THE DESIGN AND DEVELOPMENT OF A TELEOPERATED ANTHROPOMORPHIC HAND

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Declaration

"The project submitted herewith is a result of my own investigations. All information that has been obtained from other sources had been fully acknowledged. I understand that plagiarism constitutes a breach of University College rules and regulations and would be subjected to disciplinary actions"

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Abstract

The aim of this project is to design, develop and test an animatronic hand and wrist capable of mimicking human hand movements through a teleoperation system where the operator hand is the master manipulator and the animatronic hand is the slave manipulator. This is done by incorporating mechanical designs and underactuation methods based on the musculoskeletal system of the human hand to produce a 16 DoF robotic hand. The operator wears a sensory glove and wrist exoskeleton that tracks the joint movement of the user hand and wrist and translate that motion to the actuators within the animatronic hand. Evaluation of the teleoperation system and the animatronic hand is done through experimental tasks to check the hand gripping capabilities as well as the range and accuracy of motion. Such a method of remotely controlled anthropomorphic hand is not widely used and therefore this research aims to evaluate the preformance of such system while providing informative sensory and motion data for future works.

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Chapter 1 Introduction

1.1 Research Background

The field of animatronics refers to the animation of animal puppets or human characters through the means of electromechanical devices (Animatronic, 2022). Animatronic is a multidisciplinary field that involves anatomy and mechatronics as means of automation implemented through computer or human control such as teleoperation.

Anthropomorphic robots are a subset of animatronics as it relates to the robot being strictly similar to humans in nature. Humanoid robots are designed to resemble the human body by having a torso, head, two arms and two legs and then mimicking human form and movement. Anthropomorphic robots can also only focus on certain human body parts such as arms or hands and takes inspiration from the musculoskeletal system of humans to design robotic parts capable of flexible human-like motion (Tada and Kouchi, 2018). This line of robotics is helpful to preform industrial tasks such as welding and automated assembly, and as well as have usage with those missing body parts as form of prosthetic limbs.

Degree-of-Freedom (DOF) in robotics refers to the number of directions a robotic body can move in within a space and is often correlated with the number of joints the robot have (i.e.,3 movable joints translate to 3 axis and 3 DOF) (MCR, 2022). The human arm along with the shoulder, elbow and wrist joints has 9 DOF while there is a total of 21 DOF for the fingers alone. For a robotic arm with 5 to 7 DOF, the shoulder motion can be that of pitch (up and down) or yaw (left and right) or roll (rotation); elbow motion occur as pitch only; wrist motion can be pitch or yaw or rotary (WhatIs,2022). These joints and their DOF work together to position the hand, which is the end effector, to the desired location.

Teleoperation system is the remote control of a robot from a distance through a human operator regardless of level of robot autonomy (Durlach and Mavor, 1995). Telerobotic focuses on the control of semi-autonomous robots from a distance using tethered connections or using a wireless network. The usage of telerobotics allows for deployment and control of robots in dangerous, limiting or unfavourable environments and situations. For example, telerobotics allow for deep water exploration and surveying; space assembly and maintenance; for medical aid for the disabled; and for industrial machinery (Durlach and Mavor, 1995).

Current research is being conducted to develop remotely controlled assistive limbs with detailed anthropomorphic characteristics for usage in android and teleoperations due to their dexterity, precision and accurate motion planning capabilities (ISAT, 2017). By combining the fields of human anatomy, robotics, anthropomorphy and teleoperation, a remotely controlled animatronic hand capable of mimicking the human hand in real time within specified DOF can be designed and developed.

1.2 Problem Statement

Currently available teleoperated animatronic hands are complex as the sensory-motor connection needs to be filtered from kinematic and kinetic redundancies (Buzzi et al, 2017). Additionally, these animatronics hands are often limited to industrialised and research settings in which high precision movement and operator feedback is desired at the expense of higher costs. Therefore, there is a need for commercially teleoperated animatronics hands for the aid of disabled or other small-scale operations capable of mimicking the human hand movements with precision, reliably and repeatedly.

1.3 Research Objective

1. To design and develop of the animatronic hand using 3D modeling software and producing a physical prototype.
2. To design a sensory control glove used for capturing the finger, hand and wrist motion data to be mimicked by the animatronic hand.
3. To test and evaluate the performance of the animatronic hands in regards to hand gripping configurations, response speed and control accuracy.

1.4 Research Scope

The initial point of the research scope is the fabrication of the animatronic/anthropomorphic fingers and wrist in a proper compact module and configuration to accommodate the connectors and actuators. Following the fabrication of the animatronic hand, is the fabrication of the sensory control glove and implementation of data acquisition through housing flex sensors and potentiometers in the glove to collect changes in the position of the human fingers. Then a teleoperation control system is implemented to allow communication between the glove and the animatronic hand. Finally, a thorough evaluation is made on the animatronic hand and its control system to obtain quantitative evaluation in regards to range of motion and response speed, and qualitative evaluation in regards to grasping capability.

1.5 Contribution and Significance

The significance of this research is to allow for human operators to control a multi-degree of freedom animatronic hand that can then be used in various applications in which mimicry of human motion is needed such as androids, medical re-habitation and surgery, and for end-effector of exploration robots. The usage of low-cost material and 3D printing processes to fabricate the animatronic hand and its component would allow for wider commercial usage of the robotic hand. Furthermore, the research would contribute to providing data regarding the teleoperation system and measure its effectiveness to drive the animatronic hand.

Chapter 2 Literature Review

2.1 Introduction

The human arm is a flexible organ capable of a wide range of motion contributed by the shoulder, upper arm, elbow, forearm, wrist and finally the hands. These numerous degrees of motion, as shown in Figure 2-1, are difficult to map and therefore has been simplified into the seven principal degrees of freedom displayed by Figure 2-2 (Fleming, 2022). These seven principle DOF are used by articulated robots to move in the same capacity as human arm. The movements are summarised as follows:

1. Shoulder - Up and Down (Pitch)
2. Shoulder - Left and Right (Yaw)
3. Shoulder - Rotation (Roll)
4. Elbow - Up and Down (Pitch)
5. Wrist - Up and Down (Pitch)
6. Wrist - Left and Right (Yaw)
7. Wrist - Rotation (Roll)

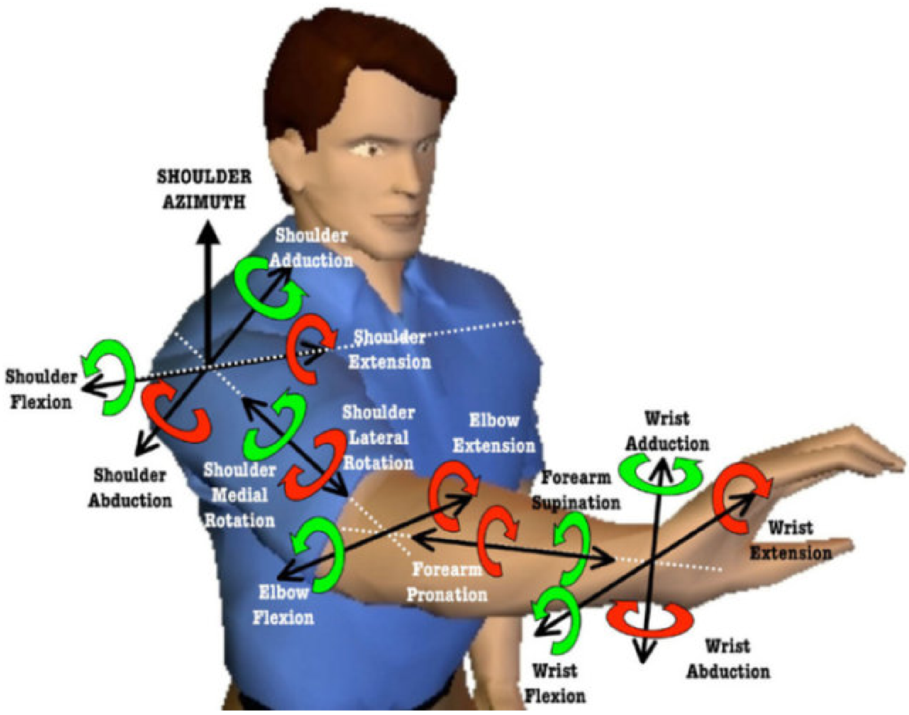


Figure 2-1 Multiple DOF of the Human arm (Wang et al, 2018)

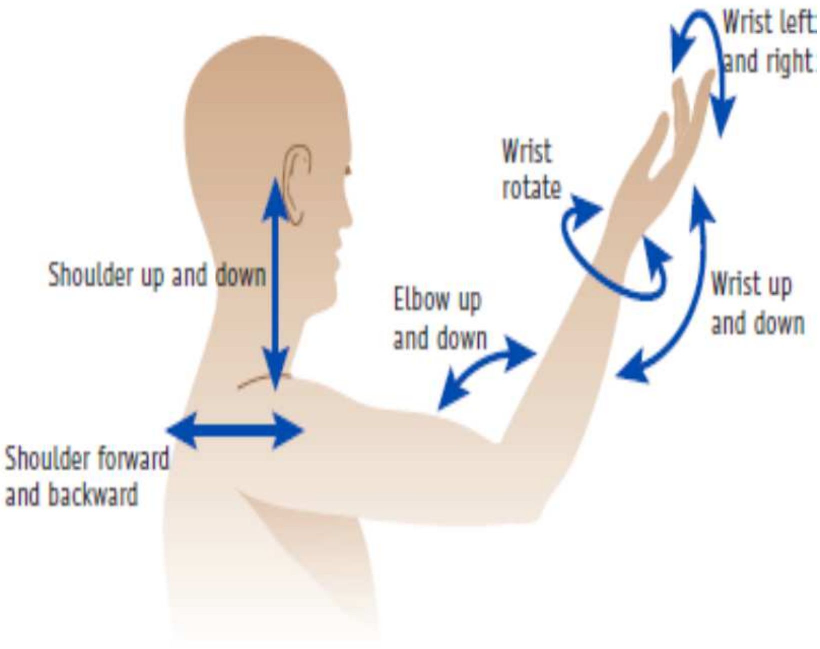


Figure 2-2 Summaries DOF of human arm (Fleming, 2022)

2.2 Concept and Theory

2.2.1 Human Hand Anatomy

2.2.1.1 Fingers

As the human arm is complex in nature, in this research project the focus would only be around the wrist motion as well as the fingers grasping and manipulation capabilities. As was previously mentioned, the human wrist can exhibit 3 DOF in order to position the end-effect, the hand, within the desired space. The human hand and fingers are then capable of multiple arrays of gripping configurations as it consists of 21 DOF (Rahman and Al-Jumaily, 2013). This level of dexterity and manipulation is due to the construct of the hand and fingers.

The human thumb consists of three joints: the interphalangeal (IP), the MCP, and the CMC joint, as shown in Figure 2-3 (Xe, 2018). The CMC joint is a compound joint with two of its nonorthogonal axes being located at different bones, thus its is more drastically offset from the other fingers. As for the other fingers, the distal interphalangeal (DIP) joint is between the distal phalanxes and the middle phalanxes; the proximal interphalangeal (PIP) joint is between the middle phalanxes and the proximal phalanxes; and the MCP joint is between the proximal phalanxes and the metacarpal bones (Xe, 2018). These joints are responsible for giving the human hand such a high level of dexterity, manipulation and grasping.

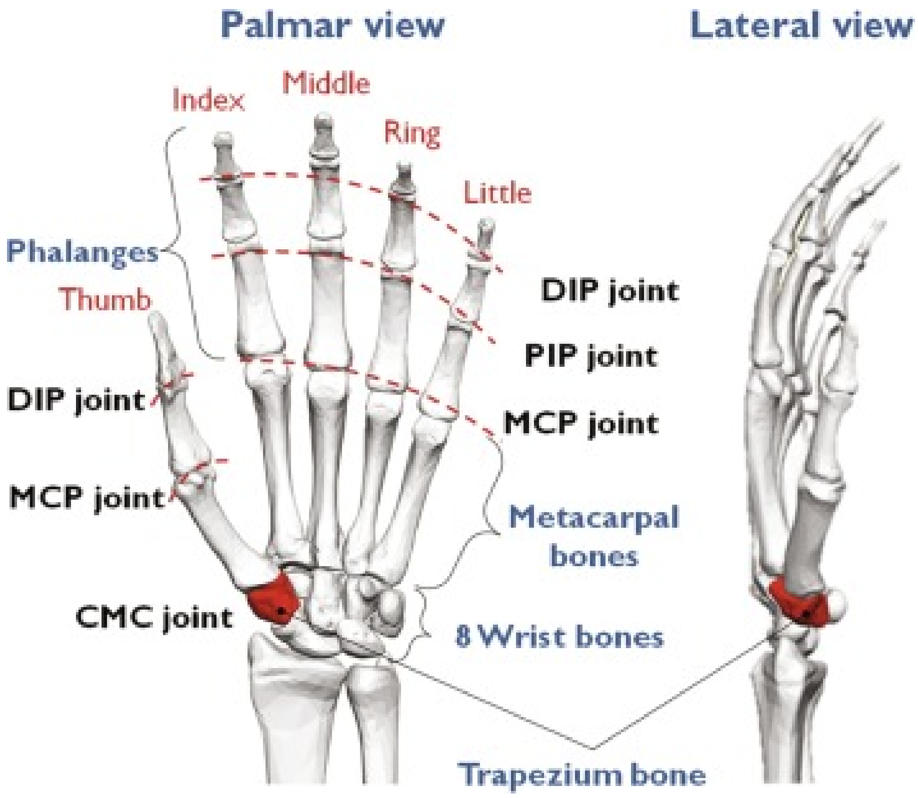


Figure 2-3 Joints and kinematic model of human hand (Xe, 2018)

2.2.1.2 Wrists

The human wrist is a deformable anatomic entity which connects the hand to the forearm and is made up of a collection of eight carpal bones, as seen as well in Figure 2-3, which are then surrounded by soft tissue. There are several joints that make up the wrist which include the radiocarpal joint, several intercarpal joints and five carpometacarpal joints (Gopura and Kiguchi, 2007). These joints work together to provide the wrist with 2 DOF, namely flexion/extension (pitch) and ulnar/radial deviation (yaw) as shown in Figure 2-4. Flexion range of motion is bending of the wrist to make the palm approach the anterior surface of the forearm, while the reverse movement is extension. As for radial deviation, it is the movement of the wrist to the thumb side while the reverse movement is ulnar deviation (Gopura and Kiguchi, 2007). These wrist movements are made around an instantaneous centre connected to the forearm that would provide rotary motion.

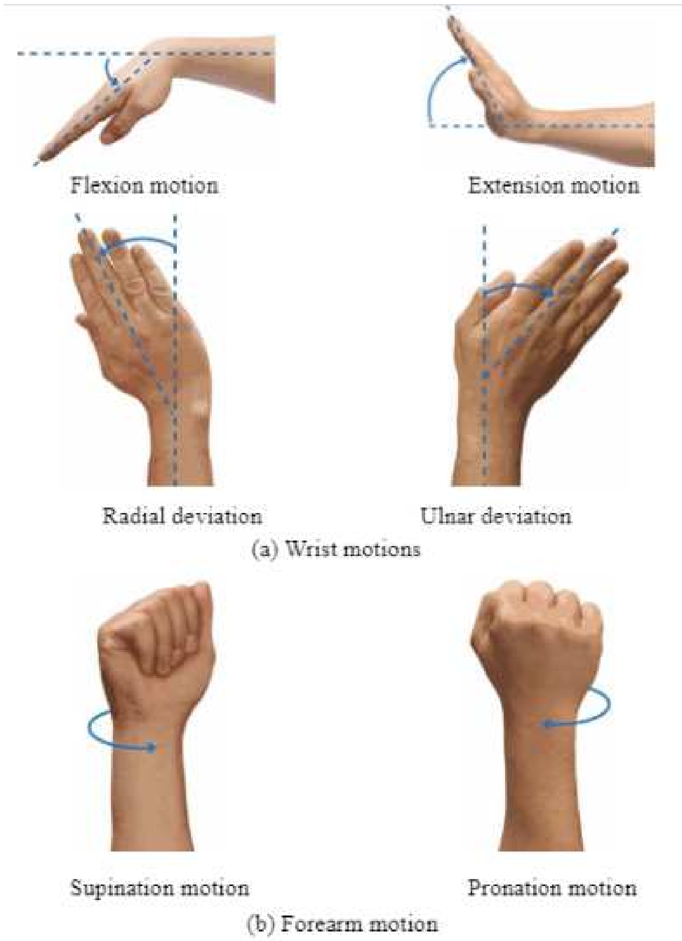


Figure 2-4 Wrist and forearm motions (Gopura and Kiguchi, 2007)

2.2.2 Mechanics of Human Hand

As the bones and joints form the skeletal structure of the human hand, tendons wind along the finger bones in intricate path and finally connect to one or more muscles. The muscles are controlled by electrical impulses from the brain that travel along the nervous system. This anatomical arrangement, shown in Figure 2-5, in which muscles and tendon move bones is known as the musculoskeletal system which is the primary system to move the human body accordingly (Pugliesi, 2018). Understanding the working principle of the human hand mechanics is crucial for replicating it through mechanical and electronic means.

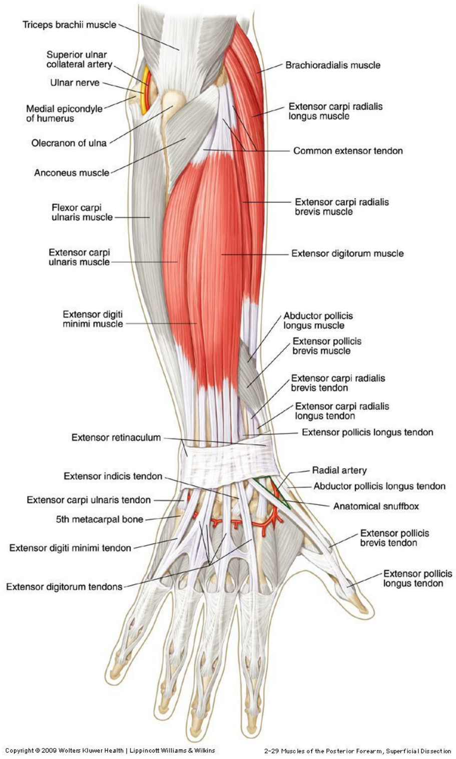


Figure 2-5 Musculoskeletal system of the human hand (HMT, 2022)

2.2.3 Complexity of Human Hand Replication & Muscle Redundancy

Among the main challenges in implementing the musculoskeletal system into robotic arm is the concern of “muscle redundancy”. Muscle redundancy refers to the phenomenon in which humans have many more muscles that would seem unnecessary to adequately move their limbs (Pugliesi, 2018). This can be noticed when some muscles appear to be redundant because they are attached to the same tendons as other muscles. The phenomenon poses an issue as it makes it more difficult to construct dexterous torque-driven animatronic hands. A breakthrough to tackle muscle redundancy was demonstrated by Dr. Zhe Xu (2016) by creating a tendon-driven anthropomorphic hand that mimic the motion of a human operator wearing a sensory glove as can be seen in Figure 2-6. Although the animatronic hand is tendon-driven it does not utilise a large number of actuators (or ’muscles’) compared to the human hand. Although the robotic hand does mimic a large array of human hand configurations it is still remains questionable whether it can mimic the full dexterity of a human hand without accurately replicating the arrangement of many muscles found in the human arm (Pugliesi, 2018).

Figure 2-6 Tendon-driven robotic hand (Xu, 2016).

2.2.3.1 Underactuated Animatronic Hand

Attention to this issue was made as to define the dexterity limit of the animatronic hand developed within this research. Over the last decade, research has been conducted to design simple but effective finger mechanisms. Underactuation is the process of reducing the degrees-of-actuator (DOAs) while maintaining the degrees-of-freedom through passive elements such as springs (Yoon and Choi,2017). This procedure would allow for construction of robotic fingers using 2 or less actuators while maintaining a certain level dexterity and manipulation. The aim of this project is not to produce a highly dexterous animatronic hand, but rather one that is capable of basic hand manipulation and configuration with added degree of motion provided by the wrist. To aid in this aim, research was conducted into means to improve the functionality of the anthropomorphic hand using limited number of actuators.

Xiong et al (2016) developed and designed a method of underactuated anthropomorphic hands to ensure reliable adaption to differently grasped objects which can be seen in Figure 2-8. They conducted an analysis method to investigate the evolution of motion in the whole underactuated grasping process as demonstrated in Figure 2-7. Then based on the evolution of motion and force, the underactuated grasping process is decomposed into four aspects which are initial contact state; grasp terminal state; grasp trajectory; and rate of progress (Xiong et al, 2016).

Moreover, based on the four aspects of the underactuated grasping process, a step-wise parameter design method was presented to achieve reliable adaptive grasp.

