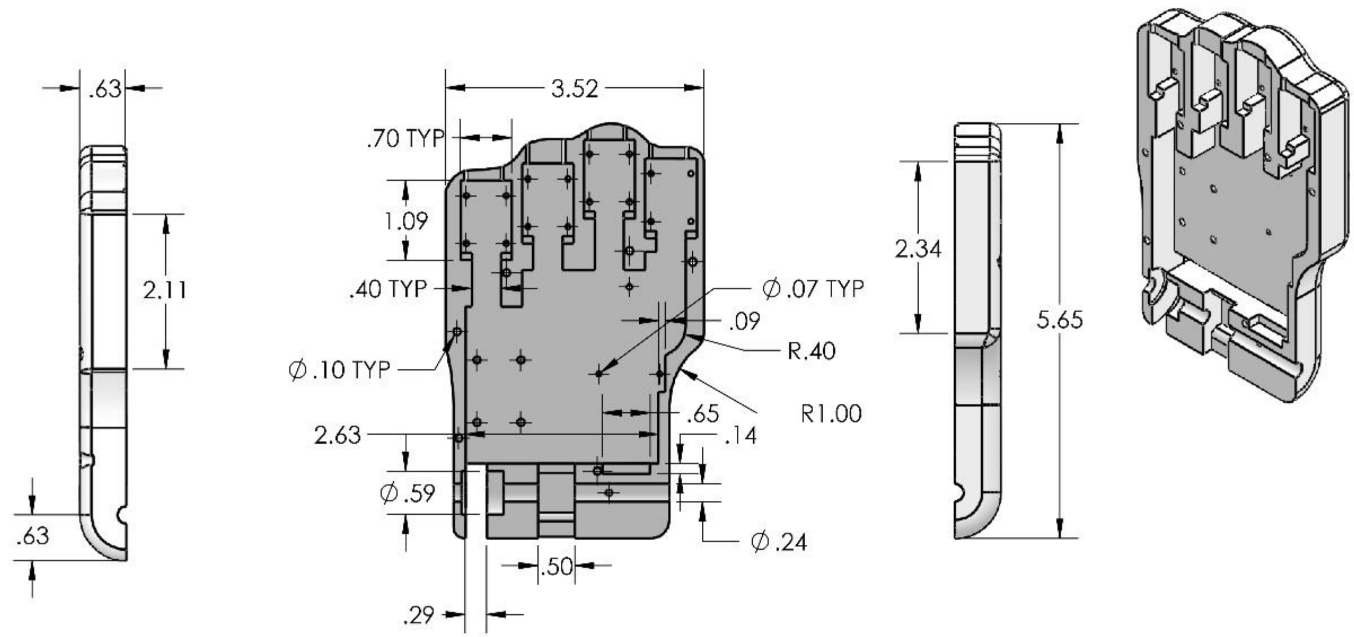
COMMENTS:

TITLE:

FINGER SUB-ASSEMBLY

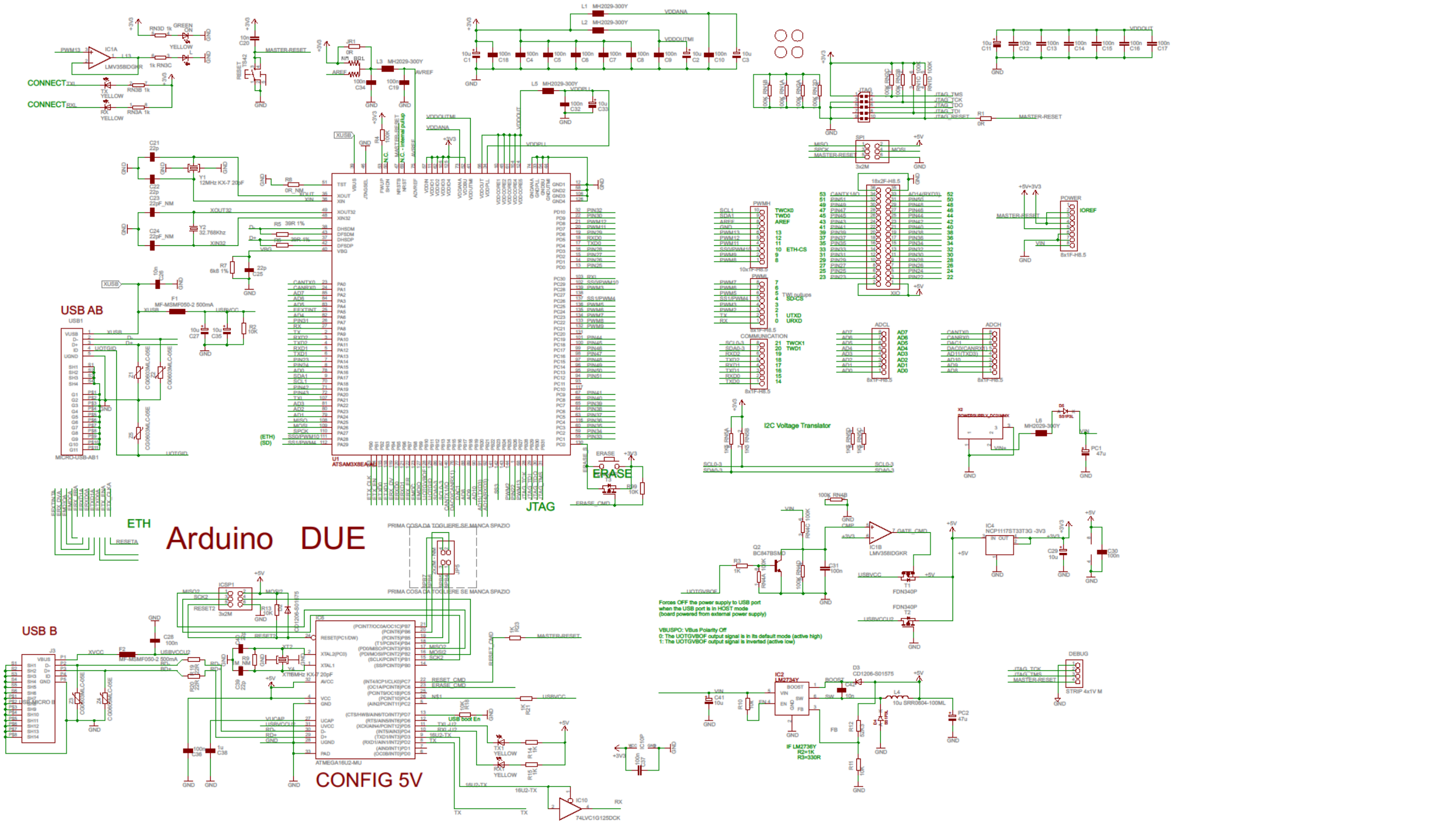
SIZE	DWG. NO.	REV
A	Finger Assembly	

SCALE: 1:2 WEIGHT: SHEET 2 OF 2



UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES TOLERANCES: TWO PLACE DECIMAL ± 0.01 THREE PLACE DECIMAL ± 0.001	DRAWN	KSULLIVAN	4/27/16	TITLE:	
	CHECKED			HAND CASE, BACKHAND	
	ENG APPR.				
	MFG APPR.				
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.				
MATERIAL ABS	COMMENTS:			SIZE A	DWG. NO. Backhand	REV
FINISH					
DO NOT SCALE DRAWING				SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	



Arduino DUE
USB AB
USB B
ETH
JTAG
ERASE
CONFIG 5V
I2C Voltage Translator

1.2 SX1508 8-channel I²C GPIO with LED Driver and Keypad Engine

Pin	Symbol	Type	Description
1	NRESET	DIO	Active low reset
2	SDA	DIO	I²C serial data line
3	SCL	DI	I²C serial clock line
4	ADDR0	DI	Address input bit 0, connect to VDDM or GND
5	I/O[0]	DIO (*1)	I/O[0], at power-on configured as an input LED driver : Intensity control (PWM)
6	I/O[1]	DIO (*1)	I/O[1], at power-on configured as an input LED driver : Intensity control (PWM)
7	VCC1	P	Supply voltage for Bank A I/O[3-0]
8	GND	P	Ground Pin
9	I/O[2]	DIO (*1)	I/O[2], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
10	I/O[3]	DIO (*1)	I/O[3], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
11	NINT	DO	Active low interrupt output
12	ADDR1	DI	Address input bit 1, connect to VDDM or GND
13	OSCIO	DIO	Oscillator input/output, can also be used as GPO
14	VDDM	P	Main supply voltage
15	I/O[4]	DIO (*1)	I/O[4], at power-on configured as an input LED driver : Intensity control (PWM)
16	I/O[5]	DIO (*1)	I/O[5], at power-on configured as an input LED driver : Intensity control (PWM)
17	VCC2	P	Supply voltage for Bank B I/O[7-4]
18	GND	P	Ground Pin
19	I/O[6]	DIO (*1)	I/O[6], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
20	I/O[7]	DIO (*1)	I/O[7], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)

D/I/O/P: Digital/Input/Output/Power
(*1) This pin is programmable through the I²C interface