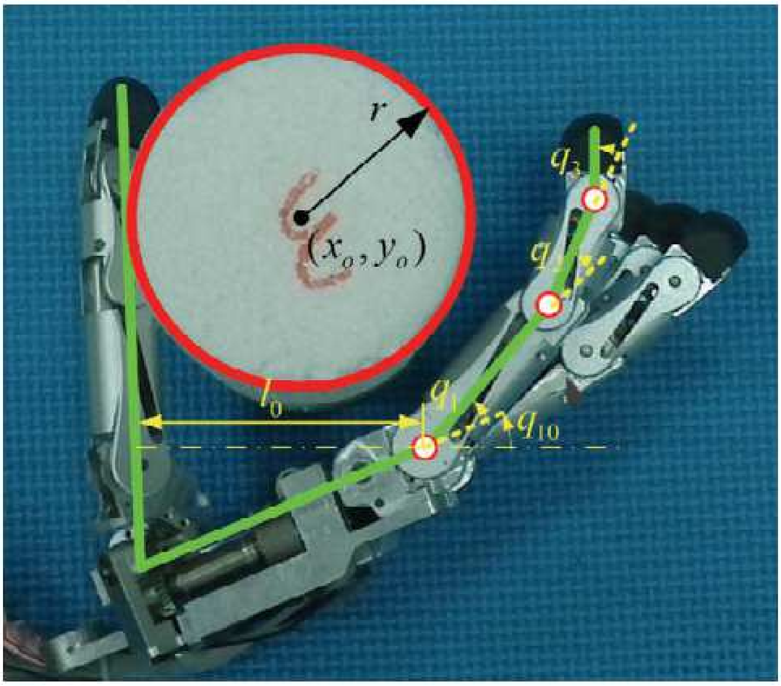


Figure 2-7 The grasping scenario of an underactuated animatronic hand (Xiong et al, 2016)

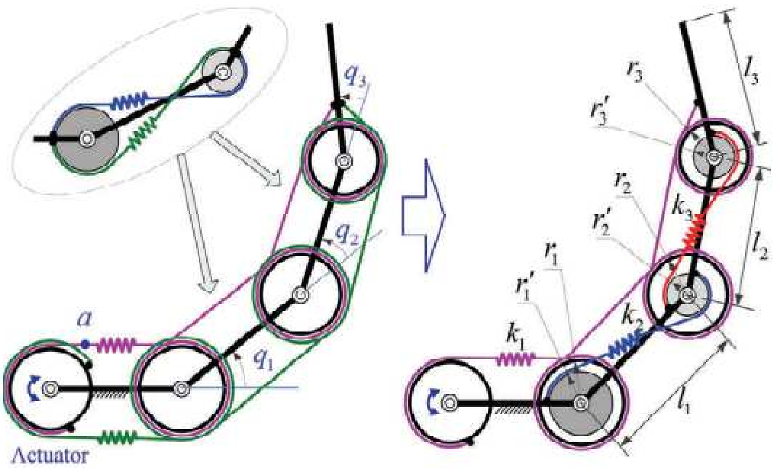


Figure 2-8 Finger of the animatronic underactuated hand (Xiong et al, 2016)

Furthermore, Tavakoli et al (2015) managed to examine the number of actuators for underactuated prosthetic hands to define 16 possible actuation strategies divided in five categories based on number of actuators ranging from one to five. The 16 actuation strategies then underwent two types of analyses which are grasp diversity analysis and grasp functionality analysis, in order to assess their level of preformance (Tavakoli et al., 2015). Their study allows for designing a prosthetic terminal; for deciding the number of actuator ; and how to allocate the available actuators to the DOF of the hand in order to get the best performance with minimum number of actuators (Tavakoli et al., 2015).

The work in regards to underactuated finger mechanism done by Yoon and Choi (2017) resulted into production of a finger capable of both self-adaptive grasping and natural motions such as flexion and extension. The design of the robotic finger consist of stackable four-bar linkages along with contractible slider-cranks having spring in each mechanism layer which resulted into a three degree-of-freedom mechanism. Design feasibility was conducted through simulations and experiments as to resolve and analyse the kinematics and static forces. Figure 2-9 shows the concept of stackable four-bar linkages mechanism: (a) and (b) the human-like flexion sequence ; (c) its main drawback that it can no longer move while in contact with the object; and (d) the self-adaptive grasping presented by Yoon and Choi. .

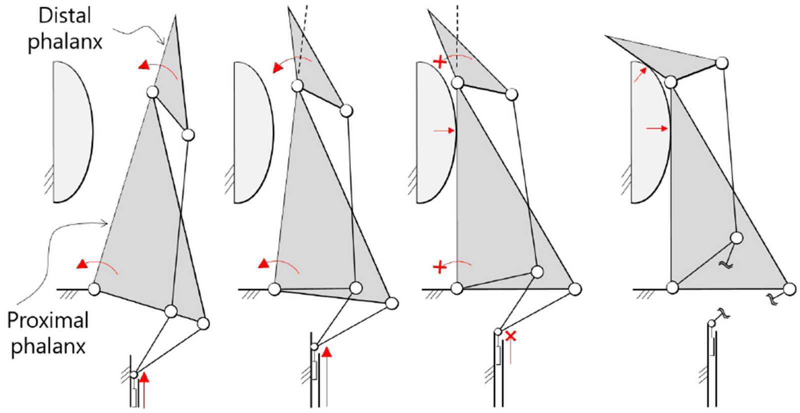


Figure 2-9 Basic concept of the stackable four-bar linkages mechanics. (Yoon and Choi, 2017)

Figure 2-10 shows the physical prototype created by Yoon and Choi for the robotic finger firstly as a 3D-CAD model with cross-section view to showcase the linear spring and brush housing. The shaft and bush in their housings are fixed by an E-type snap ring. The bush housing has a space for the shaft to linearly move, and its movement is limited by the E-type snap ring. The linear spring is installed between both housings.Yoon and Choi utilised the linear actuator PQ-12 from Firgelli Technologies to drive the finger linkages as it provided a stroke of 20mm. As for Figure 2-11, the 3D printed robotic finger was tested using static object poles to confirm the self-adaptive grasping motion. The object poles were fixed to arbitrary sites in a testbed wall, and then they were grasped by the phalanges. The linear actuator is actuated until the distal phalanx makes contact. Yoon and Choi work provided insight in regards to achieving a human-like robotic finger capable of self-adaptability and using a singular actuator without compromise on the DoF.

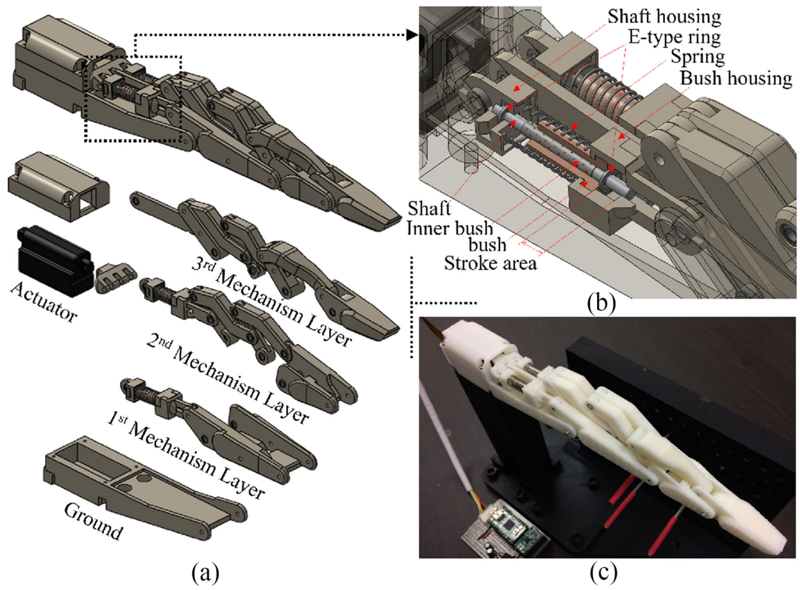


Figure 2-10 CAD 3D model of the finger prototype. (Yoon and Choi, 2017)

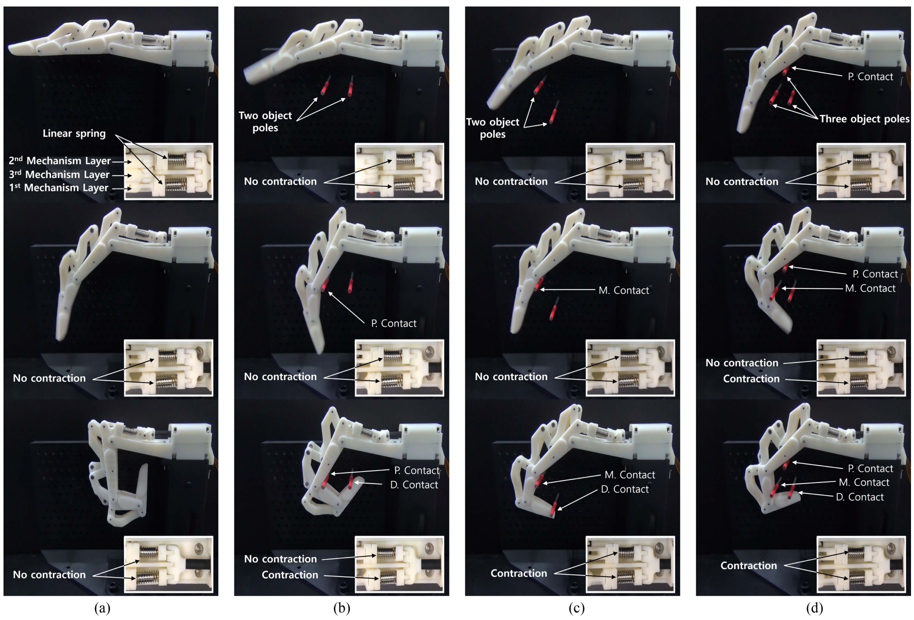


Figure 2-11 Human-like natural motion and self-adaptive grasping motions. (Yoon and Choi, 2017)

2.2.4 Anthropomorphic Hands

The development of anthropomorphic (i.e animatronic) hands consists of 2 major components. First are the fingers responsible for majority of the grasping capabilities and second component are the wrists that allows the entire hand to move in 2 DOF as previously mentioned in Section 2.2.1. Implementation of both these components would result in a versatile animatronic hand that can then mimic the movement of the fingers and wrists of the operator. The anthropomorphic hand design can consist of three major features, albeit only few animatronic hands possess all the three features (Xiong et al., 2021):

1. Anthropomorphic grasp functions - The primary factor of the hand is to be endowed with abundant grasping functions with reference to Feix Taxonomy that covers daily grasping activities (Feix, 2008).

2. Fewer actuators - The increase of actuators in an animatronic hand causes the increase in the difficulty of control whether by an autonomous system or human-machine interface system. Few actuators are embedded to avoid complexity of controlling the animatronic hand.

3. Compact structure - A compact architecture housing the integrated hardware and mechanisms that allows for flexible installation is often welcomed by users.

Research was conducted on various kinematic models of anthropomorphic hands and fingers in order to obtained robotic hands similar to those of humans. Özgür and Mezouar (2016) developed the kinematic modeling for an anthropomorphic hand using unit dual quaternion. The hand consisted of fingers coupled with joints similar to humans for forward and inverse kinematics computation. Figures 2-12 and 2-13 show the mechanical structure of the index finger that was developed along with the defined axes and frames. Furthermore, a strategy for relative pose control between the finger tips and thumb was developed (Özgür and Mezouar, 2016). Utilising geometrical analysis, the developed kinematic model would be easily integrated with the kinematics of a robotic hand to make use of the added redundancy by under actuating the hand. The kinematic model obtained was then implemented on an anthropomorphic hand for validation.

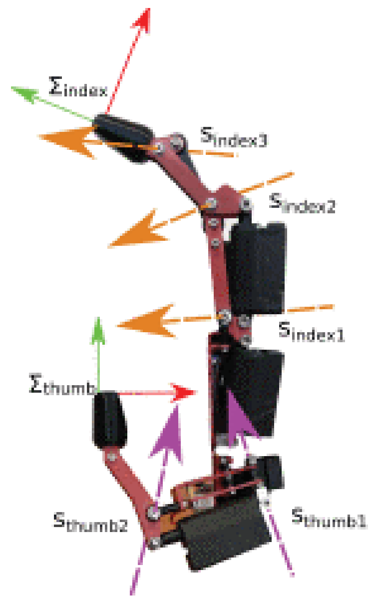


Figure 2-12 Index finger and thumb with corresponding axes and frames (Özgür and Mezouar, 2016).

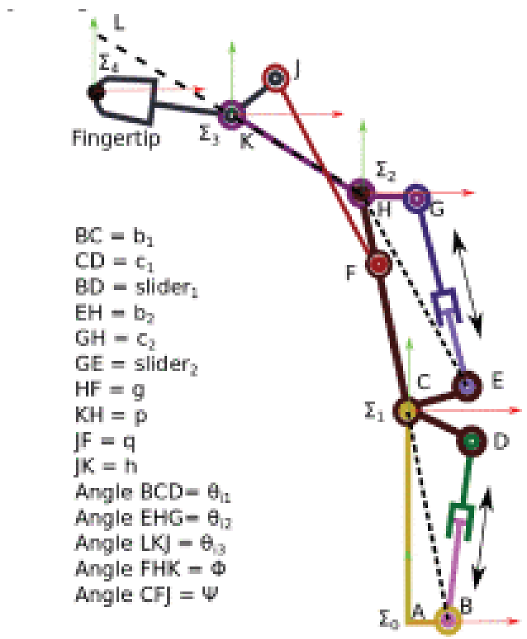


Figure 2-13 Index finger mechanism with defined frames (Özgür and Mezouar, 2016).

Park and Kim (2020) then provided an open-source anthropomorphic robot hand system called the HRI Hand with focus on the end-effector role of the collaborative robot manipulator. Their HRI advantage is that it allows for constructing end-effectors cheaper than those commercially available by using 3D printing. Furthermore, the research focused on a 5 finger underactuated system based on two four-bar linkage mechanism. Figure 2-14 shows the finger module used consisting of four links and the three joints; MCP, PIP and DIP. Link A, connects MCP and PIP joint while the PIP and DIP joints are connected to Link B. The PIP and DIP joints operate in dependence to the motor connected to the MCP joint. Figure 2-15 shows the derived kinematic diagram of the mechanical finger module while Figure 2-16 demonstrates the range or region of motion the finger joints can move in.

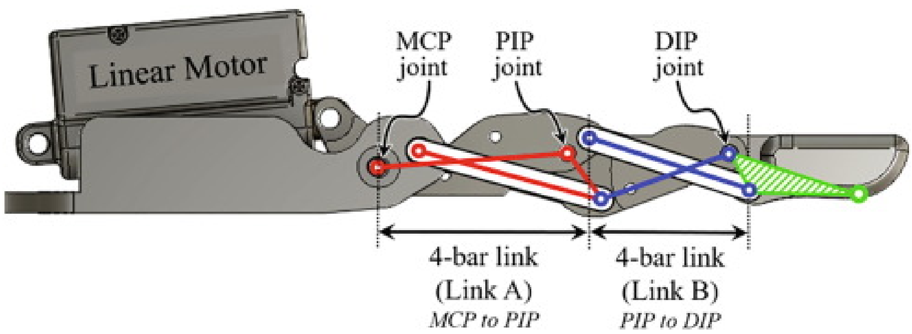


Figure 2-14 Design of the finger module (Park and Kim, 2020)

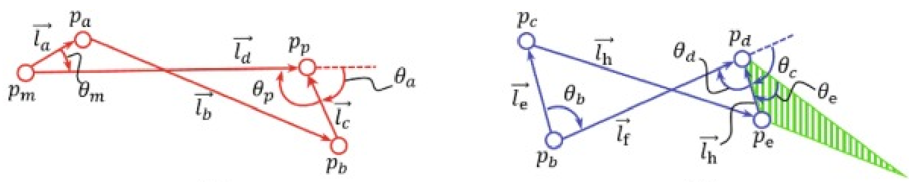


Figure 2-15 Kinematic diagram of the proposed finger module: a) kinematic diagram of Link A, b) kinematic diagram of Link B (Park and Kim, 2020).

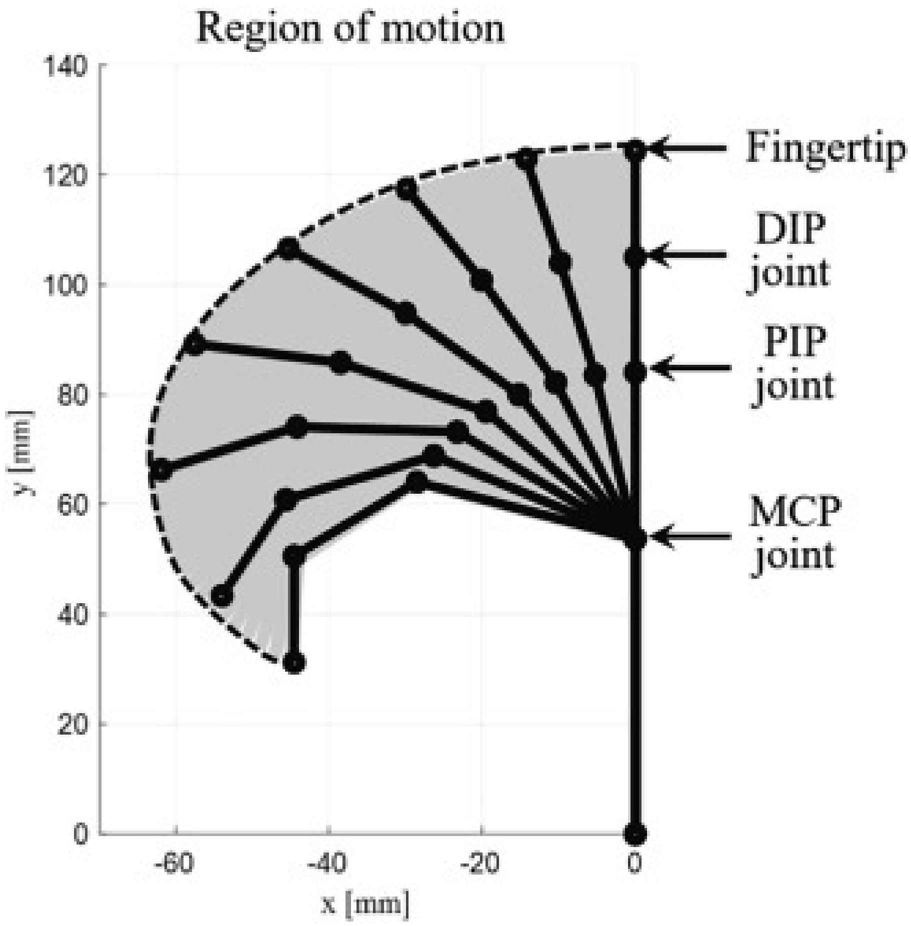


Figure 2-16 Region of motion about the finger module (Park and Kim, 2020).

Another integrated linkage-driven dexterous anthropomorphic robotic hand was developed by Kim et al (2021) to provide high flexibility and functions similar to the human hand. Similarly, in order to integrate human level dexterity and grasping force under limited actuators the linkage mechanism was used to develop an animatronic hand capable of 15 degrees of motion with a compact size at a maximum length of 218mm and low weight of 1.1kg (Kim et al., 2021). The hand was also fitted with tactile sensing capabilities.

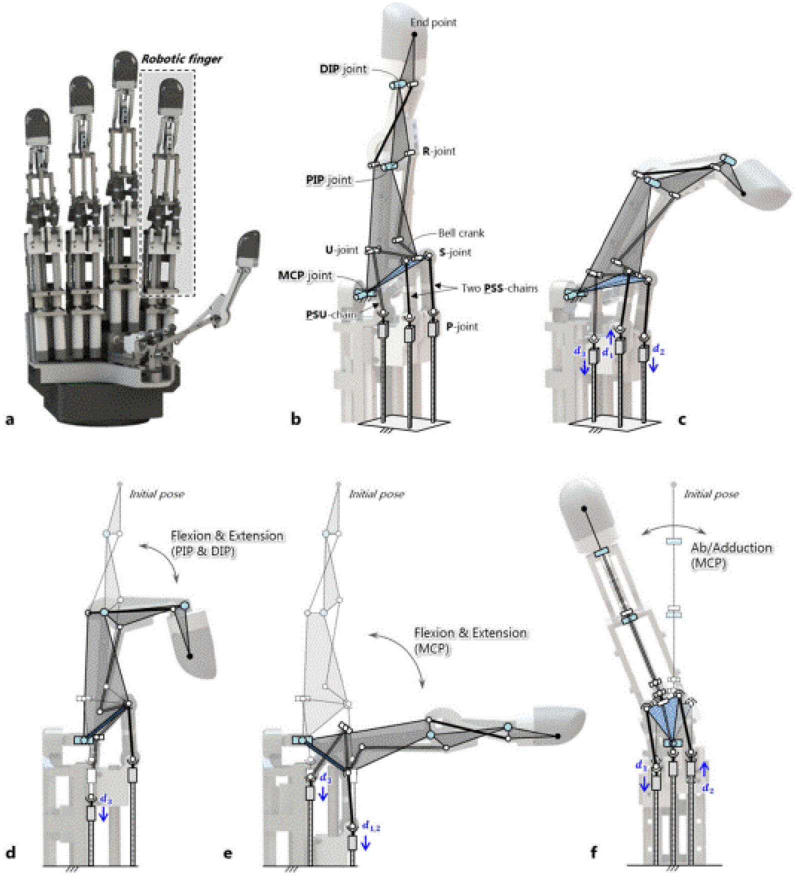


Figure 2-17 Kinematic structure of the linkage mechanism of the robotic finger (Kim et al., 2016).

From Figure 2-17, it shows a) Mechanism explained in the robotic hand; b) Kinematic structure of the finger; c) 3-DOF motion of the finger generated by three linear motions; d) Flexion and extension of the PIP joint that can be driven regardless of the movement of the MCP joint; e) Flexion and extension of the MCP joint; f) Abduction and adduction of the MCP joint.

2.2.5 Anthropomorphic Wrist

Other than the dexterous nature of the human fingers, wrists play a role in positioning the overall location of the hand and its alignment. Thus, it was important to research the available designs to replicate the human wrist into that of a robotic nature while maintaining the same level of freedom of motion. Furthermore, while the fingers positioning can be determined using sensory gloves, the wrist movement would require an exoskeleton structure to capture the pitch, yaw and rotary motion of the wrists.

Chandra and Kiguchi (2007) developed an exoskeleton robot to adapt to the human wrist and forearm motions and provide motion assistance. The proposed exoskeleton consists mainly of a forearm motion support part and a wrist motion support part directly connected to the user's forearm (Gopura and Kiguchi, 2007). The palm and wrist holders are designed to be worn easily by having a tape ribbon part. The user would insert their forearm through the hole of the forearm cover from the distal end, followed by placing the palm into the palm holder and the wrist into the wrist holder. Figure 2-18 shows the 3D model of the exoskeleton while Figure 2-19 demonstrate the range of motion allowable by the exoskeleton. The prospect of their mechanical design is to be used for following the motion of the human wrist and hand and record motion through potentiometer sensors.