Table 2 – SX1508 Pin Description

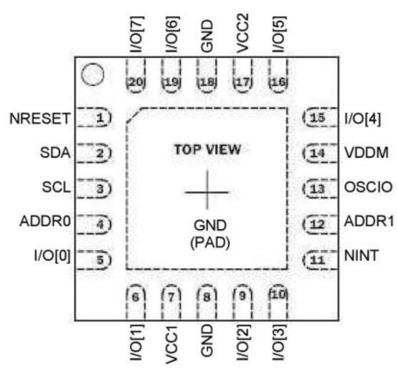


Figure 1 – SX1508 QFN-UT-20 Pinout

1.3 SX1509 16-channel I²C GPIO with LED Driver and Keypad Engine

Pin	Symbol	Type	Description
1	I/O[2]	DIO (*1)	I/O[2], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
2	I/O[3]	DIO (*1)	I/O[3], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
3	GND	P	Ground Pin
4	VCC1	P	Supply voltage for Bank A I/O[7-0]
5	I/O[4]	DIO (*1)	I/O[4], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
6	I/O[5]	DIO (*1)	I/O[5], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
7	I/O[6]	DIO (*1)	I/O[6], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
8	I/O[7]	DIO (*1)	I/O[7], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
9	NINT	DO	Active low interrupt output
10	ADDR1	DI	Address input bit 1, connect to VDDM or GND
11	OSCIO	DO	Oscillator input/output, can also be used as GPO
12	VDDM	P	Main supply voltage
13	I/O[8]	DIO (*1)	I/O[8], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
14	I/O[9]	DIO (*1)	I/O[9], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
15	I/O[10]	DIO (*1)	I/O[10], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
16	I/O[11]	DIO (*1)	I/O[11], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
17	GND	P	Ground Pin
18	VCC2	P	Supply voltage for Bank B I/O[15-8]
19	I/O[12]	DIO (*1)	I/O[12], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
20	I/O[13]	DIO (*1)	I/O[13], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
21	I/O[14]	DIO (*1)	I/O[14], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
22	I/O[15]	DIO (*1)	I/O[15], at power-on configured as an input LED driver : Intensity control (PWM), Blinking, Breathing (Fade In/Out)
23	NRESET	DIO	Active low reset
24	SDA	DIO	I²C serial data line
25	SCL	DI	I²C serial clock line
26	ADDR0	DI	Address input bit 0, connect to VDDM or GND
27	I/O[0]	DIO (*1)	I/O[0], at power-on configured as an input LED driver : Intensity control (PWM), Blinking
28	I/O[1]	DIO (*1)	I/O[1], at power-on configured as an input LED driver : Intensity control (PWM), Blinking

(*1) This pin is programmable through the I²C interface

Table 3 – SX1509 Pin Description

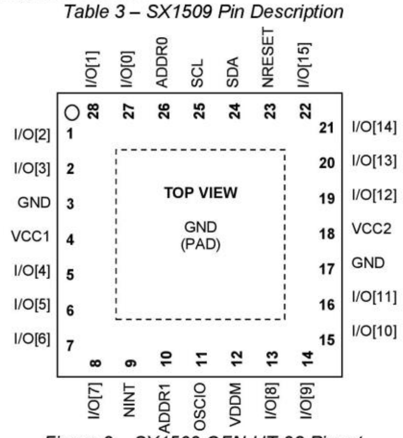


Figure 2 – SX1509 QFN-UT-28 Pinout

2 ELECTRICAL CHARACTERISTICS

2.1 Absolute Maximum Ratings

Table below applies to SX1508 and SX1509. Stress above the limits listed in the following table may cause permanent failure. Exposure to absolute ratings for extended time periods may affect device reliability. The limiting values are in accordance with the Absolute Maximum Rating System (IEC 134). All voltages are referenced to ground (GND).

Symbol	Description	Min	Max	Unit
V_{max_VDDM}	Main supply voltage	- 0.4	3.7	V
V_{max_VCC1-2}	Digital I/O pin supply voltage	- 0.4	3.7	V
V_{ES_HBM}	Electrostatic handling HBM model(1) (SX1508)	-	2000	V
	Electrostatic handling HBM model(1) (SX1509)	-	1500	
V_{ES_CDM}	Electrostatic handling CDM model	-	1000	V
V_{ES_MM}	Electrostatic handling MM model (SX1508)	-	200	V
	Electrostatic handling MM model (SX1509)	-	150	
T_A	Operating ambient temperature range	-40	+85	°C
T_C	Junction temperature range	-40	+125	°C
T_{STG}	Storage temperature range	-55	+150	°C
I_{lat}	Latchup-free input pin current(2)	+/-100	-	mA

(1) Tested according to JESD22-A114A
(2) Static latch-up values are valid at maximum temperature according to JEDEC 78 specification

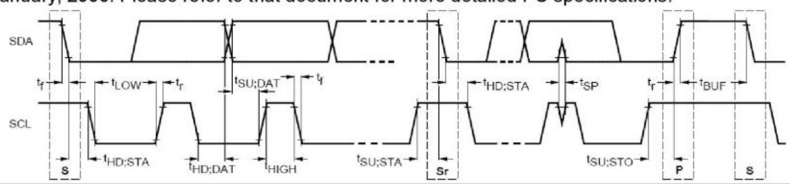
Table 5 - Absolute Maximum Ratings

2.2 Electrical Specifications

Table below applies to SX1508 and SX1509 with default registers values, unless otherwise specified. Typical values are given for T_A = +25°C, VDDM=VCC1=VCC2=3.3V.

Symbol	Description	Conditions	Min	Typ	Max	Unit
Supply						
VDDM	Main supply voltage	-	1.425	-	3.6	V
VCC1,2	I/O banks supply voltage	-	1.2	-	3.6	V
IDDM	Main supply current (SX1508, I^2C inactive)	Internal osc. OFF	-	1	5	µA
		Internal osc. ON (2MHz)	-	175	235	
		External osc. (32kHz)	-	10	-	
	Main supply current (SX1509, I^2C inactive)	Internal osc. OFF	-	1	5	µA
		Internal osc. ON (2MHz)	-	365	460	
		External osc. (32kHz)	-	10	-	
ICC1,2	I/O banks supply current(1)		-	1	2	µA
I/Os set as Input						
VIH	High level input voltage	VCC1,2 >= 2V	0.7* VCC1,2	-	5.5(8)	V
		VCC1,2 < 2V	0.8* VCC1,2	-	5.5(8)	
VIL	Low level input voltage	VCC1,2 >= 2V	-0.4	-	0.3* VCC1,2	V
		VCC1,2 < 2V	-0.4	-	0.2* VCC1,2	
ILEAK	Input leakage current	Assuming no active pull-up/down	-1	-	1	µA
CI	Input capacitance	-	-	-	10	pF
I/Os set as Output						
VOH	High level output voltage	-	VCC1,2 – 0.3	-	VCC1,2	V
VOL	Low level output voltage	-	-0.4	-	0.3	V
IOH	High level output source current	VCC1,2 >= 2V	-	-	8(2)	mA
		VCC1,2 < 2V	-	-	2(2)	
IOL	Low level output sink current	VCC1,2 >= 2V	-	-	15(2)	mA

Symbol	Description	Conditions	Min	Typ	Max	Unit
		VCC1,2 < 2V	-	-	8[(2)]	
t_{PV}	Output data valid timing	Cf. Figure 9	-	-	200	ns
NINT (Output)						
VOL	Low level output voltage	-	-0.4	-	0.3	V
IOL_M	Low level output sink current	VDDM >= 2V	-	-	8	mA
		VDDM < 2V	-	-	4	
t_{IV}	Interrupt valid timing	From input data change	-	-	4	µs
t_{IR}	Interrupt reset timing	From RegInterruptSource clearing	-	-	4	µs
NRESET (Input/Output)						
VOL	Low level output voltage	-	-0.4	-	0.3	V
IOL_M	Low level output sink current	VDDM >= 2V	-	-	8	mA
		VDDM < 2V	-	-	4	
VIH_{MR}	High level input voltage	VCC1,2 >= 2V	0.7* VDDM	-	3.6	V
		VCC1,2 < 2V	0.8* VDDM	-	3.6	
VIL_M	Low level input voltage	VCC1,2 >= 2V	-0.4	-	0.3* VDDM	V
		VCC1,2 < 2V	-0.4	-	0.2* VDDM	
ILEAK	Input leakage current	-	-1	-	1	µA
CI	Input capacitance	-	-	-	10	pF
VPOR	Power-On-Reset voltage	Cf. Figure 7	-	0.8	-	V
VDROPH	High brown-out voltage	Cf. Figure 7	-	VDDM-1	-	V
VDROPL	Low brown-out voltage	Cf. Figure 7	-	0.2	-	V
t_{RESET}	Reset time	Cf. Figure 7	0.6	-	2.5	ms
t_{PULSE}	Reset pulse from host uC	Cf. Figure 7	200	-	-	ns
ADDR0, ADDR1 (Inputs)						
VIH_{MA}	High level input voltage	VCC1,2 >= 2V	0.7* VDDM	-	VDDM +0.3	V
		VCC1,2 < 2V	0.8* VDDM	-	VDDM +0.3	
VIL_M	Low level input voltage	VCC1,2 >= 2V	-0.4	-	0.3* VDDM	V
		VCC1,2 < 2V	-0.4	-	0.2* VDDM	
ILEAK	Input leakage current	-	-1	-	1	µA
CI	Input capacitance	-	-	-	10	pF
OSCIO (Input/Output)						
VIH_{MA}	High level input voltage	VCC1,2 >= 2V	0.7* VDDM	-	VDDM +0.3	V
		VCC1,2 < 2V	0.8* VDDM	-	VDDM +0.3	
VIL_M	Low level input voltage	VCC1,2 >= 2V	-0.4	-	0.3* VDDM	V
		VCC1,2 < 2V	-0.4	-	0.2* VDDM	
ILEAK	Input leakage current	-	-1	-	1	µA
CI	Input capacitance	-	-	-	10	pF
VOH_M	High level output voltage	-	VDDM – 0.3	-	VDDM	V
VOL	Low level output voltage	-	-0.4	-	0.3	V
IOH_M	High level output source current	VDDM >= 2V	-	-	8	mA
		VDDM < 2V	-	-	2	
IOL_M	Low level output sink current	VDDM >= 2V	-	-	8	mA
		VDDM < 2V	-	-	4	
SCL (Input) and SDA (Input/Output) [(3)]						

Symbol	Description	Conditions	Min	Typ	Max	Unit
Interface complies with slave F/S mode I^2C interface as described by Philips I^2C specification version 2.1 dated January, 2000. Please refer to that document for more detailed I^2C specifications.						
						