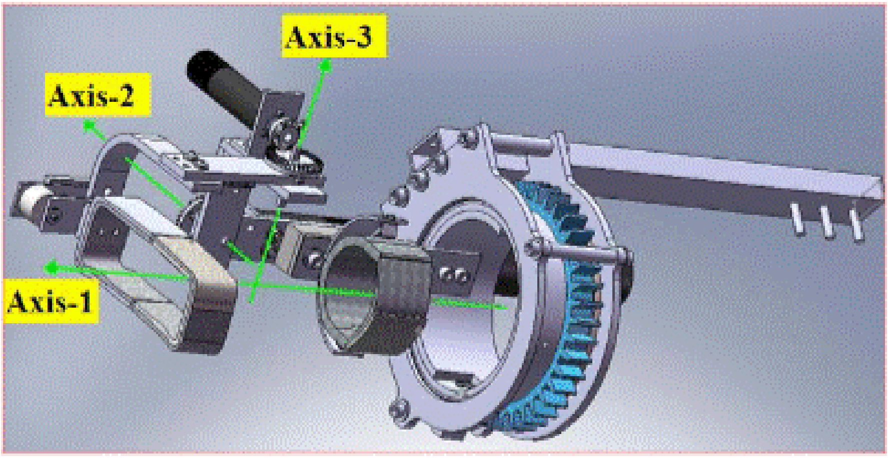


Figure 2-18 3D CAD model of the robot with rotational axis (Gopura and Kiguchi, 2007)

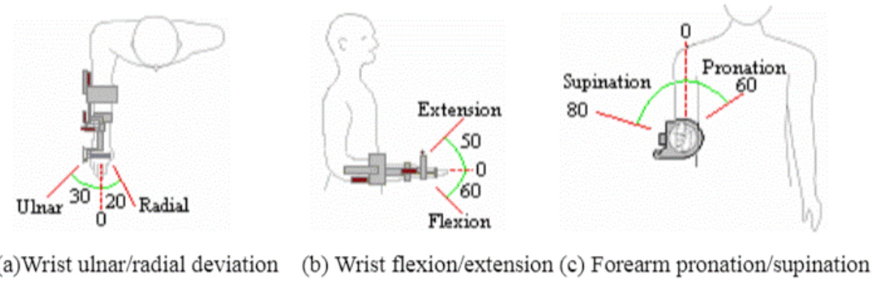
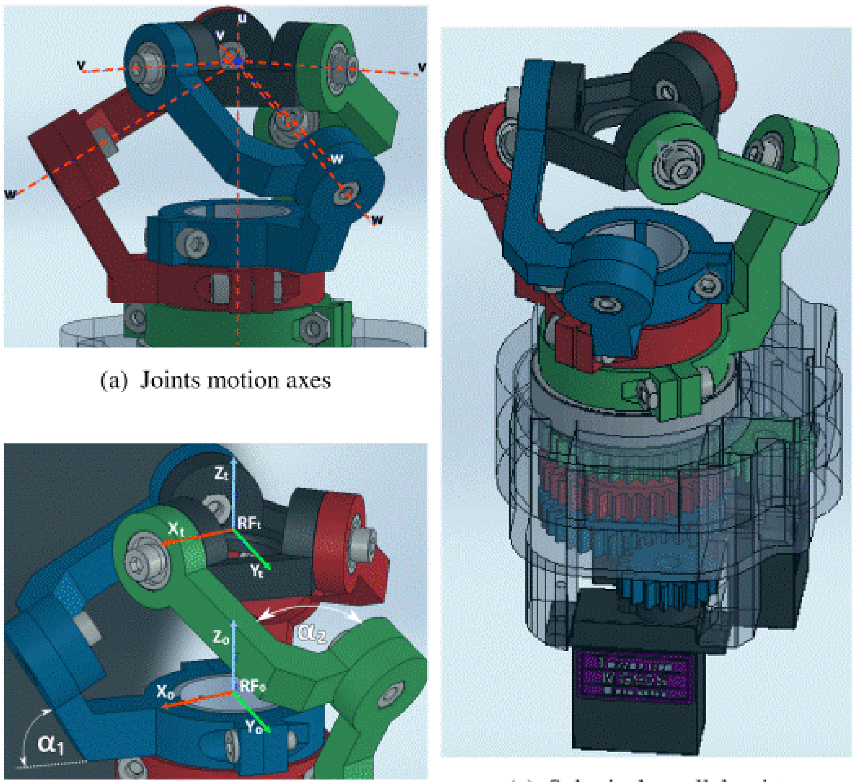


Figure 2-19 Movable ranges of the exoskeleton (Gopura and Kiguchi, 2007).

The next step is to translate the human wrist motion into that of a robotic structure while maintaining proper mimicry of the human wrist movement and angle. Bulgarelli et al (2016) developed a low-cost open-source 3D-printable robotic hand with a parallel spherical joint wrist for sign language application. The spherical wrist designed is capable of 3 DOF. The wrist mechanical structure is formed by a triangular platform and three different legs as highlighted in blue, red and green colours in Figure 2-20. Each leg is then composed of a proximal L-shaped link of angle 60° and a distal L-shaped link of angle 90°, and has three revolution joints of which only the one at the base is actuated (Bulgarelli et al, 2016).



(a) Joints motion axes

(b) $\mathbb{RF}_0$ and $\mathbb{RF}_t$

(c) Spherical parallel wrist

Figure 2-20 Overview of the spherical wrist (Bulgarelli et al, 2016).

2.2.6 Teleoperation

Over the decades, multiple and various teleoperation systems have been developed to allow human operators to conduct tasks and activities in remote or hazardous environments in a number of applications ranging from space, to under water, surveillance and nuclear plants (Durlach and Mavor, 1995). Nowadays, teleoperation exists in multiple forms such as wired, wireless, virtual, hepatic and even augmented teleoperations.

Construction of the mechanical components of the animatronic hand and wrist needs to then be configured by the controller (sensory glove and exoskeleton) to allow for remote control of the robotic hand as it mimics the operator hand movements. A robust teleoperation system with adequate human-machine interface will ensure the robotic hand moves with minimum stability problems and time delays. The teleoperation system is made up of two manipulators, the human operator controls the master manipulator (in this case - the glove and exoskeleton) to generate motion commands that are mapped to the remote manipulator, the slave manipulator (in this case - the animatronic hand).

2.2.6.1 Kinematics

The animatronic hand DOF can range depending on the mechanics of the fingers and wrist. With each finger having its own range of motion it becomes evident that for direct human control, an exoskeleton master with 7 DOF can be used to guide a slave 7 DOF manipulator. To control a redundant arm, usually the resolution is left to the discretion of the computer or through the usage of an auxiliary control for example a knob (Durlach and Mavor, 1995). Therefore, in order to avoid kinematics complexities, the utilisation of potentiometer and pressure sensors would be used to allow the robotic hand to map the motion of the fingers and wrist.

Serial mechanisms are when the joints are cascaded hence the workspace is the union of motions of the joints. As for parallel mechanism, it is the meeting of several independent linkages at a common terminal (such as the end effector) as seen in flight simulators. The human hand is viewed as a parallel mechanism as there are 5 fingers corresponding to 5 independent linkages that is capable of contacting an object (Durlach and Mavor, 1995). Additionally, parallel mechanism employs inverse kinematics to find the joint angles given the end-point position.

2.2.6.2 Actuation

Electrical actuators, rather than hydraulic or pneumatic, are the dominant actuation methods when it comes to smaller size robotic functions. Electrical motors and drives are easier to install and maintain but their payload is smaller. However, the usage of transmission elements such as gears allows for the amplification of the motor torque and to couple high-rev motors to low-rev joints.

This project will utilise servomotors as the actuation devices for the fingers and wrist. Servo motors are electromechanical actuators that produce torque and velocity based on the supplied current and voltage and works as part of a closed loop system with a feedback device. The feedback device, often attached to the signal cable, provide the servomotor controller information such as the current, velocity and position. The motor actuation is then adjusted to the desired parameters (Kollmorgen,2022).

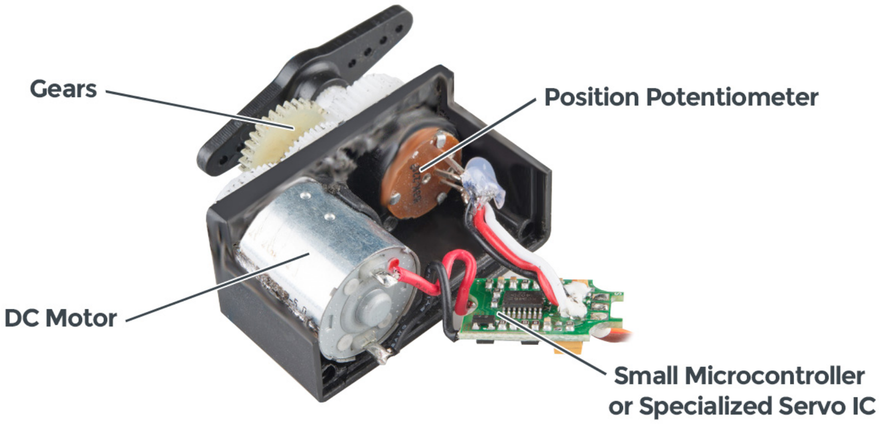


Figure 2-21 The functional components within a servomotor (Sparkfun,2022).

Figure 2-21 shows a breakdown of the internal main components within a servomotor. The DC motor is attached to a gearbox that increases the speed and torque of the motor and the gears are often either made out of plastic or metal based on application environment and work intensity. The controller circuit interprets signals sent by the controller, and the potentiometer acts as the feedback for the controller circuit to monitor the position of the output shaft (Sparkfun,2022). The servomotor has 3 connection lines that are attached to an external microcontroller (such as Arduino) which are Ground, VCC and Signal in order to setup it up for the required application.

2.2.6.3 Sensor

In order to collect the information regarding the operator hand and wrist positions, telemanipulators (such as gloves) include sensors to monitor the mechanical state of the operator hand. For use in robot fingers and hand masters, MIT Dextrous Hand used hall-effect sensors with a resolution of 0.2 deg which was sufficient for the device (Durlach and Mavor, 1995). The VPL DataGlove employs fibre optic sensing but these are costly and the effects are too coarse to be useful for the application of robotic hands.

Flex sensors are capable of measuring the amount of deflection or bending and is commonly used in applications where the user needs to modify the resistance through bending (ElProCus, 2019). The working principle of the flex sensors is that the resistance changes whenever the strip is twisted or bent effectively acting like a variable resistor. The resistance changes depend on the linearity of the surface. Rotary sensors and encoders can also be used to measure displacement of the wrist or fingers movement in a rotary fashion, either clockwise or anti-clockwise direction.

2.3 Prior Work

Previously, the various components involved with the creation of a teleoperated anthropomorphic/animatronic hand were discussed. In this section, these components are then merged together to produce a remotely controlled animatronic hands for various applications.

2.3.1 Developments of New Anthropomorphic Robot Hand and its Master-Slave System

Mouri et al (2005) presented a new developed anthropomorphic hand called KH Hand Type S, seen in Figure 2-22, that exhibit high potential of dexterous manipulation and displaying hand shape, coupled with a master-slave system using bilateral controller for five-fingers robot. To demonstrate the dexterous grasping and manipulating of an object, a peg-in-hole experiment was conducted as demonstrated in Figure 2-24. A force feedback glove (FFG) mounted on the operator hand and arm consisted of a data glove to measure the joint angle of the human finger as shown in Figure 2-23 (Mouri et al,2005).

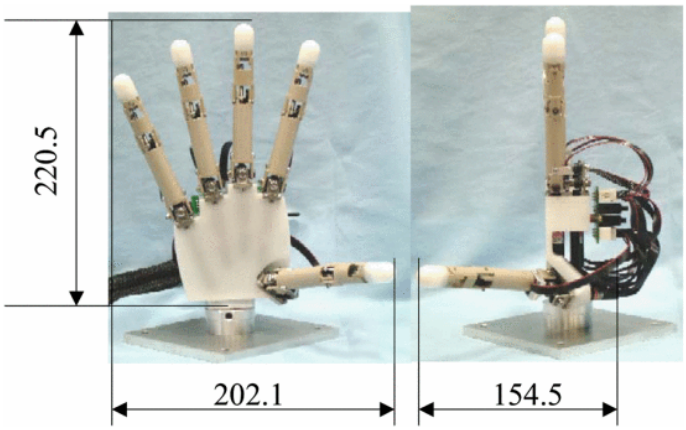


Figure 2-22 KH Hand Type S dimensions (Mouri et al,2005).

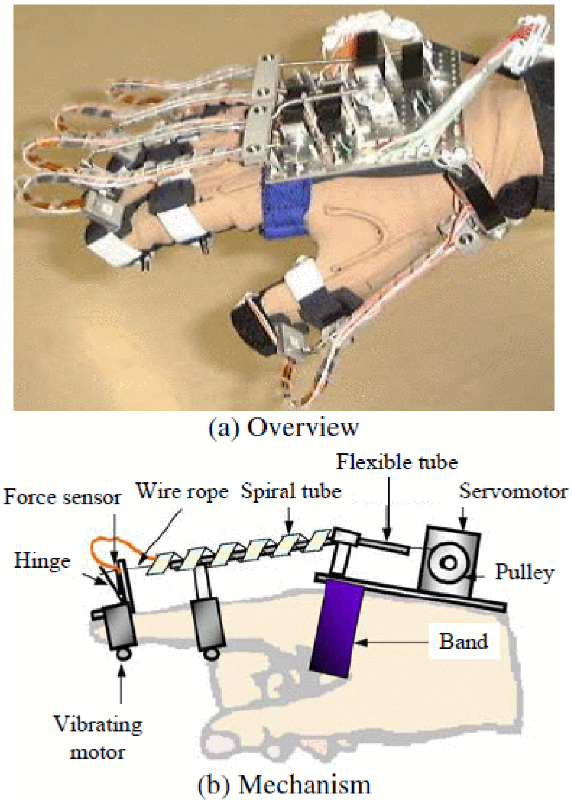


Figure 2-23 Force feedback glove mechanism (Mouri et al,2005).

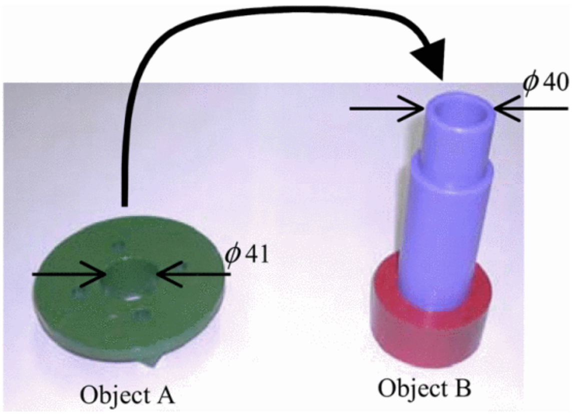


Figure 2-24 The Peg-in-hole task performed by the robotic hand (Mouri et al,2005).

2.3.1.1 Discussion

The robot hand presented by Mouri et al (2005) made improvements in regards to weight saving, and reduced the backlash of transmission and friction between gears by utilising an elastic body.The research demonstrated a working principles behind a slave and master teleoperation through the usage of custom made force glove that makes use of pulleys, force sensors and vibrating motors as means to collect the user finger position. The results of the peg-in-hole task controlled by the bilateral denote that the KH Hand Type S has higher potential to preform hand shaped display tasks as well as grasping and manipulating objects like a human hand.

2.3.2 Teleoperations of Multi-fingered Robotic Hand for Safe Extravehicular Manipulations

Extra-Vehicular Activity (EVA) is playing a more dominant role in space missions as it presents many intrinsic critical aspects that are highly hazardous for human operations (Saggio and Bizzarri, 2014). Convenient alternative is telerobotic manipulation of multi-fingered robotic hand that replicate the operator's hand. Saggio and Bizarri (2014) utilised state-of-the art sensory gloves to measure angles of human finger's joints and replicate it remotely by a standard anthropomorphic hand as seen in Figure 2-25. The feasibility and technological limits to map human operator gesture one-to-one was tested and evaluated.

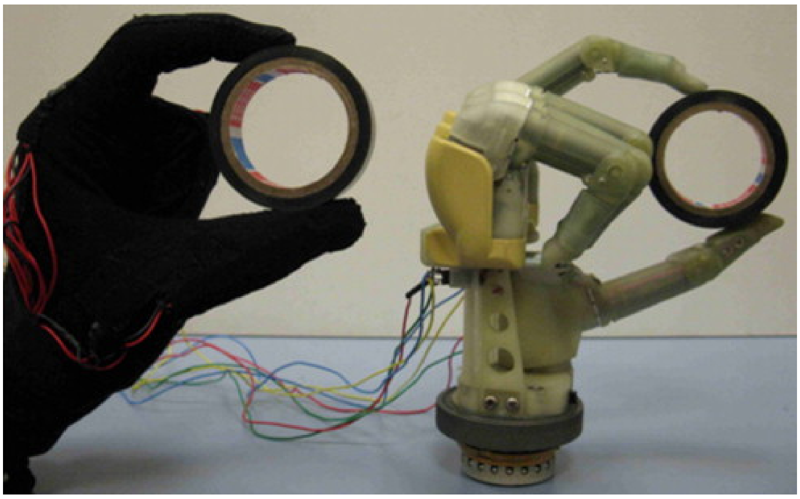


Figure 2-25 Replication of human gesture by the animatronic hand (Saggio and Bizzarri, 2014).

Five tests were conducted to quantitatively assess the repeatability by finding the range and standard deviation of the sensory glove and the replicated motion of the robotic hand. It was experimentally demonstrated that the flex sensors do not preform identically, even with similar physical parameters, but nonetheless their response maintained similar general trends even if the absolute values differed (Saggio and Bizzarri, 2014).

2.3.2.1 Discussion

The sensory glove developed by Saggio and Bizzarri (2014) preformed slightly better than others reported in their literature. The work demonstrated that an accuracy of 1.42° is obtained when measuring the human finger's joints over a maximum flexion of 120°. The research utilised a total amount of 15 flex sensors (3 per finger) in order to achieve the high accuracy displayed which facilitated the procurement of more detailed and accurate sensory information. However commercial market price of flex sensors is high therefore, usage of multiple sensors would incur a substantial development cost.

2.3.3 An Assistive Tele-operated Anthropomorphic Robot Hand: Osaka City University Hand II

Mahmoud, Ueno and Tatsumi (2011) presented an improved model of the Osaka-City-University-Hand I called Osaka-City-University-Hand II that displayed cosmetic and functionality suitable for prosthetic usage or for conducting robotic research of robot hands. The OCU-Hand II, which can be seen in Figure 2-26, was fitted with a feedback system of tactile and force sensors in order to grasp an object firmly. The control strategy adopted was through the implementation of a master light-weight glove to drive the OCU-Hand II as the slave. To facilitate proper teleoperation, arithmetic operations were done to the output of the feedback sensors to increase the resolution of the master slave driving technique and overcome hardware amplification defects.

Figure 2-26 Teleoperation experiment of the robotic hand using the sensory glove (Mahmoud, Ueno and Tatsumi, 2011)

2.3.3.1 Discussion

The result of the project was an improved mechanical design of the anthropomorphic robotic hand that addressed not only finger movement, but as well as wrist motion. The master-slave teleoperation system performed at high accuracy and allowed for new useful operation technique to use the OCU-Hand as an assistive device capable of human hand mimicry (Mahmoud, Ueno and Tatsumi, 2011). Hardware amplification defects of the sensors output were overcome through amplifying the sensors output by software arithmetic operation.

The noticeable feature of this research in regards to creating the Osaka City University Hand II is the integration of tactile sensor as means to detect objects being grasped by fingers and therefore results in better handling manipulation of the items grasped by the fingers. However, the research did not provide slave to master control of the wrist joints and relied on simple knobs and switch to actuate the wrists.

2.4 Summary

This chapter of the thesis highlighted the fundamental theories in regards to the creation of a teleoperated anthropomorphic hand as well as the various techniques and methods used to achieve dexterous and controllable motions. Furthermore, samples of the projects and research works in regards to the topic were documented, discussed and key points of each of the prior works was highlighted. The literature review provided insights into input sensory acquisition tools such as tactile, force, pressure and flex sensors to reliably collect information of the user (master) finger and hand motions. Additionally, actuation methods and designs were employed to provide a range of motion and notably the research into underactuated fingers shed light into reducing the amount of motors required to actuate a robotic finger.

2.4.1 Comparison and Review of the Literature Works

Table 2-1 Summary of the relevant literature reviewed.

Title	Author	Description	Remark
Developments of New Anthropomorphic Robot Hand and its Master-Slave System	Mouri et al (2005)	A five-finger robotic hand was controlled using a force feedback sensory glove in a master-slave system.	The research provided insight regarding mechanical structure of the animatronic hand that displayed capability to replicate sign language.
Teleoperations of Multi-fingered Robotic Hand for Safe Extravehicular Manipulations	Saggio and Bizzarri (2014)	The prosthetic robotic limb was controlled by a sensory glove housing flex sensors placed in correspondence to each joint.	The research shed light into implementation of a sensory glove to capture the joints movements with good precision.
An Assistive Tele-operated Anthropomorphic Robot Hand: Osaka City University Hand II	Mahmoud et al (2011)	The animatronic hand and wrist developed was teleoperated by a simple sensory glove to mimic operator hand movements.	The research provided mechanical insight to not only the design of a compact robotic hand but as well as incorporating a wrist joint.
Towards a Functional Evaluation of Manipulation Performance in Dexterous Robotic Hand Design	Roa et al (2014)	Kinematic design configurations and manipulation performance of the robotic hand was explored by conducting simulations and actual motion manipulation.	The research provided good dexterous designs that were evaluated to measure the reliability of the manipulation performance.
Kinematic modeling of an anthropomorphic hand using unit dual quaternion	Chandra et al (2019)	A kinematic model for an anthropomorphic hand was presented for forward and inverse kinematics computation.	The research provided a strategy to evaluation the kinematics by the usage of geometrical analysis.
An open-source anthropomorphic robot hand system: HRI hand	Park and Kim (2020)	An open-source platform for the complete development of an anthropomorphic hand at an approximate cost that is lower than commercially available robotic hands.	The research provided comprehensive guide to the creation and development of joints through linkage for underactuated situation.
Integrated linkage-driven dexterous anthropomorphic robotic hand	Kim et al (2021)	An integrated robotic hand utilising linkage-driven mechanism to provide 15 degrees of motion.	This research provided alternative mechanical design of the animatronic hand to achieve adequate dexterity.
Integrated linkage-driven dexterous anthropomorphic robotic hand	Xiong et al (2008)	A general theory for designing anthropomorphic hand with natural grasping functions was presented.	The research provided design principles for the robotic hand to reproduce digital grasping movement of the human hand.