VOL	Low level output voltage	-	-0.4	-	0.3	V
IOL_M	Low level output sink current	VDDM >= 2V	-	-	8	mA
		VDDM < 2V	-	-	4	
VIH_{MR}	High level input voltage	VCC1,2 >= 2V	0.7* VDDM	-	3.6	V
		VCC1,2 < 2V	0.8* VDDM	-	3.6	
VIL_M	Low level input voltage	VCC1,2 >= 2V	-0.4	-	0.3* VDDM	V
		VCC1,2 < 2V	-0.4	-	0.2* VDDM	
f_{SCL}	SCL clock frequency	-	-	-	400	kHz
$t_{HD;STA}$	Hold time (repeated) START condition	-	0.6	-	-	µs
t_{LOW}	LOW period of the SCL clock	-	1.3	-	-	µs
t_{HIGH}	HIGH period of the SCL clock	-	0.6	-	-	µs
$t_{SU;STA}$	Set-up time for a repeated START condition	-	0.6	-	-	µs
$t_{HD;DAT}$	Data hold time	-	0(4)	-	0.9(5)	µs
$t_{SU;DAT}$	Data set-up time	-	100(6)	-	-	ns
t_r	Rise time of both SDA and SCL	-	$20+0.1C_b$(7)	-	300	ns
t_f	Fall time of both SDA and SCL	-	$20+0.1C_b$(7)	-	300	ns
$t_{SU;STO}$	Set-up time for STOP condition	-	0.6	-	-	µs
t_{BUF}	Bus free time between a STOP and START condition	-	1.3	-	-	µs
C_b	Capacitive load for each bus line	-	-	-	400	pF
V_{nL}	Noise margin at the LOW level for each connected device (including hysteresis)	-	-	0.1* VDDM	-	V
V_{nH}	Noise margin at the HIGH level for each connected device (including hysteresis)	-	-	0.2* VDDM	-	V
t_{SP}	Pulse width of spikes suppressed by the input filter	-	-	-	50	ns
Miscellaneous						
RPULL	Programmable pull-up/down resistors for IO[0-7]	-	-	42	-	kΩ
f_{OSC}	Oscillator frequency	Internal	1.3	2	2.6	MHz
		External from OSCIN	-	-	2.6	

(1) Assuming no load connected to outputs and inputs fixed to VCC1,2 or GND.
(2) Can be increased by tying together and driving simultaneously several I/Os.
(3) All values referred to $VIH_{MR\ min}$ and $VIL_{M\ max}$ levels.
(4) A device must internally provide a hold time of at least 300ns for the SDA signal (referred to $VIH_{MR\ min}$) to bridge the undefined region of the falling edge of SCL.
(5) The maximum $t_{HD;DAT}$ has only to be met if the device does not stretch the LOW period (t_{LOW}) of the SCL signal.
(6) A Fast-mode I^2C-bus device can be used in a Standard-mode I^2C-bus system, but the requirement $t_{SU;DAT} \geq 250$ ns must then be met. This will automatically be the case if the device does not stretch the LOW period of the SCL signal.
If such a device does stretch the LOW period of the SCL signal, it must output the next data bit to the SDA line $t_{r\ max} + t_{SU;DAT} = 1000 + 250 = 1250$ ns (according to the Standard-mode I2C-bus specification) before the SCL line is released.
(7) C_b = total capacitance of one bus line in pF. If mixed with Hs-mode devices, faster fall-times are allowed.
(8) With RegHighInput bit enabled (VCCx min =1.65V), else 3.6V (VCCx min = 1.2V)

Table 6 – Electrical Specifications

Specification

If not stated otherwise, the given values are over lifetime and full performance temperature and voltage ranges, minimum/maximum values are ±3 sigma.

1.1 Electrical specification

Table 0-1: Electrical parameter specification

OPERATING CONDITIONS BNO055						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Supply Voltage (only Sensors)	V_{DD}	--	2.4	--	3.6	V
Supply Voltage (µC and I/O Domain)	V_{DDIO}	--	1.7	--	3.6	V
Voltage Input Low Level (UART, I2C)	V_{DDIO_VIL}	V_{DDIO} = 1.7-2.7V	--	--	0.25	V_{DDIO}
		V_{DDIO} = 2.7-3.6V	--	--	0.3	V_{DDIO}
Voltage Input High Level (UART, I2C)	V_{DDIO_VIH}	V_{DDIO} = 1.7-2.7V	0.7	--	--	V_{DDIO}
		V_{DDIO} = 2.7-3.6V	0.55	--	--	V_{DDIO}
Voltage Output Low Level (UART, I2C)	V_{DDIO_VOL}	V_{DDIO} > 3V , I_{OL} =20mA	--	0.1	0.2	V_{DDIO}
Voltage Output High Level (UART, I2C)	V_{DDIO_VOH}	V_{DDIO} > 3V , I_{OH} =10mA	0.9	0.8	--	V_{DDIO}
POR Voltage threshold on VDDIO-IN rising	V_{DDIO_POT+}	V_{DDIO} falls at 1V/ms or slower	--	1.45	--	V
POR Voltage threshold on VDDIO-IN falling	V_{DDIO_POT-}		--	0.99	--	V
Operating Temperature	T_A	--	-40	--	+85	°C
Total supply current normal mode at T_A (9DOF @100Hz output data rate)	I_{DD} + I_{DDIO}	V_{DD} = 3V, V_{DDIO} = 2.5V	--	--	12.3	mA
Total supply current Low power mode at T_A	I_{DD_LPM}	V_{DD} = 3V, V_{DDIO} = 2.5V	0.33	2.72#		mA
Total supply current suspend mode at T_A	I_{DD_SuM}	V_{DD} = 3V, V_{DDIO} = 2.5V	--	--	0.04	mA

80% suspend mode and 20% normal mode with 9DOF @100Hz output data rate
* using I2C as communication protocol

1.2 Electrical and physical characteristics, measurement performance

Table 0-2: Electrical characteristics BNO055

OPERATING CONDITIONS BNO055						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Start-Up time	T_{Sup}	From Off to configuration mode		400		ms
POR time	T_{POR}	From Reset to Config mode		650		ms
Data Rate	DR	s. Par. Fusion Output data rates				
Data rate tolerance 9DOF @100Hz output data rate (if internal oscillator is used)	DR_{tol}			±1		%

OPERATING CONDITIONS ACCELEROMETER						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Acceleration Range	g_{FS2g}	Selectable via serial digital interface		±2		g
	g_{FS4g}			±4		g
	g_{FS8g}			±8		g
	g_{FS16g}			±16		g

OUTPUT SIGNAL ACCELEROMETER (ACCELEROMETER ONLY MODE)						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Units**
Sensitivity	S	All g_{FSXg} Values, T_A=25°C		1		LSB/mg
Sensitivity tolerance	S_{tol}	Ta=25°C, g_{FS2g}		±1	±4	%
Sensitivity Temperature Drift	TCS	g_{FS2g}, Nominal V_{DD} supplies, Temp operating conditions		±0.03		%/K
Sensitivity Supply Volt. Drift	S_{VDD}	g_{FS2g}, T_A=25°C, $V_{DD\_min} \le V_{DD} \le V_{DD\_max}$		0.065	0.2	%/V
Zero-g Offset (x,y.z)	Off_{xyz}	g_{FS2g}, T_A=25°C, nominal V_{DD} supplies, over life-time	-150	±80	+150	mg
Zero-g Offset Temperature Drift	TCO	g_{FS2g}, Nominal V_{DD} supplies		±1	+/-3.5	mg/K
Zero-g Offset Supply Volt. Drift	Off_{VDD}	g_{FS2g}, T_A=25°C, $V_{DD\_min} \le V_{DD} \le V_{DD\_max}$		1.5	2.5	mg/V
Bandwidth	bw_8	2nd order filter, bandwidth programmable		8		Hz
	bw_{16}			16		Hz
	bw_{31}			31		Hz
	bw_{63}			63		Hz
	bw_{125}			125		Hz
	bw_{250}			250		Hz
	bw_{500}			500		Hz
	bw_{1000}			1,000		Hz

Nonlinearity	NL	best fit straight line, g_{FS2g}		0.5	2	%FS
Output Noise Density	n_{rms}	g_{FS2g}, T_A=25°C Nominal V_{DD} supplies Normal mode		150	190	µg/√Hz

MECHANICAL CHARACTERISTICS ACCELEROMETER

Parameter	Symbol	Condition	Min	Typ	Max	Units
Cross Axis Sensitivity	CAS	relative contribution between any two of the three axes		1	2	%
Alignment Error	E_A	relative to package outline		0.5	2	°

OPERATING CONDITIONS GYROSCOPE

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Rate Range	R_{FS125}	Selectable via serial digital interface		125		°/s
	R_{FS250}			250		°/s
	R_{FS500}			500		°/s
	R_{FS1000}			1,000		°/s
	R_{FS2000}			2,000		°/s

OUTPUT SIGNAL GYROSCOPE (GYRO ONLY MODE)

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Sensitivity via register Map	S	Ta=25°C		16.0 900		LSB/°/s rad/s
Sensitivity tolerance	S_{tol}	Ta=25°C, R_{FS2000}	--	±1	±3	%
Sensitivity Change over Temperature	TCS	Nominal V_{DD} supplies -40°C ≤ T_A ≤ +85°C R_{FS2000}		±0.03	±0.07	%/K
Sensitivity Supply Volt. Drift	S_{VDD}	T_A=25°C, V_{DD_min} ≤ V_{DD} ≤ V_{DD_max}		<0.4		%/V
Nonlinearity	NL	best fit straight line R_{FS1000}, R_{FS2000}		±0.05	±0.2	%FS
Zero-rate Offset	Off Ω_x Ω_y and Ω_z	Nominal V_{DD} supplies T_A=25°C, Slow and fast offset cancellation off	-3	±1	+3	°/s
Zero-Ω Offset Change over Temperature	TCO	Nominal V_{DD} supplies -40°C ≤ T_A ≤ +85°C R_{FS2000}		±0.015	±0.03	°/s per K
Zero-Ω Offset Supply Volt. Drift	OffΩ_{VDD}	T_A=25°C, V_{DD_min} ≤ V_{DD} ≤ V_{DD_max}		0.1		°/s/V
Output Noise	n_{rms}	rms, BW=47Hz (@ 0.014°/s/√Hz)		0.1	0.3	°/s