Title	Author	Description	Remark
A Low-Cost Open Source 3D-Printable Dexterous Anthropomorphic Robotic Hand with a Parallel Spherical Joint Wrist for Sign Languages Reproduction	Andrea et al (2016)	A dexterous anthropomorphic hand for sign language application was developed.	This research provided insight to adding dexterity to the animatronic hand through a spherical joint wrist. Furthermore, it provided systematic kinematic analysis methodology.
An Exoskeleton Robot for Human Forearm and Wrist Motion Assistive	Gopura and Kiguchi (2008)	An exoskeleton structure worn by a human operation as an orthotic device.	The research shed light on ways to monitor the movement of the human hand wrist and forearm.
Benchmarking anthropomorphic hands through grasping simulations	Harillo (2022)	A standard benchmark for assessing the design alternatives of anthropomorphic hands was presented	A standard benchmark for assessing the design alternatives of anthropomorphic hands was presented This research provided computer simulation alternative to physically experimenting and evaluating animatronic hands.
Underactuated anthropomorphic hands: Actuation strategies for a better functionality	Tavakoli (2015)	Actuation strategies were presented for an anthropomorphic hand running with 1 to 5 actuators.	This research provided design strategies and templates to use in order to drive an anthropomorphic hand with a limited number of actuators.
Underactuated anthropomorphic hands: Actuation strategies for a better functionality	Chen and Xiong (2016)	The paper developed design method for underactuated anthropomorphic hands to guarantee reliable adaptation to various grasped objects	The research provided an analysis method to evaluate multiple aspects of motion and force in order to come up with proper mechanism parameters for the robotic hand.
Underactuated Finger Mechanism Using Contractible Slider-Cranks and Stackable Four-Bar Linkages.	Yoon and Choi (2017)	Slider-cranks, linkages and springs were used to actuate a single linear motor robotic finger.	The research provided schematic diagrams and analysis of underactuated robotic finger using linkages and spring
Underactuated finger mechanism for natural motion and self-adaptive grasping towards bionic partial hand.	Dukchan et al (2016)	Tests and analysis was made to create the design of an underactuated finger with superior grasping capabilities.	The research group managed to create a highly self adaptive underactuated robotic finger that reduced the degrees of actuation while maintaining Degrees of freedom

Chapter 3 Methodology

3.1 Research Framework

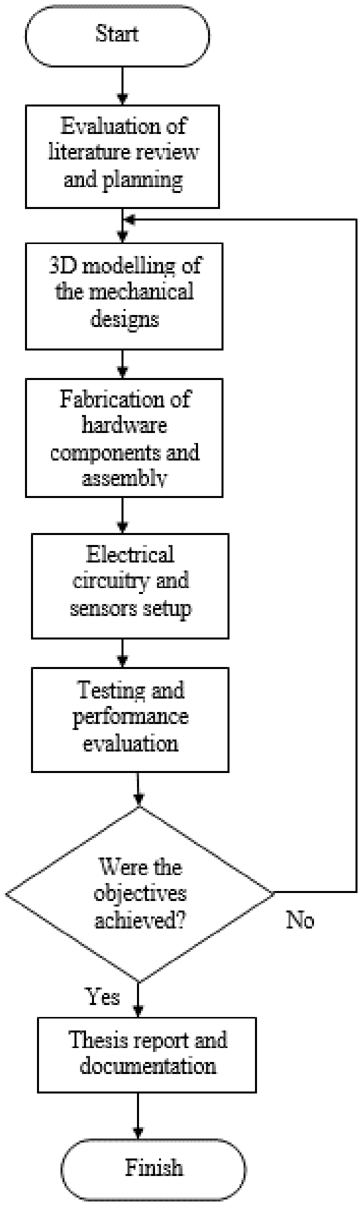


Figure 3-1 Research Framework and processes involved.

The steps that would be taken to tackle the research objectives are shown in the flowchart of Figure 3-1. The initial step would be to evaluated and review the previously conducted literature review in order to clarify the project needs and plan in detail the layout of the animatronic hand system. The next step would be the 3D designing of the project physical parts through the usage of computer aided software as well as simulation of the 3D models to check for joints and parts integrity. Once the design phase is complete, the fabrication process using 3D printers is initiated to produce the mechanical parts of the system which would then be assembled according to the simulated plans. The next step would be the integration of the electrical circuitry such as the motors, microcontroller, wires and sensors into the mechanical parts. Once the system is assembled, the setup and program code are then tested to ensure the system is working properly without glitches, mechanical failures or circuitry issues. The system performance is then evaluated and experimented upon, and when the project objectives are met results would be documented, otherwise, re-evaluation of the system would be conducted to address the shortcomings whether in the hardware or software components of the project.

The teleoperated animatronic system consists of the several major parts illustrated in Figure 3-2. The sensory glove (master manipulator) collects the user finger and wrist positions and sends it to the Arduino microcontroller. The Arduino microcontroller communicates with the PC in order to resolve the kinematics needed and send the results for the final position to the animatronic hand (slave manipulator). The animatronic hand fitted with servomotors connected to mechanical links would then move to the targe position . The PC is used to monitor the data being used to control the animatronic hand and resolve any issues retaining to the control of the system.

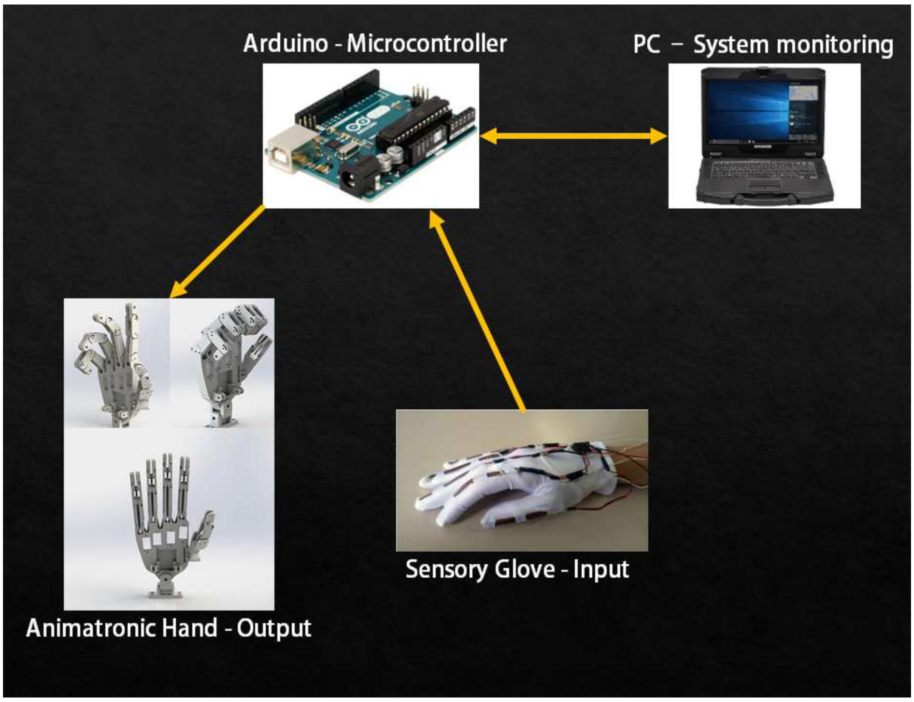


Figure 3-2 Proposed animatronic system illustration.

3.2 Gantt Chart

No	Task	Duration	First Semester (Weeks)											
			1	2	3	4	5	6	7	8	9	10	11	12
1	**Deciding on the research topic**	**2**												
2	Investigate existing projects and identify the research value	1												
3	Preliminary literature review to obtain research methodology	1												
4	**Complete Chapter 1: Introduction**	**1**												
5	Construct the project objectives, scope and contribution	1												
6	**Complete Chapter 2: Literature Review**	**5**												
7	Research background information regarding animatronics, teleoperation and human anatomy	2												
8	Research regarding anthropomorphic hands and prior work	3												
9	**Complete Chapter 3: Methodology**	**2**												
10	Identify the research framework and schedule	1												
11	Identify the type of evaluation tests to be conducted	2												
12	Identify the required hardware and software resources needed for the project	1												
13	**Format and review of the proposal report**	**2**												

Figure 3-3 First semester Gantt chart and milestones.

No	Task	Duration	Second Semester (Weeks)											
			1	2	3	4	5	6	7	8	9	10	11	12
1	**Evaluation of literature review and planning**	**1**												
2	**3D modelling of mechanical designs**	**3**												
3	Modelling the fingers	1												
4	Modelling the hand	1												
5	Modelling the wrist	1												
6	**Fabrication of hardware**	**2**												
7	**Components assembly and sensory setup**	**1**												
8	**Testing and performance evaluation**	**3**												
9	**Thesis report and documentation**	**2**												

Figure 3-4 Second semester Gantt and milestones.

The need for Gantt Chart was emphasized on the the second phase of the project (FYP 2) as there were multiple tasks that need to be tackled which were prototype designing, 3D printing and procurement of required electrical components. The usage of the Gantt Chart provided adequate timeline and milestone monitoring and proper handling of the tasks at hand.

3.3 Hardware

The hardware to be utilised in this project consists of the sensors, actuators, mechanical components and electrical circuitry. The sensors to be used are flex sensors and potentiometer/variable resistors to acquire the bending motion of the fingers and wrist joints in the form of a sensory glove and exo-skeleton. The actuators would be metal gear servomotors that are used to drive the animatronic hand finger joints and wrist joint coupled with shaft and pulley systems to ensure enough torque is generated for smooth movement. The mechanical components consist of the animatronic hand frame, linkages and connectors that needs to be 3D printed and assembled together. The electrical circuitry is required to connect the sensors, actuators and the Arduino microcontroller together in order to generate a teleoperated system for controlling the animatronic hand.

3.4 Software

The 3D computer aided design software AutoDesk Solidworks software was utilised to create the mechanical model and parts of the animatronic hand. Furthermore, the software was used to convert the solidworks designs into Standard Triangle Language (STL) file that is commonly used for 3D printing purposes. Moreover, TinkerCAD software was used to design and test the electronic circuitry involved. Finally, the Arduino microcontroller board comes along with its own Integrated Development Environment (IDE) software to program the board.

3.5 3D Printing

3D printing or additive manufacturing is a process of making three dimensional solid objects from a digital file usually an STL file.The creation of a 3D printed object is achieved using additive processes. In an additive process an object is created by laying down successive layers of material until the object is created. Each of these layers can be seen as a thinly sliced cross-section of the object (3D Printing,2022). 3D printing was chosen as it allows for rapid prototyping of the hand models in a matter of days, cutting down on labour and tool costs to fabricate the parts.In order for fast and cheap 3D printing, the fabrication specifications are as follows:

a) Procedure:

Fused deposition modeling (FDM) is a technology where the melt extrusion method is used to deposit filaments of thermal plastics according to a specific pattern. Similar to 3DP, the layout for FDM consists of a print head able to move along X and Y directions above a build platform as shown by Figure 3-5.

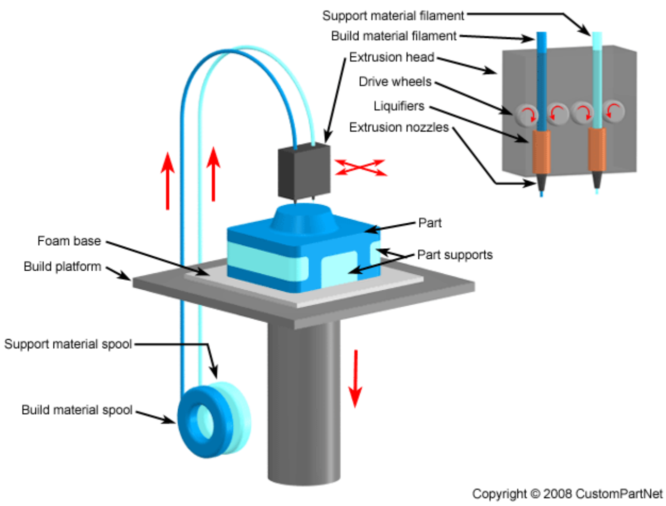


Figure 3-5 FDM 3D Printing (CustomPartnet,2022).

b) Material:

Poly-lactic Acid as known as PLA is biodegradable and has high hardness and stiffness but is slightly brittle however it starts to deform at 60°C. PLA is resistant to most chemicals and virtually free from shrinkage (3dGadgets,2021). This makes it suitable for the anthropomorphic hand.

c) Print Quality:

Print Quality mainly affected by the thickness of each layer of a 3D printed object. A finer layer gives higher details and less visible layer line but longer print time as demonstrate by Figure 3-6. A thicker layer will reduce print time but with lower details and more visible layer line in the end result (3dGadgets,2021). A print quality of 0.10mm was used as some of the finger parts are fine and detailed.

Figure 3-6 3D Printing Quality and time taken to finish a part (3dGadgets,2021).

d) Infill Density:

As printing a fully solid object is time consuming and costly, a series of repeated patterns called infill are used instead to fill up the internal of a 3D printed object. The density of the 3D printing infill, is measured in percent as can be seen in Figure 3-7. A higher infill density makes for a heavier, more solid print. In contrast, a lower infill density would provide a simpler, more lightweight result (3dGadgets,2021). An infill density of 25% was chosen as to maintain sturdy component parts while still being lightweight.

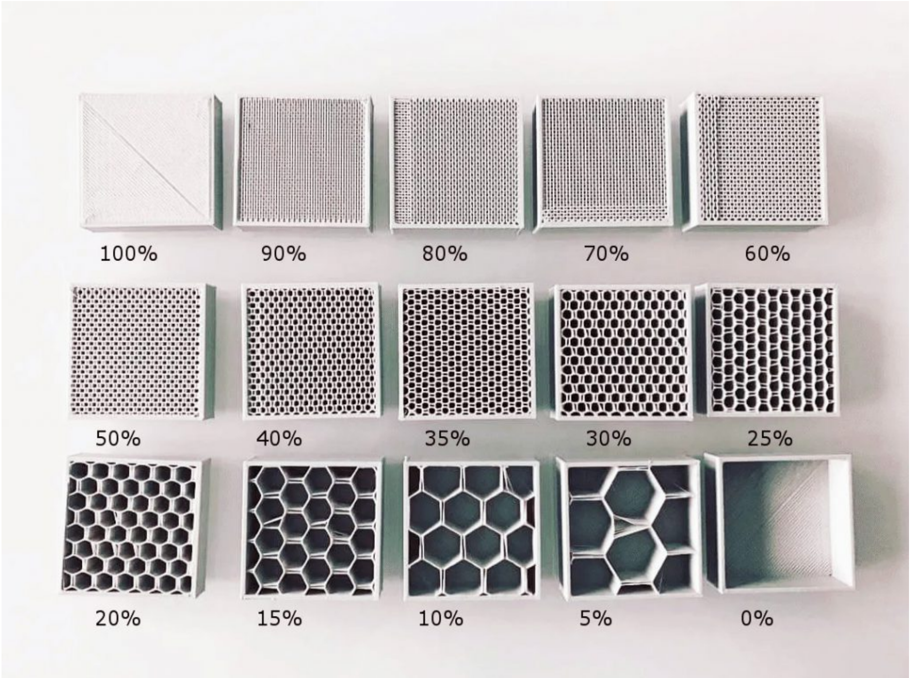


Figure 3-7 3D Printing infill density and corresponding mesh pattern (3dGadgets,2021).

3.6 Evaluation and Testing

The teleoperated animatronic hand would undergo testing and experimentation in order to evaluate its performance quantitatively and qualifiedly. Based on those quantities and qualitative results, the preformance of the animatronic hand and its teleoperation system would be discussed. The following tests are to be conducted by the teleoperated animatronic hand:

1. Direct movement of each of the animatronic hand fingers and wrist by inputting the precise angle, then measuring the accuracy in which the fingers and wrist move to the desired position.
2. Using the sensory glove worn by an operator to separately measure and record the bending degree of the fingers and wrist movement for the flex sensor and potentiometer respectively.
3. The teleoperation system is deployed in its fullest and the animatronic hand is to replicate the motion of the human operator hand movement captured by the sensory glove. Evaluation of mimicry precision and accuracy between the glove and robotic hand is to be made.

Chapter 4 Design and Fabrication Process

4.1   Mechanical Design

The anthropomorphic hand design, henceforth called “MyHand”, consists of two main criteria which are

1) Implementation of an underactuation mechanism to limit the number of actuating servo motors to six (5 for fingers; 1 for wrist).

2) The hand design should allow for wrist joint connections to increase the anthropomorphic hand range of motion. For this reason, string/tension based finger actuation limits the addition of wrist joints.

4.1.1   Fingers

In order to overcome and fulfill the first criteria Park and Kim (2020) underactuated finger design was adopted then further modified to suit the current application. The underactuated finger and its mechanism proposed by Park and Kim was discussed in Chapter 7.4 Anthropomorphic Hand. It utilises a pair of bar linkages to facilitate flexion and extension of the finger which is also similar to the work done by Yoon and Choi (2017) in terms of design principle. However, Park and Kim design involved the usage of PQ12 Linear Actuators which are costly. Therefore, in order to commercialize and minimise the cost required to fabricate an underactuated finger, a rotary servo motor was used instead.

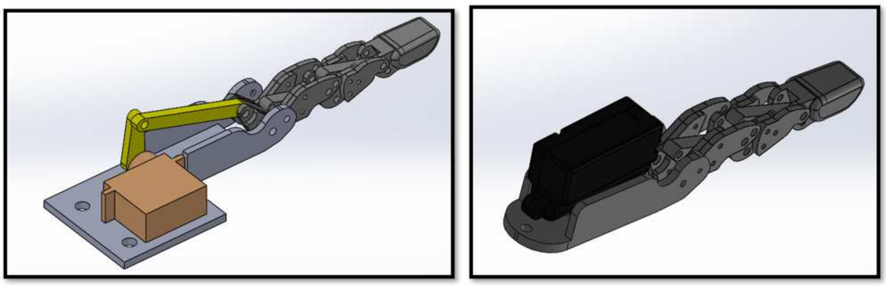


Figure 4-1 Park and Kim underactuated finger (right) and MyHand finger assembly (Left).

Figure 4-1 shows the design differences between Park and Kim underactuated finger and MyHand finger, specifically the increase in the finger base area due to the addition of the servomotor. It is noted that a lever and linkage mechanism was used in order to convert the rotary motion of the servomotor into that of a linear motion that would drive finger as shown in Figure 4-2. The servomotor range of motion is at approximately 40˚ between an extended and flexed finger. The anthropomorphic finger parts were designed to mimic the finger tip ,medial and proximia phalanges of the human finger.

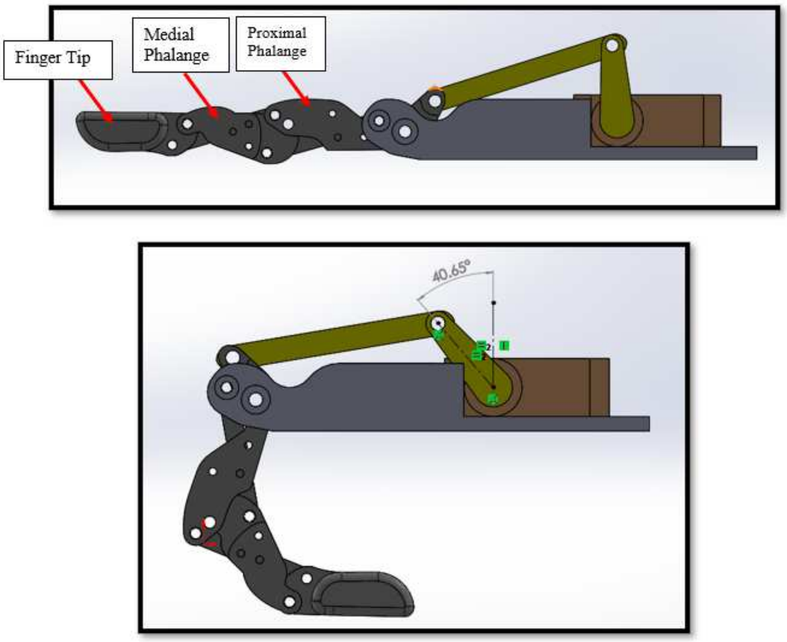


Figure 4-2 MyHand rotary to linear motion mechanism as well as labeling of the finger parts.

4.1.2 Palm

Having designed the fingers, the palm design should be adequate enough support the fingers in a manner capable of grasping objects. Additionally, due to the utilisation of servomotors, the finger base area has increased, thus the palm and hand had to be scaled to accommodate for the wider palm surface. Furthermore, the thumb finger had an extruding segment to facilitate better grasping and holding capabilities as seen in Figure 4-3. A mounting area for wrist joint was added as seen by the palm base so that a simple rotary servomotor with metal brackets can support and actuate the wrist in flexion and extension positions.

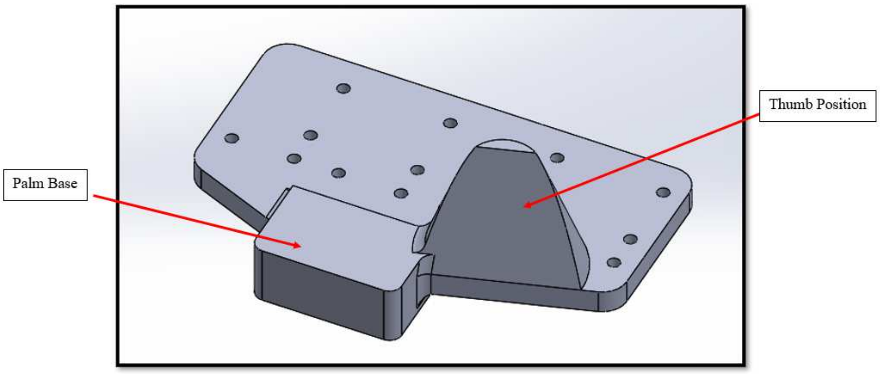
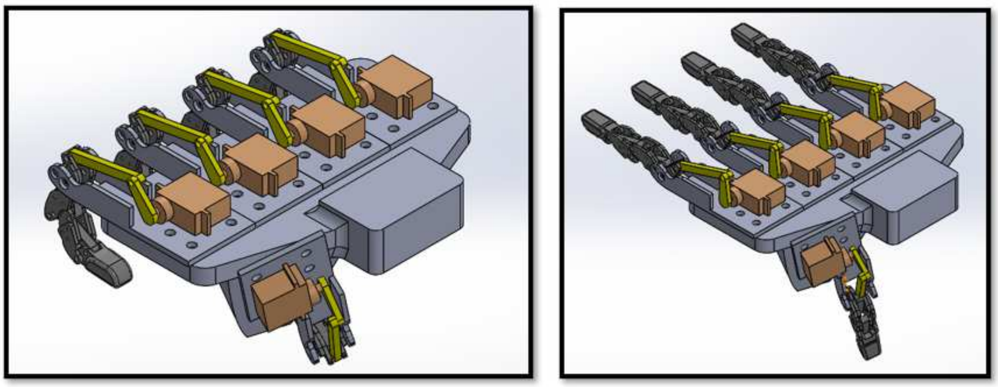


Figure 4-3 MyHand palm design.

4.1.3 Complete Hand Design

After the completion of the individual finger parts, the assembled parts of the MyHand anthropomorphic hand can be seen in Figures 4-4 and 4-5. Figure 4-4 demonstrates the grasping and opening range of the anthropomorphic hand from a top view whereas as Figure 4-5 demonstrates the grasping and opening range of the anthropomorphic hand from the bottom view. It is noted that all the fingers including the thumb are of the same design specifications (same linkage length and servomotors) to facilitate easier control configuration.



a) b)

Figure 4-4 MyHand assembly grasping (flexion) and opening (extension) top view.

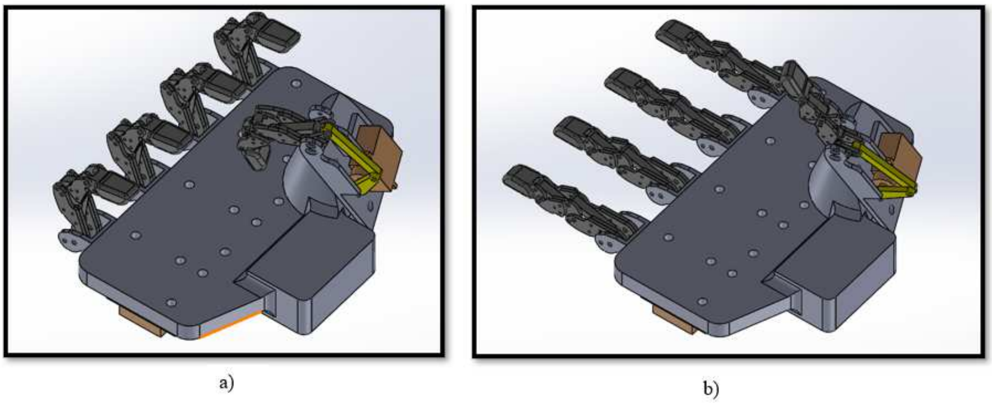


Figure 4-5 MyHand assembly grasping (flexion) and opening (extension) bottom view.

4.1.4 Sensory Glove

Having designed the anthropomorphic hand and fingers, the next step was designing the sensory glove exoskeleton. The sensory glove itself is very straightforward as any glove is brought and embedded with flex sensors at every finger location. However, the exoskeleton responsible for capturing the motion of the wrist flexion and extension requires careful design considerations. Since a potentiometer will be utilised, it needs a location to be secured to allowing it to detect the motion of the wrist. Figure 4-6 shows the exoskeleton wrist that would be worn alongside the sensory glove. A potentiometer base is embedded and secured into Wrist Latch #1 (blue) whereas the tip of the potentiometer,that is capable of rotating, is then attached to Wrist Latch #2 (green). Wrist Latch #2 has an extended cylindrical column that would be be latched to the palm of the hand. Then when the hand moves, Wrist Latch #2 would rotate, spinning the tip of the potentiometer as well. Troves were cut through Wrist Latch #1 so that a wrist band can be weaved through for better stability.

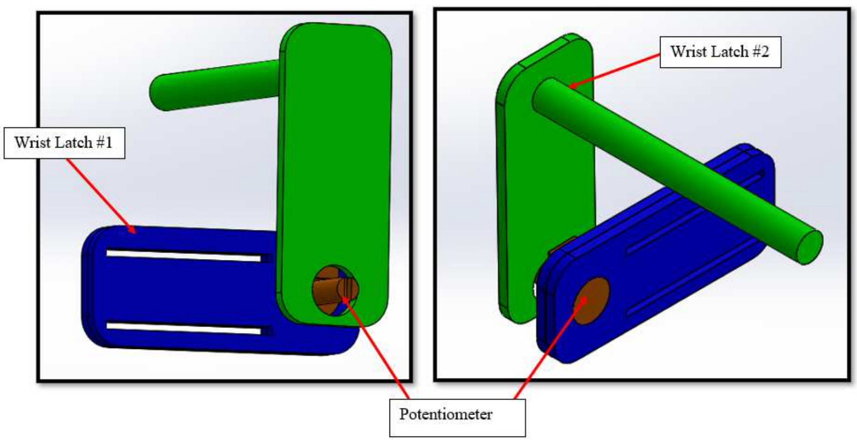


Figure 4-6 Exoskeleton wrist and its parts.

4.1.5 Components List

Having designed the anthropomorphic hand components, the parts would then need to be converted into STL file and 3D printed. Table 4-1 below documents the 3D printed parts required for the assembly of the hand and fingers to ease calculation of costs later on. The glove and wrist exoskeletons would be manually fabricated.

Table 4-1 List of 3D printable components of MyHand.

Components	Group	Quantity
Hand Base	Base	1
Finger Base (To hold Servomotors)	Base	5
Shaft Extension	Rotary to Linear Mechanism	5
Linkages	Rotary to Linear Mechanism	5
Finger PIP Links	Finger	5
Finger DIP Links	Finger	5
Finger Tip (Distal Phalanges)	Finger	5
Medial Phalange	Finger	20
Proximal Phalange	Finger	20

4.2 Electrical Design

4.2.1 Servomotors

The electrical actuators used to move the fingers and the wrist joint are servomotors. In particular the servomotors models used to handle the task are MG90s Metal Gear servomotor and Feetech FR0109m 10kg servomotor that comes with metal brackets. Figure 4-7 shows the MG90s Metal Gear servomotor, this servomotor would be the one actuating the finger joints. Its size and usage of metal gears allows it to provide enough torque to push and pull the finger linkage shafts while consuming as little space as possible. Figure 4-8 however shows Feetech FR0109m 10kg servomotor which is much larger and comes along with metal brackets making it perfect as the hand wrist joint. The other end of the metal brackets can then be used to attach the anthropomorphic hand to a robotic arm.

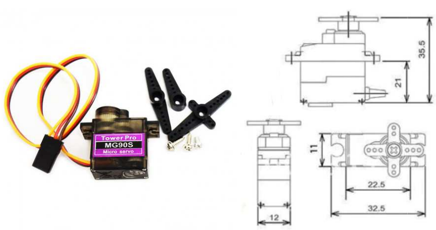


Figure 4-7 MG90s Metal Gear Servomotor and its design dimensions (Autobotic,2022)

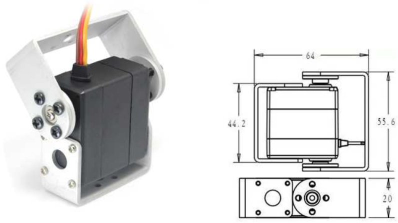


Figure 4-8 Feetech FR0109m 10kg servomotor with attached metal brackets (Autobotic,2022)

4.2.2 Flex Pressure Sensor

Flex pressure sensors are variable resistors that varies in resistance upon being bent allowing for measurement of deflection. A flex sensor consists of a phenolic resin substrate with conductive ink deposited. A segmented conductor is placed on top to form a flexible potentiometer in which resistance changes upon deflection (LSM,2022).Conductive ink-based flex sensor uses a special ink whose resistance varies when bent. The ink may contain carbon or silver to make it conductive. The spacing between carbon particles are larger when bent and closer when straight which results in a change of resistance as shown in Figure 4-9. The sensory glove would be utilising five 2.2inch flex sensor to collect the bending data of the fingers.

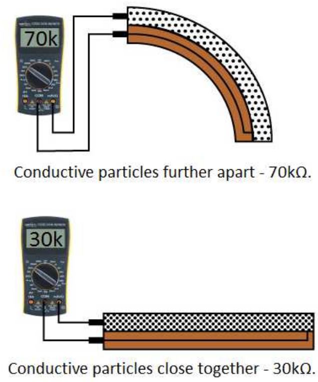


Figure 4-9 Flex sensor working principle (TechMe Micro,2022)

4.2.3 Potentiometer

A potentiometer is a three-terminal resistor with a sliding or rotating contact that forms an adjustable voltage divider. It is commonly used as a type of position sensor and exists in either linear potentiometers or rotational displacement potentiometers. The potentiometer produces analogue data corresponding to varying resistances which is then used to calculate the position of the wrist. Figure 4-10 showcases the common connection pins for a potentiometer. The output pin #2 would be connected to the Arduino board analogue pin.

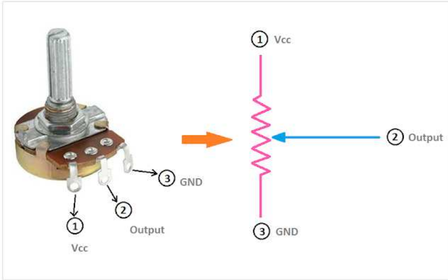


Figure 4-10 Potentiometer pins (EtechNog,2022)

4.2.4 Arduino UNO

Arduino UNO is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header and a reset button (Arduino, 2022). Figure 4-11 provides labeling for the Arduino UNO components and pins. In this project the Arduino UNO power source will be used to provide sufficient voltages for all the sensors and actuators. Furthermore, the analogue pins of the Arduino UNO is used to feed in sensory analogue data from the potentiometer and flex sensors. The digital pins are used to provide position signal to the servomotors in respond to the input data.

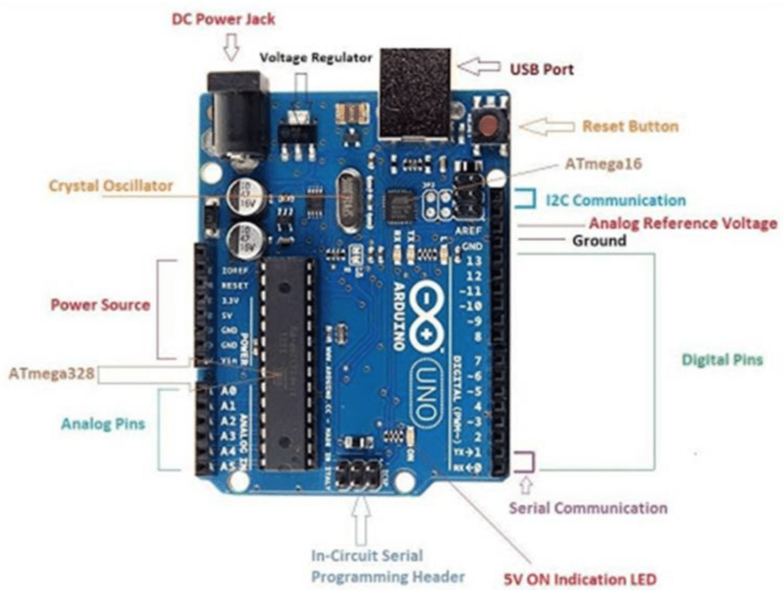


Figure 4-11 Arduino UNO specifications and pins (Arduino,2022).

4.2.5 Electronic Circuit

As there are multiple electrical components involved and thus an electrical schematic diagram is required to visualize the inputs and outputs connections and their related pins. TinkerCAD is a free web app for 3D design, electronics and coding and was used to design the required electronic circuitry. Figure 4-12 shows the TinkerCAD simulation design of the electrical components involved for the sensory glove, wrist exoskeleton and servomotors.

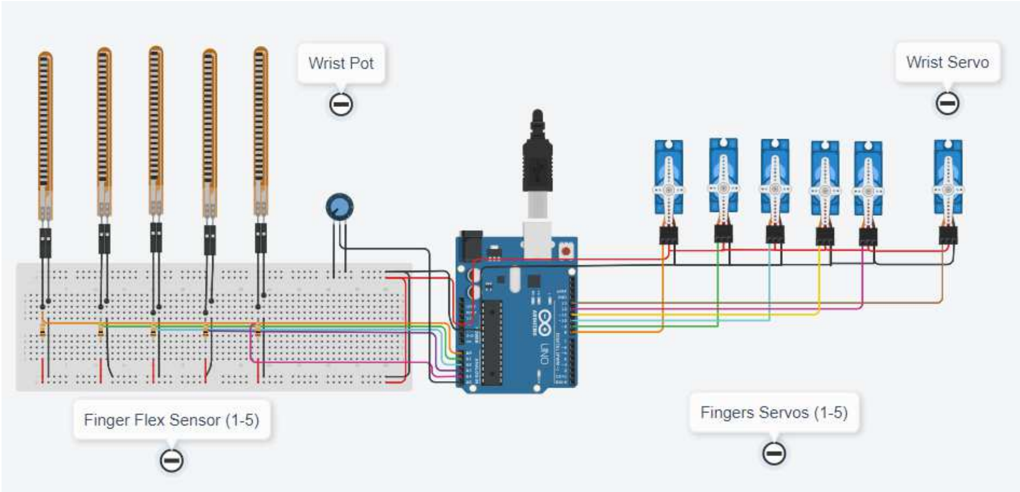


Figure 4-12 TinkerCAD based electronic circuit simulation and design.

Furthermore, Table 4-2 below lists down the electronic parts and their corresponding pins for the Arduino UNO board.Sensors are connected to the analogue pins of the board whereas the actuators are connected to the digital pins of the board.

Table 4-2 List electronic parts and their pin connections.

Components	Group	Pin
Potentiometer	Wrist Sensor	A0
Thumb Flex Sensor	Finger Sensor	A1
Index Flex Sensor	Finger Sensor	A2
Middle Finger Flex Sensor	Finger Sensor	A3
Ring Finger Flex Sensor	Finger Sensor	A4
Pinky Finger Flex Sensor	Finger Sensor	A5
Servo 0	Wrist Actuator	13
Servo 1	Finger Actuator	12
Servo 2	Finger Actuator	11
Servo 3	Finger Actuator	10
Servo 4	Finger Actuator	9
Servo 5	Finger Actuator	8

Chapter 5 Results and Discussion

5.0.1 Animatronic Hand

The assembly of the 3D printed components and the electronics was done. M2 headless bolts were used as the interlock and joints needed to join the different pieces of the fingers, then soldering was used to one end of the bolts to ensure that the bolts do not slip out. Furthermore, adhesive substance was used to attached parts of the fingers together. M3 bolts, which are thicker than M2 bolts, were then used to mount the finger base assembly onto the main hand of the robot, as well as attaching the robot hand on the metal brackets of the Feetech FR0109m servomotor. Figures 5-1 showcases the final assembled view of the robotic fingers and their connections to the MG90s servomotors. Figure 5-2 shows the entire hand assembly as it is mounted on an elevated platform. The end of the anthropomorphic hand can be placed as the end of a robotic hand to act as an end effector.

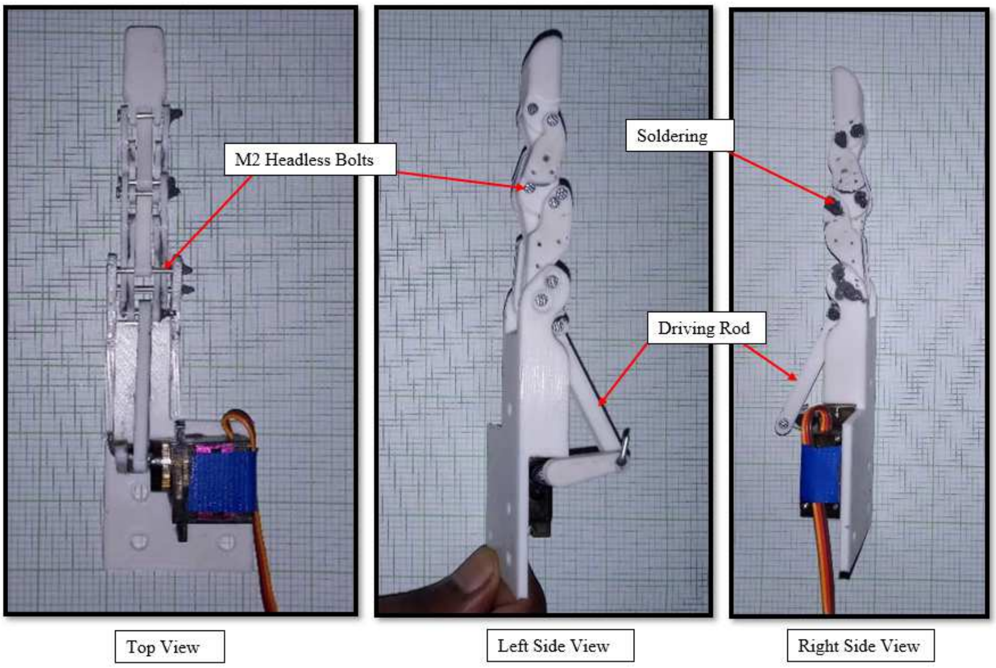


Figure 5-1 Anthropomorphic finger component assembly along with MG90s servomotor.

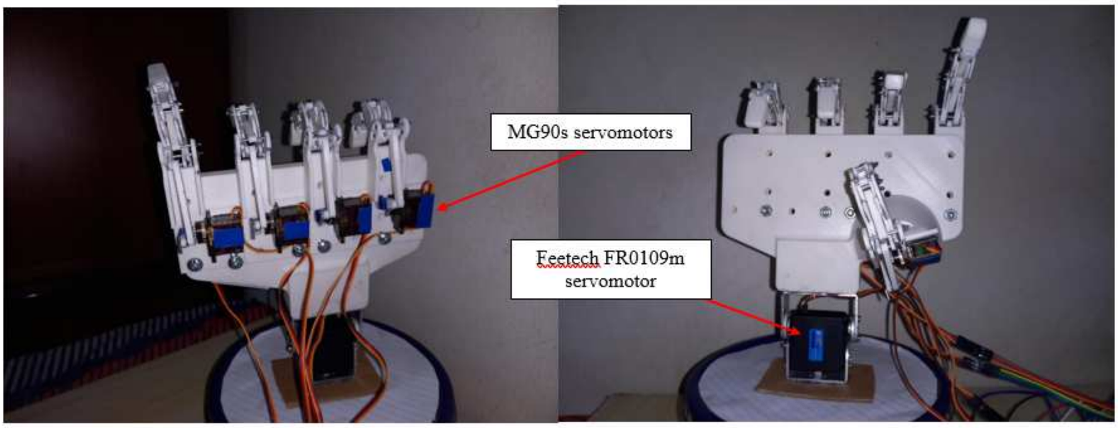


Figure 5-2 Entire hand assembly front and back view.

5.0.2 Sensory Glove and Exoskeleton

The next step was the assembly and building of the sensory glove embedded with flex sensors as well as the wrist exoskeleton. The flex sensors tip were glued on the glove specific bending locations to correspond to the human finger bending maneuvers. As for the exoskeleton, it consists of 2 parts; one part housing the potentiometer base is secured on the forearm using a green band; another part which will connect to the tip of the potentiometer and has a rod extending to the hand palm. Figure 5-3 showcases the sensory glove whereas Figure 5-4 showcases the wrist exoskeleton, and Figure 5-5 displays all the components involved in the project.

Figure 5-3 Sensory glove with embedded flex sensors.

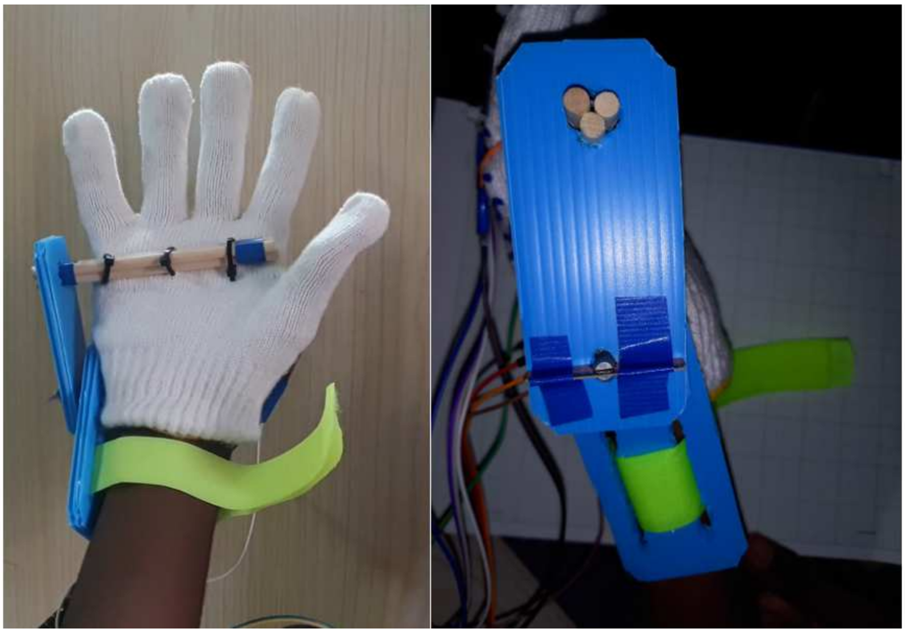


Figure 5-4 Wrist latch exoskeleton parts.