Parameter	Symbol	Condition	Min	Typ	Max	Units
Bandwidth BW	f_{-3dB}			523 230 116 64 47 32 23 12		Hz
MECHANICAL CHARACTERISTICS GYROSCOPE						
Cross Axis Sensitivity	CAS	Sensitivity to stimuli in non-sense-direction		±1	±3	%

OPERATING CONDITIONS MAGNETOMETER (MAGNETOMETER ONLY MODE)

Parameter	Symbol	Condition	Min	Typ	Max	Units
Magnetic field range[1]	Brg,xy	TA=25°C	±1200	±1300		µT
	Brg,z		±2000	±2500		µT
Magnetometer heading accuracy[2]	As heading	30µT horizontal geomagnetic field component, TA=25°C			±2.5	deg

MAGNETOMETER OUTPUT SIGNAL

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Device Resolution	$D_{res,m}$	T_A=25°C		0.3		µT
Gain error[3]	$G_{err,m}$	After API compensation T_A=25°C Nominal V_{DD} supplies		±5	±8	%
Sensitivity Temperature Drift	TCS_m	After API compensation -40°C ≤ T_A ≤ +85°C Nominal V_{DD} supplies		±0.01	±0.03	%/K
Zero-B offset	OFF_m	T_A=25°C		±40		µT
Zero-B offset[4]	$OFF_{m,cal}$	After calibration in fusion mode -40°C ≤ T_A ≤ +85°C		±2		µT
Zero-B offset Temperature Drift	TCO_m	-40°C ≤ T_A ≤ +85°C		±0.23	±0.37	µT/K
Full-scale Nonlinearity	$NL_{m, FS}$	best fit straight line			1	%FS

[1] Full linear measurement range considering sensor offsets.
[2] The heading accuracy depends on hardware and software. A fully calibrated sensor and ideal tilt compensation are assumed.
[3] Definition: *gain error = ((measured field after API compensation) / (applied field))* – 1
[4] Magnetic zero-B offset assuming calibration in fusion mode. Typical value after applying calibration movements containing various device orientations (typical device usage).

Output Noise	$n_{rms,lp,m,xy}$	Low power preset x, y-axis, T_A=25°C Nominal V_{DD} supplies		1.0		µT
	$n_{rms,lp,m,z}$	Low power preset z-axis, T_A=25°C Nominal V_{DD} supplies		1.4		µT
	$n_{rms,rg,m}$	Regular preset T_A=25°C Nominal V_{DD} supplies		0.6		µT
	$n_{rms,eh,m}$	Enhanced regular preset T_A=25°C Nominal V_{DD} supplies		0.5		µT
	$n_{rms,ha,m}$	High accuracy preset T_A=25°C Nominal V_{DD} supplies		0.3		µT
Power Supply Rejection Rate	$PSRR_m$	T_A=25°C Nominal V_{DD} supplies		±0.5		µT/V

2. **Absolute Maximum Ratings**

Table 2-1: Absolute maximum ratings (preliminary target values)

Parameter	Symbol	Condition	Min	Max	Units
Voltage at Supply Pin	V_{DD} Pin		-0.3	4.2	V
	V_{DDIO} Pin		-0.3	3.6	V
Voltage at any Logic Pin	$V_{non\text{-}supply}$ Pin		-0.3	V_{DDIO}+ 0.3	V
Passive Storage Temp. Range	Trps	≤ 65% rel. H.	-50	+150	°C
Mechanical Shock	$MechShock_{200\mu s}$	Duration ≤ 200µs		10,000	g
	$MechShock_{1ms}$	Duration ≤ 1.0ms		2,000	g
	$MechShock_{freefall}$	Free fall onto hard surfaces		1.8	m
ESD	ESD_{HBM}	HBM, at any Pin		2	kV
	ESD_{CDM}	CDM		400	V
	ESD_{MM}	MM		200	V

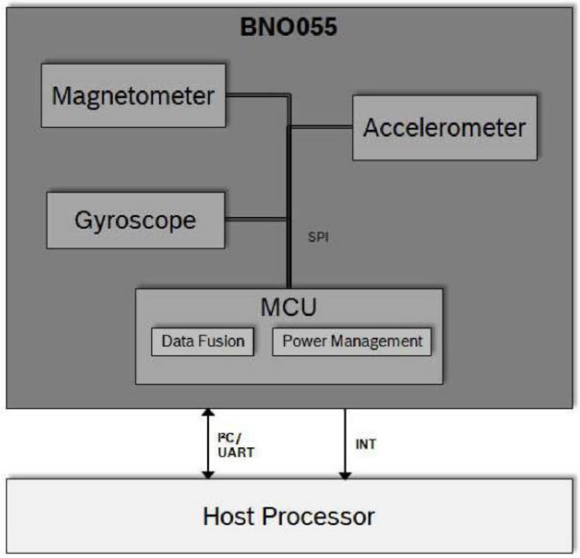
Note:
Stress above these limits may cause damage to the device. Exceeding the specified electrical limits may affect the device reliability or cause malfunction.