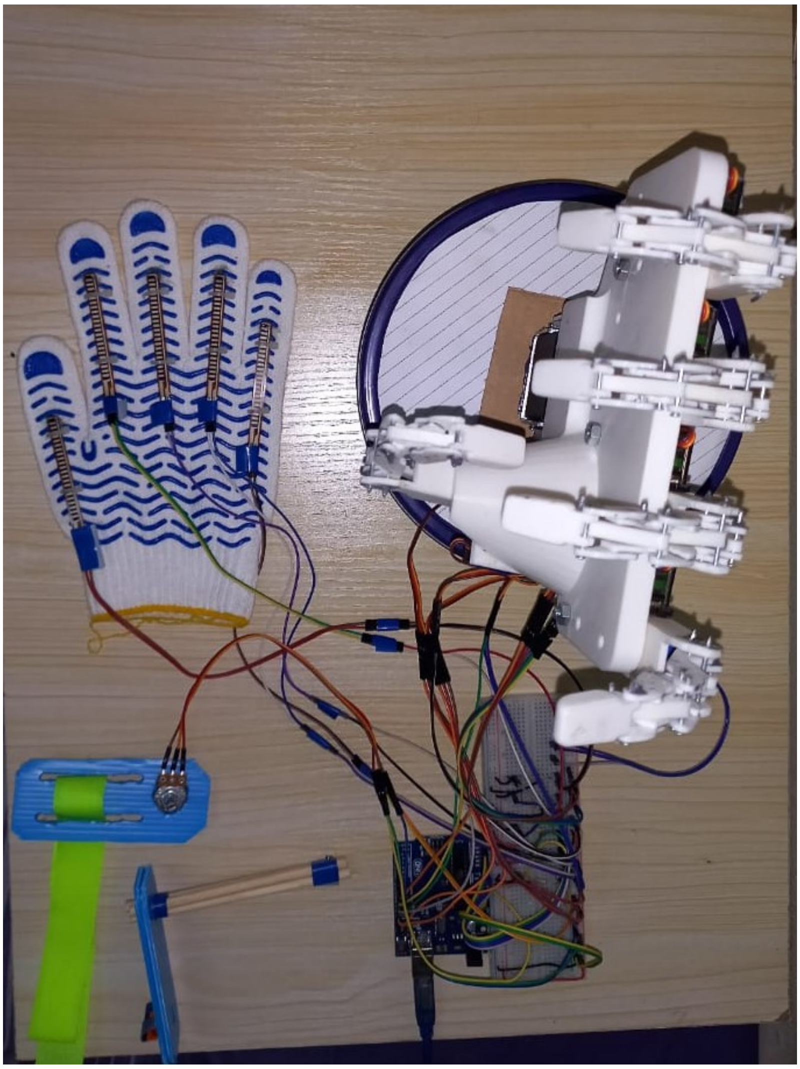


Figure 5-5 Overview of the entire MyHand assembly and electronic components.

5.0.3 Firmware Implementation

Once the relevant electronic connections were setup, the next step is the firmware implementation through the usage of Arduino Integrated Development Environment (IDE) which is an open source software consisting of text editor for writing codes, message area, text console and toolbar to summon and use common establish function libraries. Arduino IDE allows for writing codes that are then uploaded to the Arduino board.Several codes were used to test and build the program that would act as the interface between the input and output devices.

Arduino Codes #1,#2 would be used in Experiment 2 in order to establish the kind of sensory data the potentiometer and flex sensor feedback to the Arduino board. Arduino Code #3 is the entire project code used to teleoperated the MyHand anthropomorphic hand. All relevant codes are attached in Appendix I.

5.0.3.1 Arduino Code #1 - Potentiometer - Servo Control

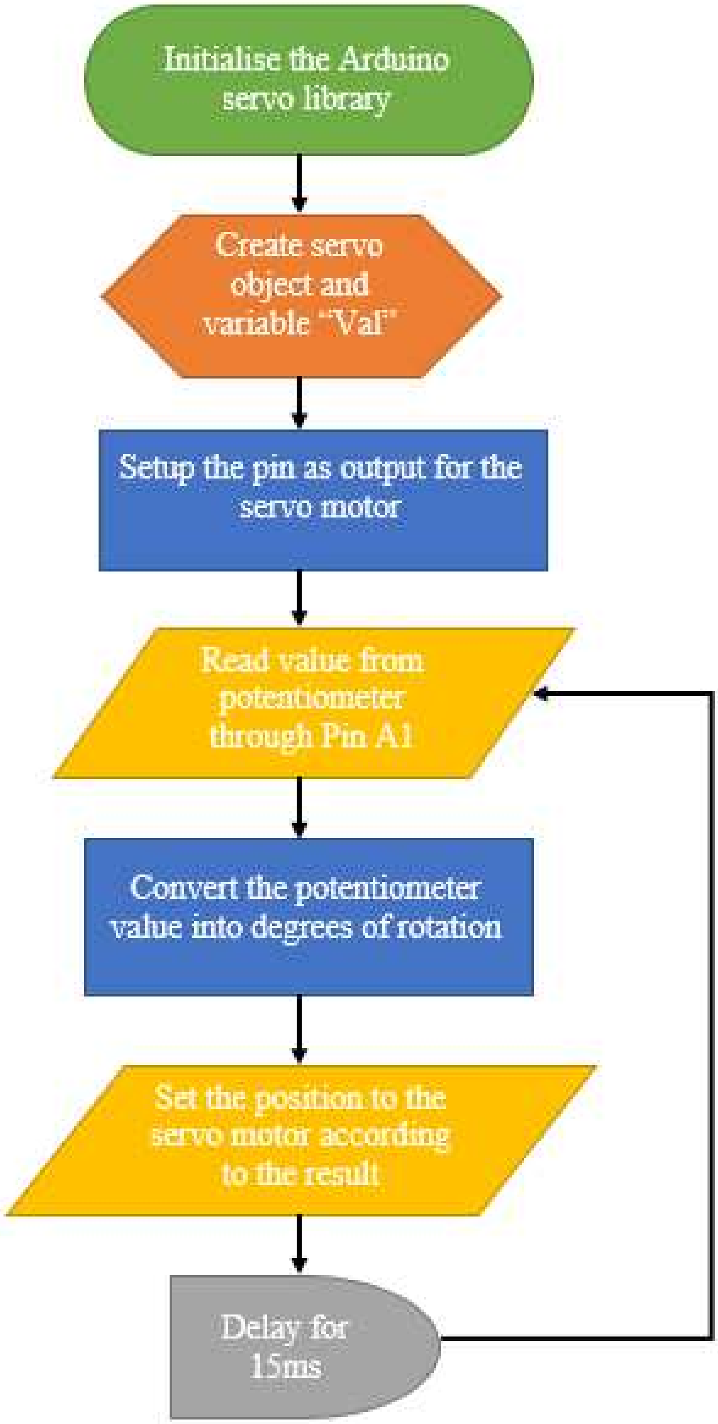


Figure 5-6 Flowchart for the Arduino IDE code for potentiometer-servomotor control.

```
//Potentiometer Servo Control
#include <Servo.h> //accesses the Arduino Servo Library

Servo myservo;  // creates servo object to control a servo

int val;    // variable to read the value from the analog pin

void setup()
{
  myservo.attach(8);  // ensures output to servo on pin X
}


//To control using potentiometer
void loop()
{
  // reads the value of the potentiometer from A1 (value between 0 and 1023)
  val = analogRead(1);
  // converts reading from potentiometer to an output value in degrees of rotation
  val = map(val, 0, 1023, 0, 180);
  // sets the servo position according to the input from the potentiometer
  myservo.write(val);
  // waits 15ms for the servo to get to set position
  delay(15);
}
```

Figure 5-7 Arduino IDE code for potentiometer-servomotor control.

The potentiometer was firstly tested and its capability to control a servomotor and its code is shown by Figure 5-7 and Figure 5-6 provides the process flow for the code. Three varying potentiometers were used which are 100ohm, 10kohm and 50kohm potentiometers. It was noted that as the maximum resistance of the potentiometer increased, the servomotor movements becomes smoother and less erratic. Reasoning behind this behavior is that the larger resistance potentiometer allows for more sensitive reading from the 0 to 1023 range.

The potentiometer control code was used to determine the initial and maximum rotation value of the servomotors actuating the fingers.This is crucial step because if the angle fed into the servomotor was for instance too small or too large, the shaft will pull or push the finger connecting linkage to either extreme ends (over flexing/over extension) which would then damage the finger parts, links and screws.

5.0.3.2 Arduino Code #2 - Flex Sensor Reader

A voltage divider circuit is required in order to obtain readings from the flex sensors. As was seen in the TinkerCAD simulation, flex sensor was connected to a fixed value resistor of 51kohm to create a voltage divider. Figure 5-8 shows the voltage divider circuitry,one end of the sensor to Power and the other to a pull-down resistor. The point between the fixed value pull-down resistor and the flex sensor is connected to the ADC input of an Arduino. Furthermore the output voltage can also be calculated from the known constants.

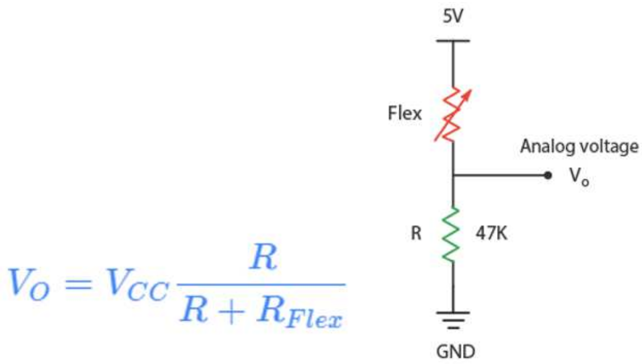


Figure 5-8 Voltage divider circuitry and output voltage equation.

For example, with a 5V VCC and 51K resistor, and when the sensor is flat (0˚), the relative resistance to low is around 10k ohm. Output voltage is then

$$Vo = 5V\frac{51k}{51k + 10k} = 4.18V$$

with a 5V VCC and 51K resistor, and when the sensor is bent (90˚), the relative resistance to low is around 80k ohm. Output voltage is then

$$Vo = 5V\frac{51k}{51k + 80k} = 1.94V$$

Based on this relation, an Arduino code script was made in order to measure and record the angle of bending of the flex sensor. Figure 5-10 displays the code used and the flowchart in Figure 5-9 describes the code flow.

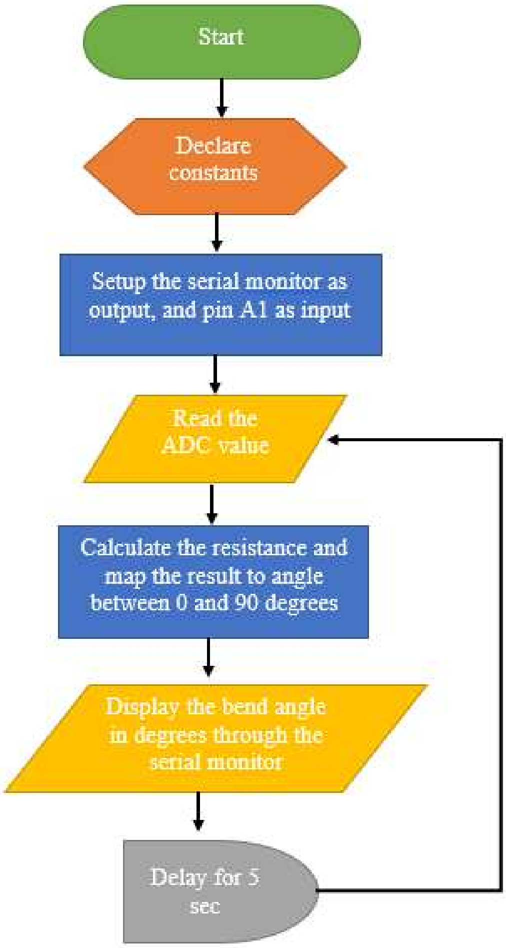


Figure 5-9 Flowchart for Arduino IDE code for reading flex sensor data version #1.

```
//Flex Sensor Reader 2
const int flexPin = A1;      // Pin connected to voltage divider output

// The constants were derived from the components used
const float VCC = 5;       // voltage at Ardunio 5V line
const float R_DIV = 50000.0;  // resistor used to create a voltage divider
const float flatResistance = 10000.0; // resistance when flat
const float bendResistance = 80000.0;  // resistance at 90 deg

void setup() {
  Serial.begin(9600);
  pinMode(flexPin, INPUT);
}

void loop() {
  // Read the ADC, and calculate voltage and resistance from it
  int ADCflex = analogRead(flexPin);
  float Vflex = ADCflex * VCC / 1023.0;
  float Rflex = R_DIV * (VCC / Vflex - 1.0);
  Serial.println("Resistance: " + String(Rflex) + " ohms");

  // Use the calculated resistance to estimate the sensor's bend angle:
  //Map the values from 0 to 90 degrees
  float angle = map(Rflex, flatResistance, bendResistance, 0, 90.0);
  Serial.println("Bend: " + String(angle) + " degrees");
  Serial.println();

  delay(5000);
}
```

Figure 5-10 Arduino IDE code for reading flex sensor data version #1.

Another more direct method was used to capture the analogue data of the and display it in a range of continuous signals is shown in Figure 5-12 and corresponding flowchart in Figure 5-11. This step allowed for identifying the maximum and minimum sensor values that would then be used in the main code of the robotic hand.

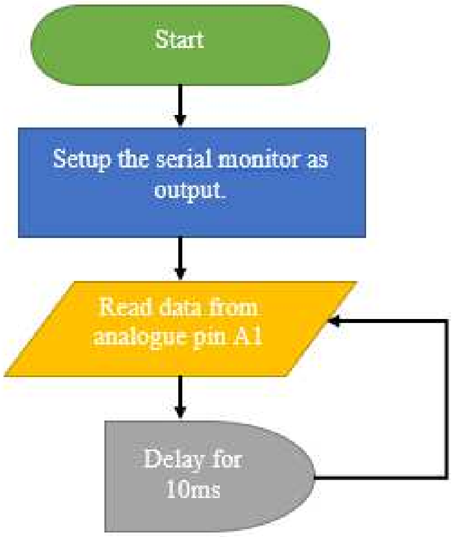


Figure 5-11 Flowchart for the Arduino IDE code for reading flex sensor data version #2.

```
//Arduino Code #2 - Flex Sensor Reader (Version 1)
void setup() {
Serial.begin(9600); //To allow series data communication
}

void loop() {
Serial.println(analogRead(1));  //read the data from analogue pin 1
delay(10);
}
```

Figure 5-12 Arduino IDE code for reading flex sensor data version #2.

5.0.3.3 Arduino Code #3 - "MyHand" Teleoperated Robotic Hand

Having tested and configured the separate sensors and servomotors, the next step was to write a code that would then teleoperate the animatronic hand. Figures 5-14 and 5-15 show part of the code used while Figure 5-13 shows the entire code process. The first step is to initialize the sensors and servomotors using Arduino library objects. After which, the potentiometer controlled wrist was configured using the "Wrist control" segment. As for the flex sensors and fingers servomotor, the segments "Thumb Control" up-to "Pinky Control" were written to read data from the flex sensors and map it to the servomotors. Adjustments to each of the control units was required the sensors configurations slightly differed from one another,thus the code needs to accommodate for those slight changes in max/min sensory values.

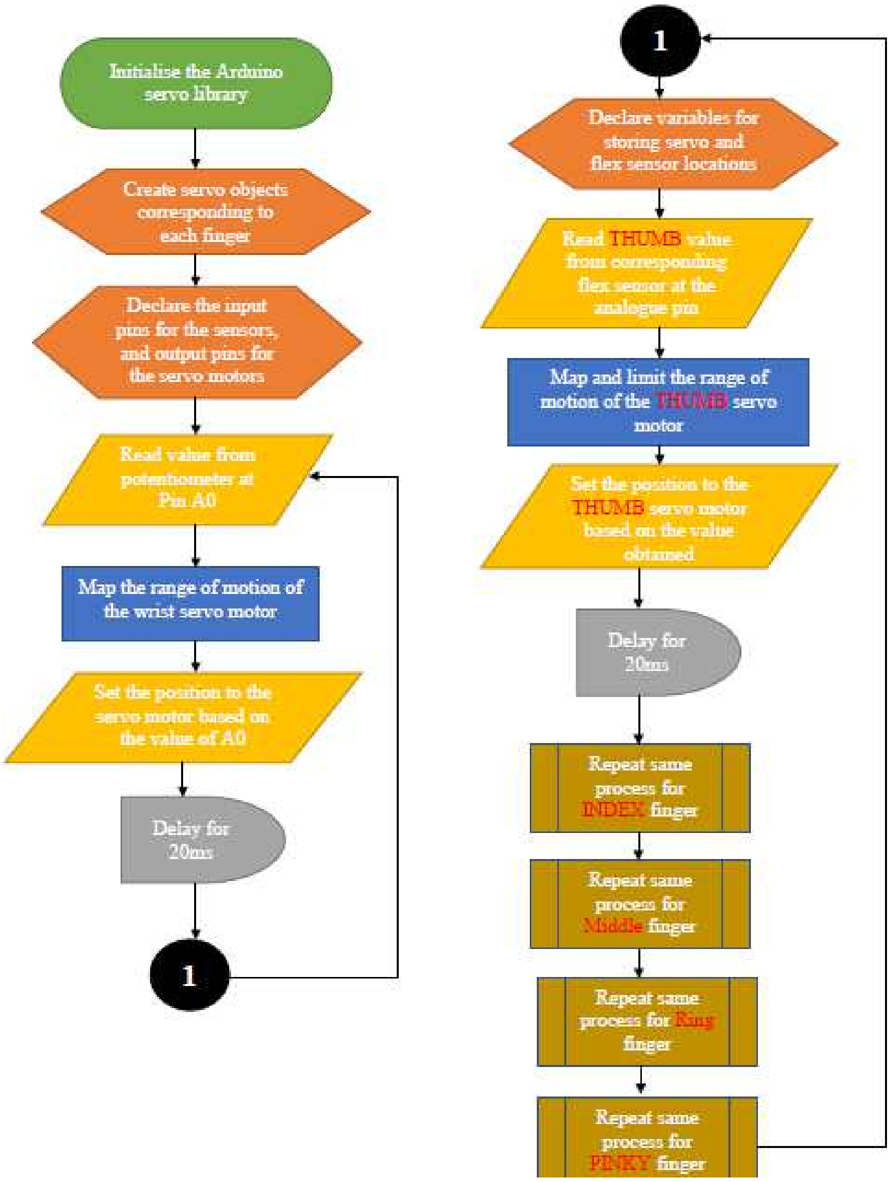


Figure 5-13 Flowchart for the Arduino IDE code for “MyHand” teleoperated robotic hand.

```
//Mosaab Adil Elamin
//FYP Project Title: Design and Development of an Animatronic Hand
//Utilises Flex Pressure Sensors and Potentiometer
//To drive 6 servomotors


//Access Arduino Servo Library
#include <Servo.h>

//Create Servo Objects
Servo servo0; //Wrist
Servo servo1; //Thumb
Servo servo2; //Index
Servo servo3; //Middle Finger
Servo servo4; //Ring Finger
Servo servo5; //Pinky

//Configuring Sensor Pins for Input
int wrist_val;              //Wrist (A0)
int FlexSensor1 = 1;        //Thumb (A1)
int FlexSensor2 = 2;        //Index  (A2)
int FlexSensor3 = 3;        //Middle Finger (A3)
int FlexSensor4 = 4;        //Ring Finger (A4)
int FlexSensor5 = 5;        //Pinky (A5)
```

```
void setup()
{
//Configuring Servomotors Pins for Output
servo0.attach(13);  //Wrist
servo1.attach(12);  //Thumb
servo2.attach(11);  //Index
servo3.attach(10);  //Middle Finger
servo4.attach(9);   //Ring Finger
servo5.attach(8);   //Pinky


}


void loop()
{
  ///////////////////////////////////////////////////////////////
                  // Wrist Control//
  wrist_val = analogRead(0);        //Read Potentiometer from A0
  //Configure range of motion - Limited to only 30 degree to 150 degree
  wrist_val = map(wrist_val, 0, 1023, 30, 150);  //Configure range of motion
  servo0.write(wrist_val);
  delay (20);
```

Figure 5-14 The first and second parts of the Arduino code.

```
//////////////////////////////////////////////////////////////////
                        // Thumb Control//
//Declaring ServoMotor position and Flex Sensor position
int flexpos1;
int servopos1;

//Read flex sensor value through Analogue Input
flexpos1 = analogRead(FlexSensor1);

//Mapping the sensory value to servomotor position
//servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo));
servopos1 = map(flexpos1, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers
servopos1 = constrain(servopos1, 80, 120);

//Writing servo position
servo1.write(servopos1);
```

```
//////////////////////////////////////////////////////////////////
                        // Index Control//
//Declaring ServoMotor position and Flex Sensor position
int flexpos2;
int servopos2;

//Read flex sensor value through Analogue Input
flexpos2 = analogRead(FlexSensor2);

//Mapping the sensory value to servomotor position
//servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo));
servopos2 = map(flexpos2, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers
servopos2 = constrain(servopos2, 80, 120);

//Writing servo position
servo2.write(servopos2);
```

Figure 5-15 Consequent parts of the Arduino code

5.0.4 Experiment 1 - Individual Fingers and Wrist Range of Motion

In this section, each of the fingers and wrist range of motion was documented as to identify the maximum and minimum flexion and extension of the finger and wrists.

5.0.4.1 Finger

Figure 5-16 shows the range of motion of a single anthropomorphic finger. The finger base (Proximal Phalange),middle (Medial Phalange) and tip (Distal Phalanges) extend and flex in response to the connecting rod attached to the servomotor. The finger maximum flexion is seen in Figure 5-16-A whereas the maximum extension is seen in Figure 5-16-D. The finger mechanical structure does not allow it to flex and extend beyond those range of motion. Figure 5-17 maps and overlaps the motion of the finger parts as it flexes/extends to visualize the range of motion the anthropomorphic finger can exhibit.

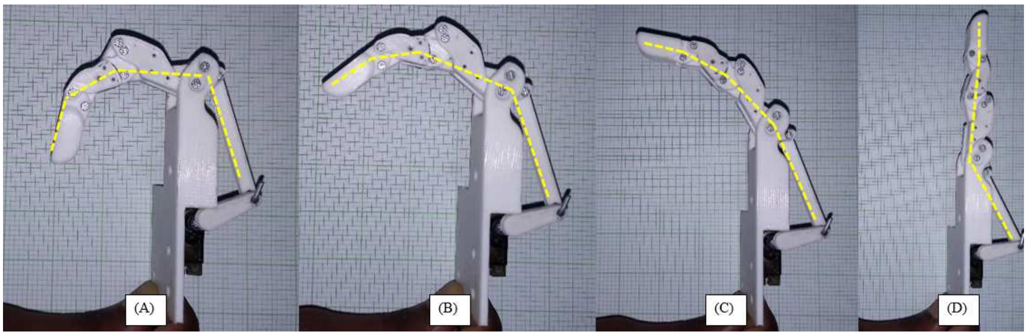


Figure 5-16 Anthropomorphic finger range of motion as it extends from A to D

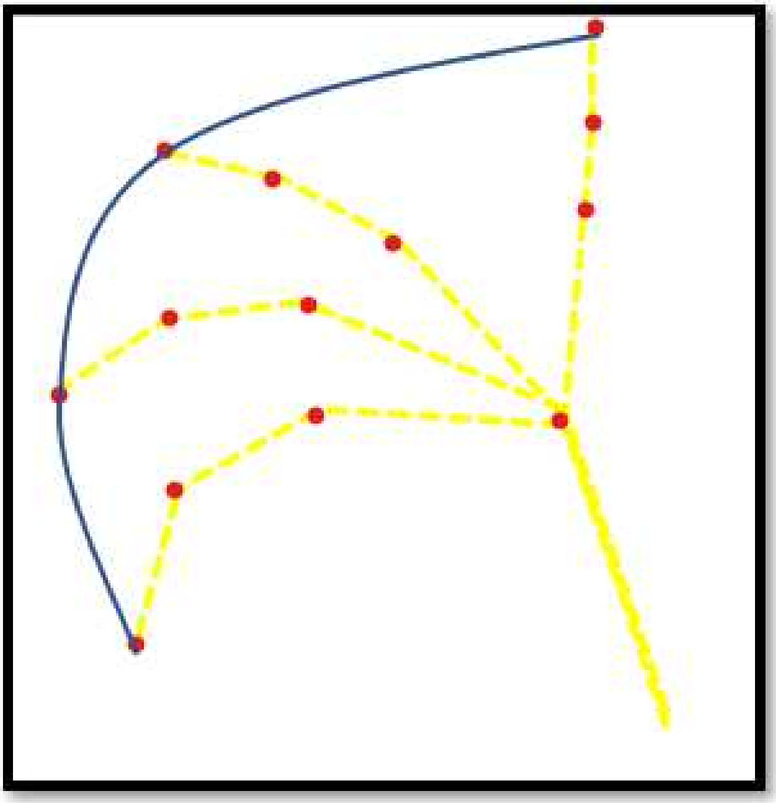


Figure 5-17 Anthropomorphic finger range of motion map.

5.0.4.2 Wrist

Figure 5-18 shows the full extension and flexion possible for the wrist joint as it moves the entire hand and Figure 5-19 maps the motion range of the wrist joint. It was measured and recorded that the wrist joint is capable of total maximum of 143° rotation as it secured to the platform limiting its range of motion, but it should be able to go up-to 180° with a smaller arm/attachment platform. The rotational angles of the wrist where recorded based on the location of the wrist at its maximum flexion, extension and upright positions.

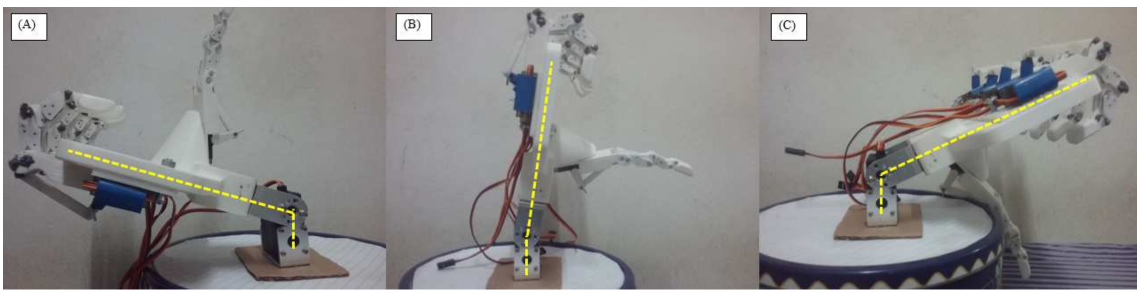


Figure 5-18 Wrist joint as it rotates from one side to another.

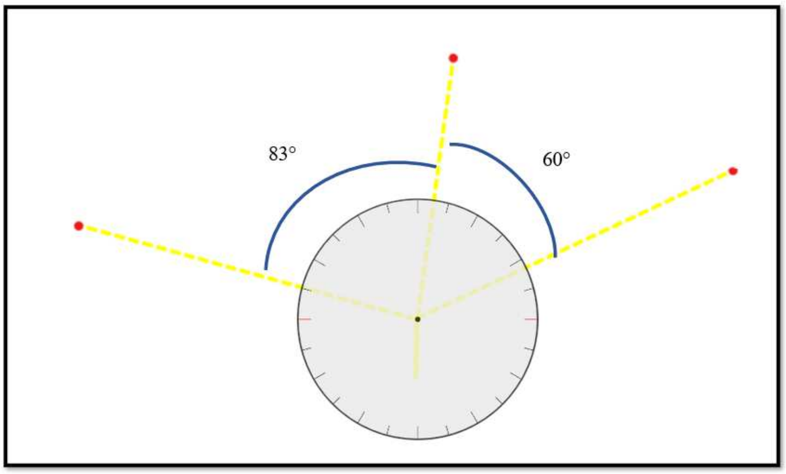


Figure 5-19 Wrist joint range of motion map.

5.0.5 Experiment 2 - Sensory Glove Data Acquisition

In this section, the Arduino codes #1 and #2 documented earlier were uploaded to the Arduino board in order to collect the input data generated by the wrist latch potentiometer and the flex sensors embedded into the glove. Serial monitor and serial plotter of the Arduino IDE were used to display the data.

5.0.5.1 Potentiometer Data

Figure 5-120 shows the range of data provided by the analogue potentiometer using the Arduino Serial Plotter. It can be noticed that the potentiometer digital data ranges from 0 to 1023, and the reading fluctuates within this range as the potentiometer head is rotated. Acquisition of the potentiometer input data and identifying its range would then be mapped to the servomotor in units of degree as was shown in Arduino Code #3.

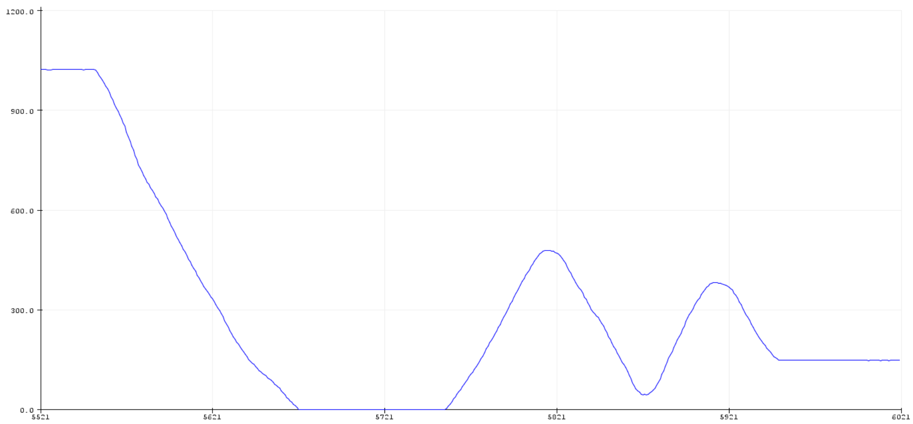


Figure 5-20 potentiometer input data as it being twisted between maximum to minimum.

5.0.5.2 Flex Sensor Data

The flex sensor data was collected graphically and numerically. Figure 5-21 uses the Arduino Serial plotter and Arduino Code #2 (Version 2) to graph the data input changes that occur when the flex sensor is bent then relaxed. It can be seen that the flex sensor data ranges from 0 to 730 and when bent has a peak of 730, whereas when it is relaxed the peak is at around 350. Due to the nature of the flex sensor, input data fluctuates to produce those high and low peaks seen. In order to reduce the fluctuation of the input data received from the flex sensor, maximum and minimum values were recorded to determine the position state of the flex sensor. Max value means the flex sensor is fully bent, whereas Min value means the flex sensor is fully relaxed. It needs to also be noted that each flex sensor have slight differences in the Max and Min values due to slight changes in circuitry resistances. As shown in Figure 5-22, the input data is better recorded through the use of the Arduino Serial monitor and Arduino Code #2 (Version 1) to convert the flex sensor resistance into digital values corresponding to unit degrees. These input sensory values can then be transformed into an excel sheet for further studying on the bending variations of the flex sensors.

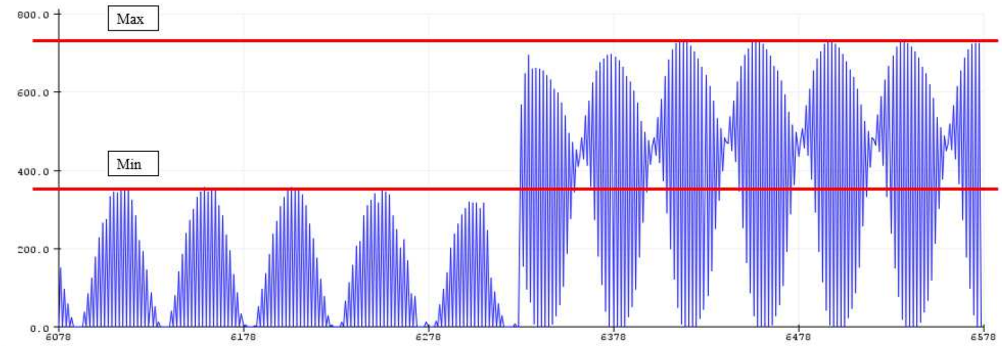


Figure 5-21 Flex sensor input data using Arduino serial plotter.

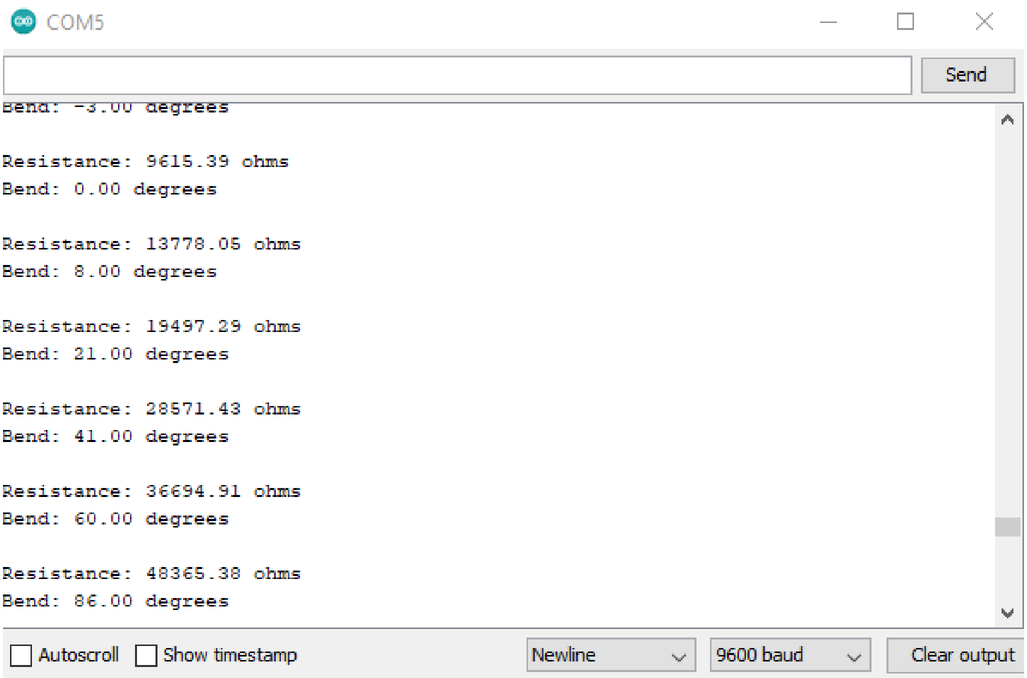


Figure 5-22 Flex sensor input data using Arduino serial monitor.

5.0.6 Experiment 3 - Teleoperation of the Anthropomorphic Hand

5.0.6.1 Mimicry of Human Hand and Wrist

In this section, the Arduino codes #3 was uploaded to the Arduino UNO board in order to teleoperate the anthropomorphic hand and wrist. Figure 5-23 demonstrates the teleoperation of the MyHand fingers (slave) as they mimic the human hand (master). The flex sensor reads whether the finger is bent or not, then sends that data to the Arduino board. The servomotors are then actuated to rotate the shaft connecting the finger linkages to fully extend or flex the fingers. When flex sensor is bent, the fingers are flexed; when the flex sensor is relaxed, the fingers are extended. Figure 5-24 demonstrates the teleoperation of the MyHand wrist joint as the human wrist gets twisted.

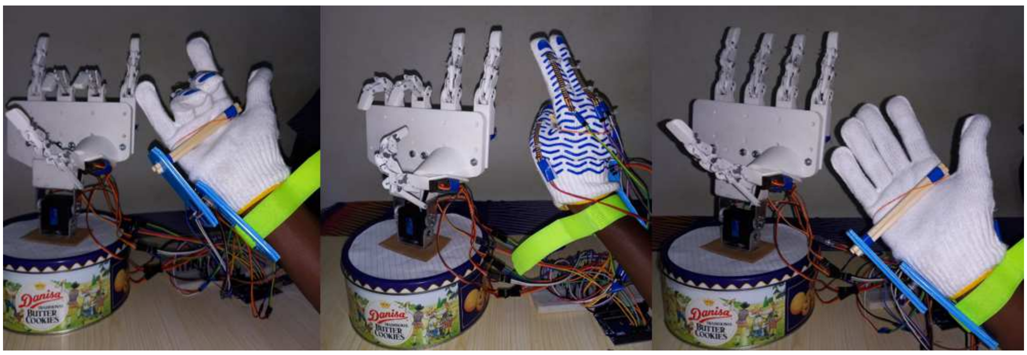


Figure 5-23 Teleoperation of the fingers using various finger gestures.

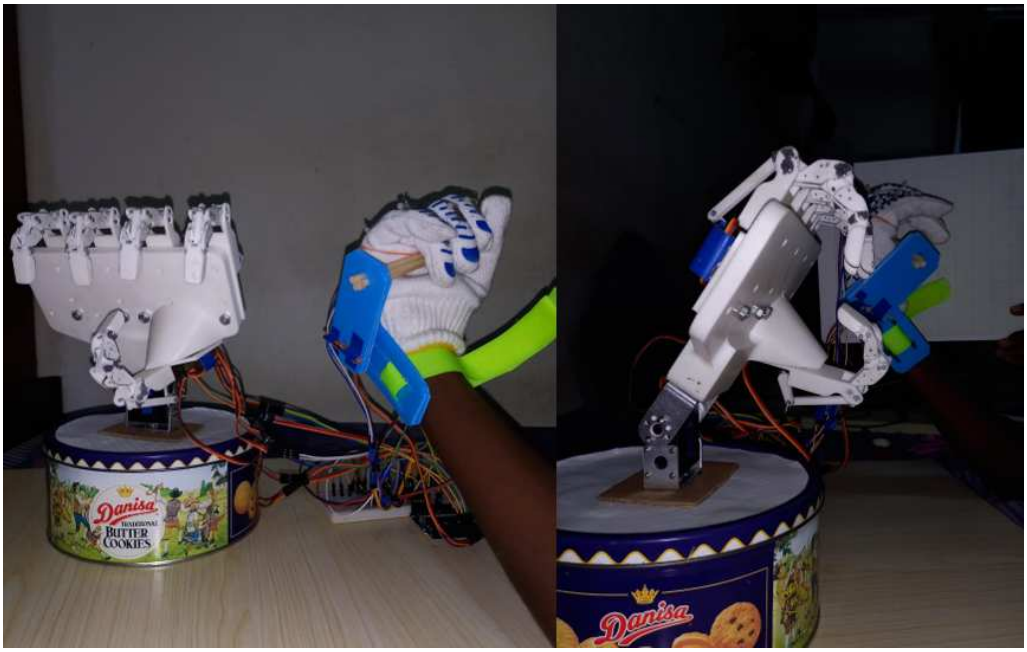


Figure 5-24 Teleoperation of the wrist joint by twisting the human wrist.

However, during the testing of the teleoperation of anthropomorphic hand there were some issues faced. Firstly, the servomotors would sometimes get actuated and would extend/flex without the relaxing/bending of the flex sensor which leads to erratic behavior of the fingers. Possible reason could be the sudden resistance spikes when the flex sensor is bent/relaxed that would then lead to the servomotor getting actuated prematurely. Secondly, in regards to the wrist motion, the potentiometer maximum degree of motion when mounted to the wrist latch was determined to be 120° which is due to the mechanical structure of the wrist latches not capable of fully following the 180° natural motion of the human hand, thus the potentiometer could only capture less than 120° of motion.

5.0.6.2 Grasping Capabilities

In this segment, the grasping potential of the anthropomorphic hand was tested as shown in Figure 5-25. Different items were placed within the proximity of the robotic fingers then using the sensory glove, the robotic fingers were flexed to enclose and hold the item. The hand was capable of firmly holding an item as long as it was cylindrical and large enough to be enclosed by the fingers. If the item size was small or of another shape, the robotic hand grasping would be significantly more loose causing the item to fall off the hand. The main reasoning behind this behavior comes to the mechanical structure and spacing of the robotic fingers. The fingers were spaced out which leads to smaller items not being held firmly as they may fall into the gap between the fingers. Furthermore the robotic fingers do not enclose completely on the object. Figure 5-26 demonstrates the rectangular area which is beyond the finger holding range and therefore items within that size can not be grasped by the fingers.

Figure 5-25 Teleoperation of the fingers to hold and grasp various items.

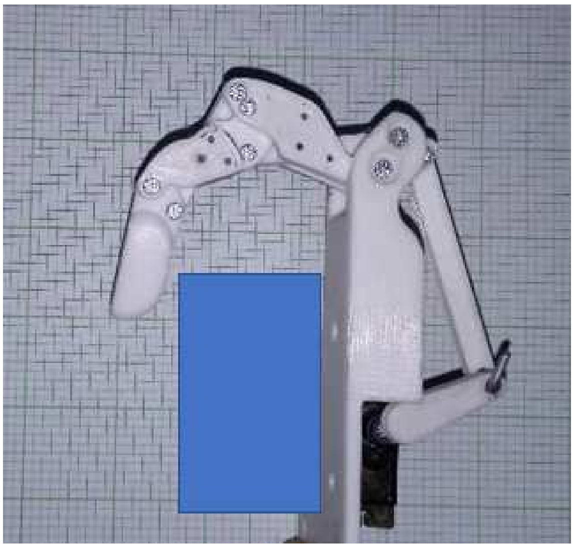


Figure 5-26 Gap in which the robotic fingers are unable to grasp the item.

5.0.7 Limitations

As it was previously discussed, one of the limitations of the robotic hand is its inability of grasping objects of certain size that is smaller than what the finger modules can hold.Furthermore, due to the adoption of servomotors as substitutes for linear actuators, the finger assembly and width area increased, which resulted in the robotic hand having an overall much wider dimensions than those of the human hand. This lead to the reduced dexterity in grasping and holding of small sized objects.

Moreover, the flex sensor configuration allows for only two sets of motion which are flexion or extension; either fully extended or fully flexed with no in between. This means that if a human finger semi-bends, the robotic hand would mimic it in terms of fully extend or fully flex within the allowable 40° of motion of the servomotor shaft. Due to this limitation, the accuracy of the robotic hand in mimicking the human finger is reduce to only encompass a limited range of motion, even though the human finger is capable of more range and accurate positioning. This could be overcome by installing smaller flex sensor at each of the finger 3 joints to detect the bending of that specific joint. The data can then be used to actuate the motors into more specific degrees of rotation.

Another limitation that was noted in the project is the that the robotic hand and sensory glove utilises wired connections in order to be teleoperated. Wired connections limits the work space area of the robotic hand and sensory gloves and their distance from the control unit. One method to overcome this issue is to equip the robotic hand and sensory glove with wireless/WiFi microcontroller such as Realtk RTL8195 or Raspberry Pi Pico W that would send and receive command data and accept commands.

5.0.8 Prototype Specifications and Approximate Cost

In order for the robotic hand to be commercially available, the specifications and estimated cost are tabulated below. Table 5-1 lists specifications of the robotic, sensory glove and wrist exoskeleton. Table 5-1 lists the approximate overall cost of the project.

Table 5-1 MyHand Anthropomorphic Hand Specification.