3. **Functional Description**

3.1 Architecture

The following figure shows the basic building blocks of the BNO055 device.

Figure 1: system architecture



3.2 Power management

The BNO055 has two distinct power supply pins:

- V_{DD} is the main power supply for the internal sensors
- V_{DDIO} is a separate power supply pin used for the supply of the µC and the digital interfaces

For the switching sequence of power supply V_{DD} and V_{DDIO} it is mandatory that V_{DD} is powered on and driven to the specified level before or at the same time as V_{DDIO} is powered ON. Otherwise there are no limitations on the voltage levels of both pins relative to each other, as long as they are used within the specified operating range.

The sensor features a power-on reset (POR), initializing the register map with the default values and starting in CONFIG mode. The POR is executed at every power on and can also be triggered either by applying a low signal to the nRESET pin for at least 20ns or by setting the RST_SYS bit in the SYS_TRIGGER register.

The BNO055 can be configured to run in one of the following power modes: normal mode, low power mode, and suspend mode. These power modes are described in more detail in section Power Modes

1 Overview

This datasheet is applicable to the final VL6180X ROM code revision.

1.1 Technical specification

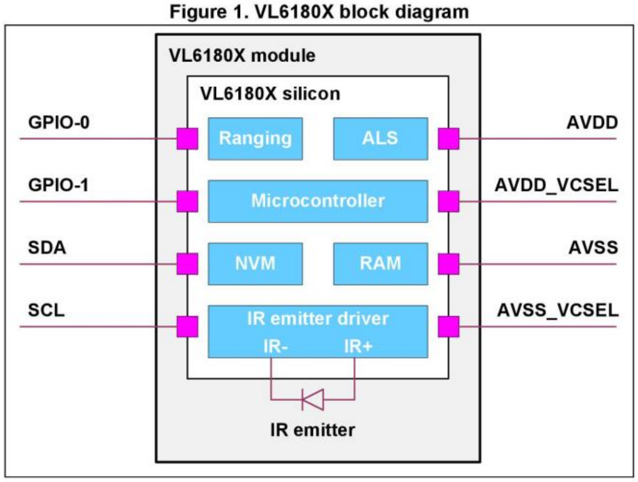
Table 1. Technical specification

Feature	Detail
Package	Optical LGA12
Size	4.8 x 2.8 x 1.0 mm
Ranging	0 to 100 mm(1)
Ambient light sensor	< 1 Lux up to 100 kLux(2) 16-bit output(3) 8 manual gain settings
Operating voltage: • Functional range • Optimum range(4)	 2.6 to 3.0 V 2.7 to 2.9 V
Operating temperature: • Functional range • Optimum range(4)	 -20 to 70°C -10 to 60°C
Typical power consumption	Hardware standby (GPIO0 = 0): < 1 µA Software standby: < 1 µA ALS: 300 µA Ranging: 1.7 mA (typical average)(5)
IR emitter	850 nm
I^2C	400 kHz serial bus Address: 0x29 (7-bit)

1. Ranging beyond 100 mm is possible with certain target reflectances and ambient conditions but not guaranteed
2. When used under a cover glass with 10% transmission in the visible spectrum
3. Digital output easily converted to Lux
4. Please refer to *Table 19.: Ranging specification*
5. Assumes 10 Hz sampling rate, 17% reflective target at 50 mm

1.2 System block diagram

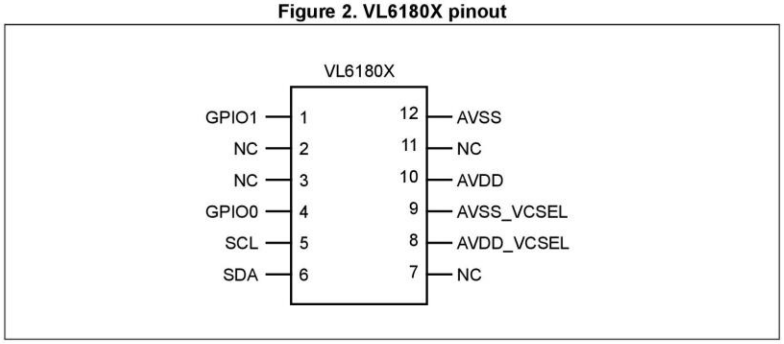
Figure 1. VL6180X block diagram



1.3 Device pinout

Figure 2 shows the pinout of the VL6180X.

Figure 2. VL6180X pinout



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Abstract	Both
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Design and Specifications: Design	Kathleen Sullivan
Performance and Evaluation: Finger and Electronics	Max Merlin
Performance and Evaluation: Palm	Kathleen Sullivan
Performance and Evaluation: Overall Evaluation	Both
Recommendations	Both
Appendices	Both