Index	Specification
Total Weight	510g
Weight of Finger Assembly	60g
Robotic Hand Configuration	5 Fingers,1 Wrist; 6 Rotary Motors
Sensory Glove Configuration	5 Flex Sensors, 1 Potentiometer
Operating Voltage	5V
Degrees of Freedom	16
Size of MyHand	176 mm × 114 mm × 68mm (W × L × H)
Size of Finger Assembly	44mm × 157 mm × 30 mm (W × L × H)
Microcontroller	Arduino UNO Rev-3
Robotic Wrist Joint Range	180°
Wrist Exoskeleton Range	120°

Table 5-2 Estimates for the cost of the project components.

Item	Cost (RM)
3D Printing of parts	~257
Flex Sensors (5)	225
Freetech 10kg Servomotor	62
MG90S Metal Gear (5)	70
Arduino UNO Rev-3	25
Miscellaneous (Wires/bolts/etc)	~55
Total Cost	~694

Chapter 6 Conclusion

In this research, the working principles of the human hand, fingers and wrist were studied and their range of motion was reviewed as well as the teleoperation methods using sensory and actuation devices coupled with microcontroller. Furthermore, research was conducted on the various actuation techniques and designs of anthropomorphic hands, fingers and wrists. In particular the design of underactuated robotic fingers that reduces the degrees of actuation while maintaining the degrees of freedom was studied.

The result was the fabrication and production of a master-slave system compromising of a sensory glove and wrist exoskeleton that teleoperates a robotic hand with fingers and a wrist controlled using servomotors. The 3D model of the robotic hand using underactuation techniques and housing the fingers actuators was produced which was then 3D printed to form a physical prototype. The sensory glove built utilised 5 flex sensors to detect the bending of the human finger and the wrist exoskeleton was designed to capture the rotation of the human wrist as it flexes or extends. Electrical connections between the input and output devices and the microcontroller were established and configured. The input analogue data is collected by an Arduino UNO microcontroller that converts it into digital information that is then used to actuate 6 servomotors.

Testing was conducted in order to evaluate the preformance of the animatronic hand as well as the accuracy and precision of mimicry of the robotic hand to the motion of the human hand. The response speed of the robotic hand to the changes in the position of the human finger allowed it to instantly adjust to the desired position. Furthermore, the robotic hand was capable of mimicking the bending movement of the human finger and responds by either fully extending or flexing the finger modules. Moreover, the wrist joint was capable of rotating to the required angular position captured from the wrist exoskeleton however it is limited by the wrist exoskeleton being capable of reading upto 120 degrees of motion. The grasping capability of the robotic hand was tested and demonstrated and it was found that cylindrical object were firmly grasped whereas other objects of different sizes are either loosely held by the fingers or sometimes can not be grabbed.

6.1 Recommendation

Further work can be made in order to improve the preformance of the robotic hand and its teleoperation system to achieve better control and accurate mimicry of the human hand motion. Tactile sensors that are capable of measuring information arising from physical interaction with its environment can be mounted on the robotic fingers in order to detect the presence of an object being held. This would provide the robotic fingers with more dexterity and sensitivity while handling items as it prevents the items from being compressed or crushed. Additionally, muscle sensors or disk light encoders can be attached to the forearm in order to capture the pronation and supination of the wrist and forearm which would then be used to further add another degree of freedom to the base of the robotic hand and joint.

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Appendix I

6.2 Arduino Code #1

//Arduino Code #1 - Potentio Servo Control #include <Servo.h> //accesses the Arduino Servo Library

Servo myservo; // creates servo object to control a servo Servo thumb; Servo index; Servo middle; Servo ring; Servo pinky; int val; // variable to read the value from the analog pin

void setup() { myservo.attach(13); // ensures output to servo on pin X thumb.attach(12); index.attach(11); middle.attach(10); ring.attach(9); pinky.attach(8); }

/* //To control using potentiometer void loop() { // reads the value of the potentiometer from A1 (value between 0 and 1023) val = analogRead(1); // converts reading from potentiometer to an output value in degrees of rotation val = map(val, 0, 1023, 0, 180); // sets the servo position according to the input from the potentiometer myservo.write(val); // waits 15ms for the servo to get to set position delay(15); } */

//Configure Motor Location void loop() { val = 130; myservo.write(val); thumb.write(val); index.write(val); middle.write(val); ring.write(val); pinky.write(val); delay(150);

//val = 90; //myservo.write(val); //delay(1500); /* val = 90; myservo.write(val); delay(1500);

val = 135; myservo.write(val); delay(1500);

val = 180; myservo.write(val); delay(1500); val = 150; myservo.write(val); delay(150); val = 160; myservo.write(val); delay(1500); */ }

6.3 Arduino Code #2

//Arduino Code #2 - Flex Sensor Reader (Version 1) void setup() { Serial.begin(9600); //To allow series data communication }

void loop() { Serial.println(analogRead(1)); //read the data from analogue pin 1 delay(10); }

//Arduino Code #2 - Flex Sensor Reader (Version 2) const int flexPin = A1; // Pin connected to voltage divider output

// The constants were derived from the components used const float VCC = 5; // voltage at

Ardunio 5V line const float R_DIV = 50000.0; // resistor used to create a voltage divider const float flatResistance = 10000.0; // resistance when flat const float bendResistance = 80000.0; // resistance at 90 deg

void setup() { Serial.begin(9600); pinMode(flexPin, INPUT); }

void loop() { // Read the ADC, and calculate voltage and resistance from it int ADCflex = analogRead(flexPin); float Vflex = ADCflex * VCC / 1023.0; float Rflex = R_DIV * (VCC / Vflex - 1.0); Serial.println("Resistance: " + String(Rflex) + " ohms");

// Use the calculated resistance to estimate the sensor's bend angle: //Map the values from 0 to 90 degrees float angle = map(Rflex, flatResistance, bendResistance, 0, 90.0); Serial.println("Bend: " + String(angle) + " degrees"); Serial.println();

delay(5000); }

6.4 Arduino Code #3

//Mosaab Adil Elamin //FYP Project Title: Design and Development of an Animatronic Hand //Utilises Flex Pressure Sensors and Potentiometer //To drive 6 servomotors

//Access Arduino Servo Library #include <Servo.h>

//Create Servo Objects Servo servo0; //Wrist Servo servo1; //Thumb Servo servo2; //Index Servo servo3; //Middle Finger Servo servo4; //Ring Finger Servo servo5; //Pinky

//Configuring Sensor Pins for Input int wrist_val; //Wrist (A0) int FlexSensor1 = 1; //Thumb (A1) int FlexSensor2 = 2; //Index (A2) int FlexSensor3 = 3; //Middle Finger (A3) int FlexSensor4 = 4; //Ring Finger (A4) int FlexSensor5 = 5; //Pinky (A5)

void setup() { //Configuring Servomotors Pins for Output servo0.attach(13); //Wrist servo1.attach(12); //Thumb servo2.attach(11); //Index servo3.attach(10); //Middle Finger servo4.attach(9); //Ring Finger servo5.attach(8); //Pinky

}

void loop() { // // Wrist Control// wrist_val = analogRead(0); //Read Potentiometer from A0 //Configure range of motion - Limited to only 30 degree to 150 degree wrist_val = map(wrist_val, 0, 1023, 30, 150); //Configure range of motion servo0.write(wrist_val); delay (20); // // Thumb Control// //Declaring ServoMotor position and Flex Sensor position int flexpos1; int servopos1;

//Read flex sensor value through Analogue Input flexpos1 = analogRead(FlexSensor1);

//Mapping the sensory value to servomotor position //servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo)); servopos1 = map(flexpos1, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers servopos1 = constrain(servopos1, 80, 120);

//Writing servo position servo1.write(servopos1); // // Index Control// //Declaring ServoMotor position and Flex Sensor position int flexpos2; int servopos2;

//Read flex sensor value through Analogue Input flexpos2 = analogRead(FlexSensor2);

//Mapping the sensory value to servomotor position //servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo)); servopos2 = map(flexpos2, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers servopos2 = constrain(servopos2, 80, 120);

//Writing servo position servo2.write(servopos2);

// // Middle Finger Control// //Declaring ServoMotor position and Flex Sensor position int flexpos3; int servopos3;

//Read flex sensor value through Analogue Input flexpos3 = analogRead(FlexSensor3);

//Mapping the sensory value to servomotor position //servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo)); servopos3 = map(flexpos3, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers servopos3 = constrain(servopos3, 80, 120);

//Writing servo position servo3.write(servopos3); // // Ring Finger Control// //Declaring ServoMotor position and Flex Sensor position int flexpos4; int servopos4;

//Read flex sensor value through Analogue Input flexpos4 = analogRead(FlexSensor4);

//Mapping the sensory value to servomotor position //servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo)); servopos4 = map(flexpos4, 300, 700, 80, 120);

//limit the servo value between Open Fingers and Closed Fingers servopos4 = constrain(servopos4, 80, 120);

//Writing servo position servo4.write(servopos4); // // Pinky Control// //Declaring ServoMotor position and Flex Sensor position int flexpos5; int servopos5;

//Read flex sensor value through Analogue Input flexpos5 = analogRead(FlexSensor5);

//Mapping the sensory value to servomotor position //servoposX = map(flexposX, min(sensor), max(sensor), min(servo), max(servo)); servopos5 = map(flexpos5, 300, 700, 80, 120);

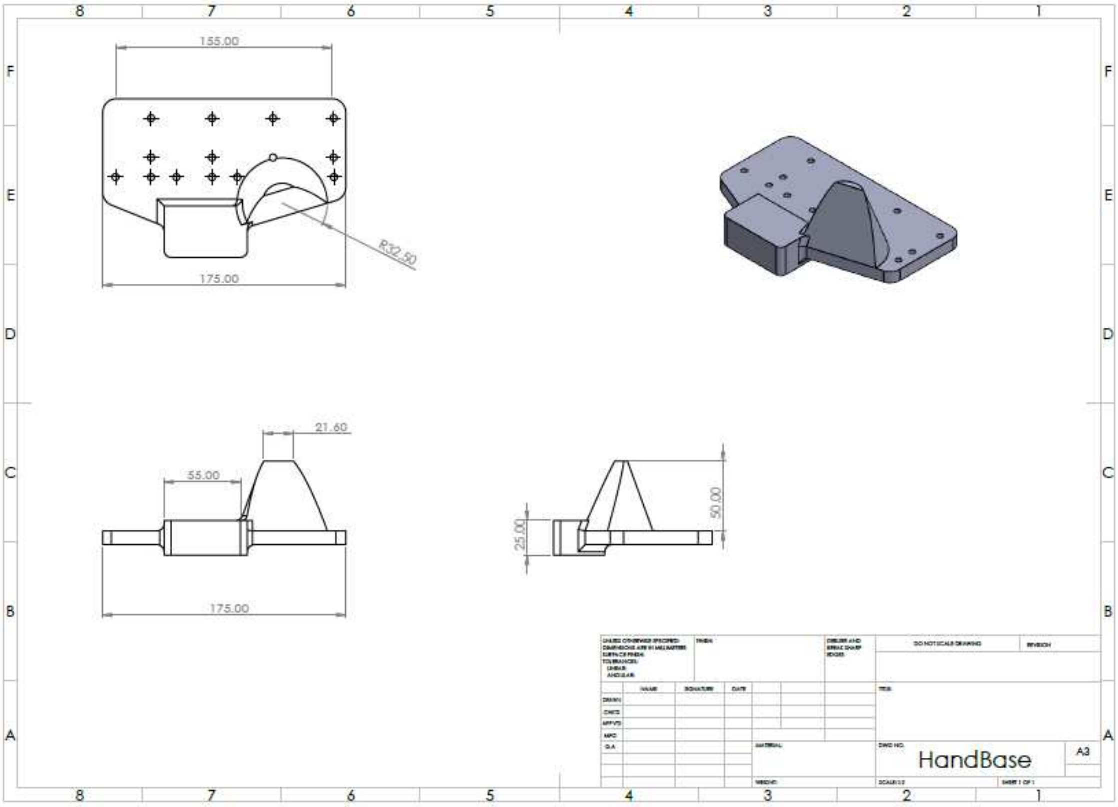
//limit the servo value between Open Fingers and Closed Fingers servopos5 = constrain(servopos5, 80, 120);

//Writing servo position servo5.write(servopos5);

*/ delay(20);

}

Appendix II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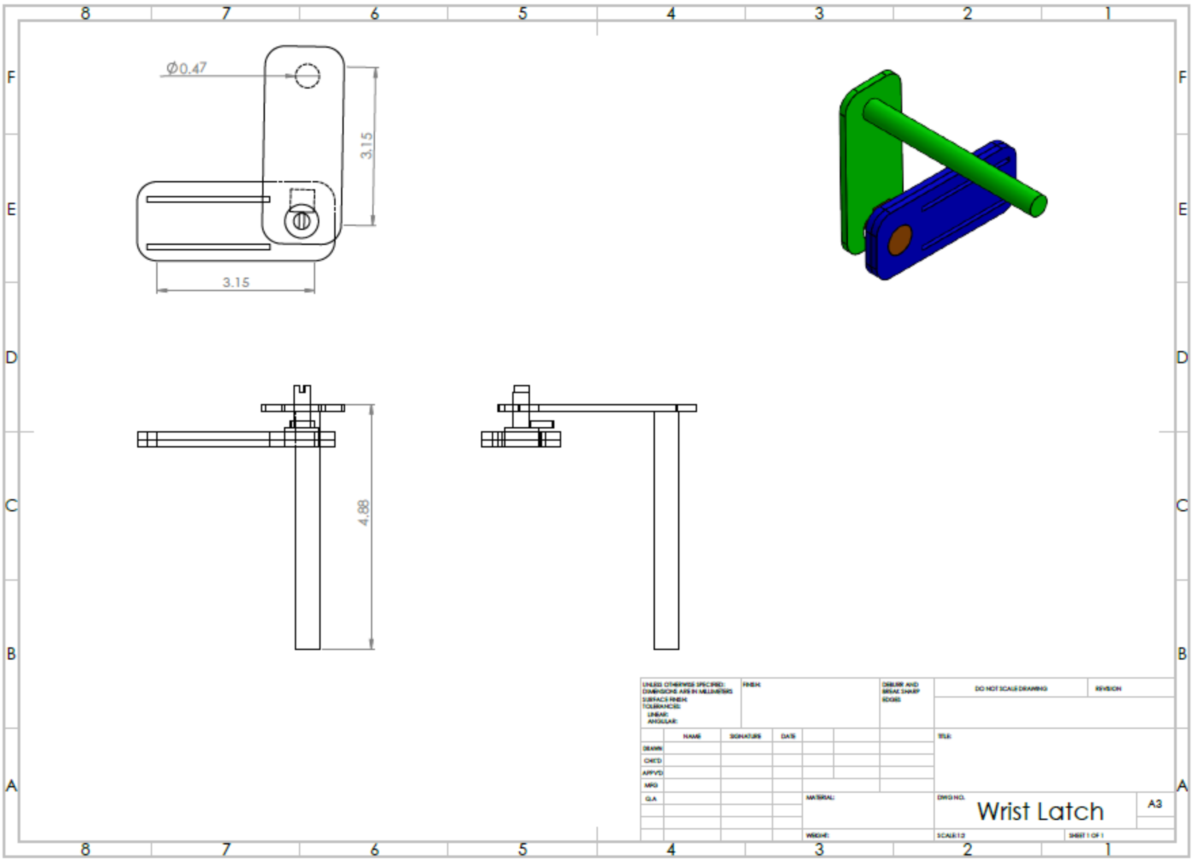
25.00
50.00
HandBase
A3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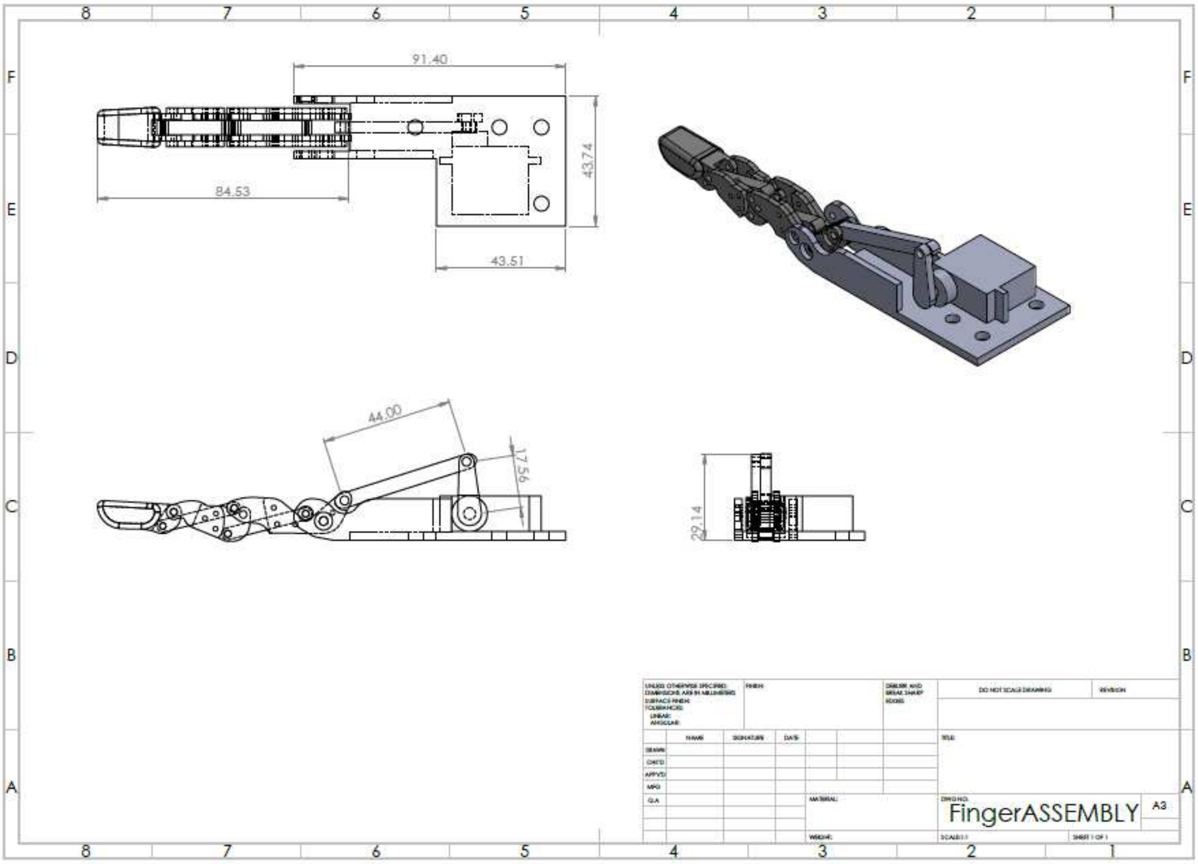
3.15
3.15
4.88
Wrist Latch
A3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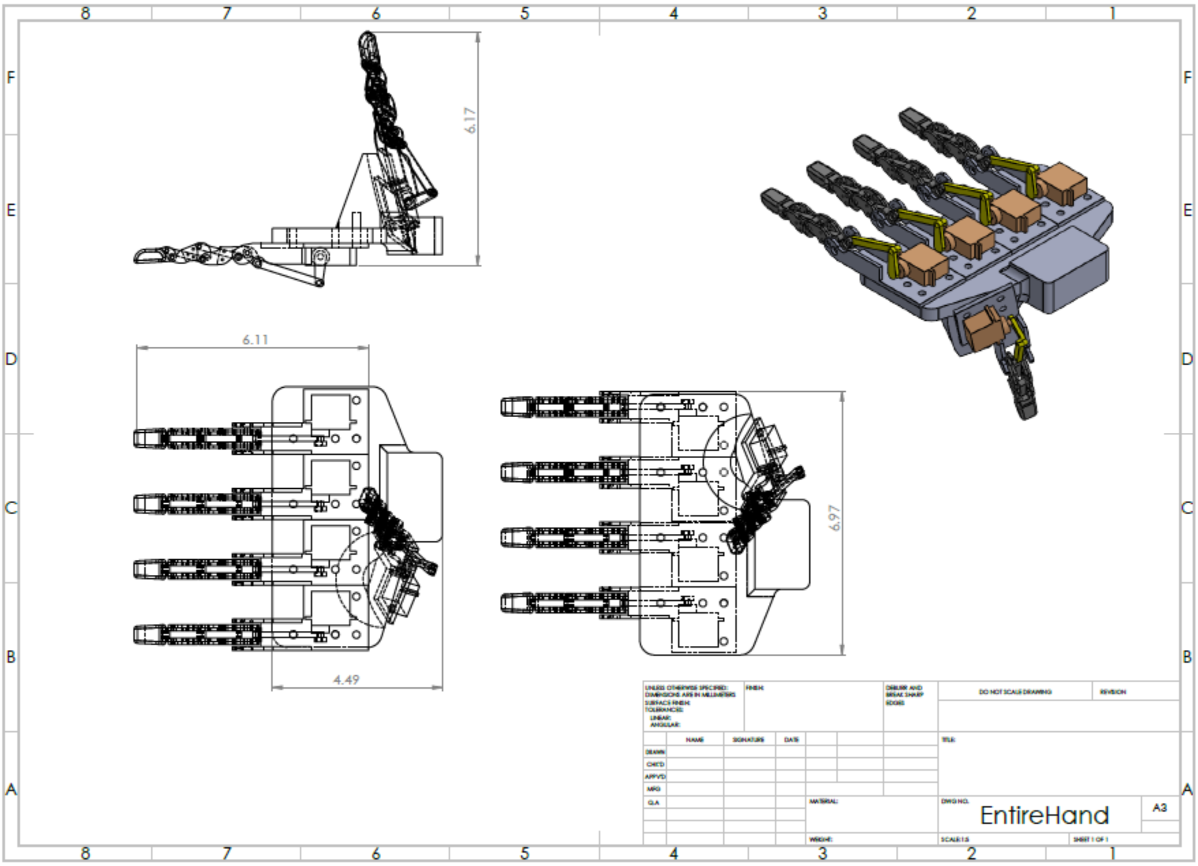
17.56
29.14
FingerASSEMBLY
A3


6.17
6.11
4.49
6.97
EntireHand
A3