The Design and Development of a Teleoperated Anthropomorphic Hand

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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 performance of such system while providing informative sensory and motion data for future works.

Keywords: anthropomorphic, Degree-of-actuation, underactuation, teleoperation

1 INTRODUCTION

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. 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. 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). 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. 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. 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.

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. 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.

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.

2 LITERATURE REVIEW

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 1, are difficult to map and therefore has been simplified into the seven principal degrees of freedom. These seven principle DOF are used by articulated robots to move in the same capacity as human arm. The movements are summarized 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)

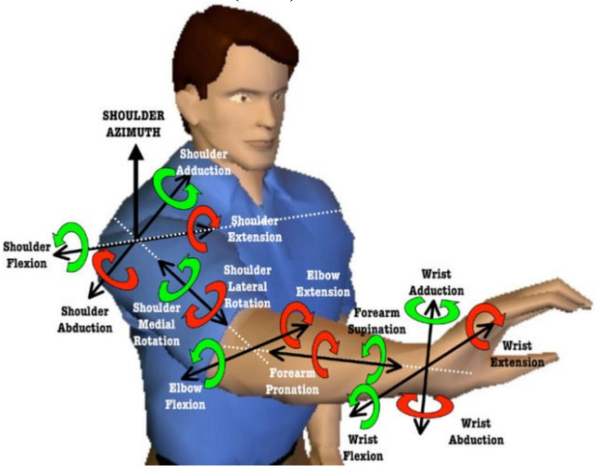

Figure 1. Multiple DOF of the Human arm

2.1 Human Hand Anatomy

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. 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. The CMC joint is a compound joint with two of its nonorthogonal axes being located at different bones, thus it 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. These joints are responsible for giving the human hand such a high level of dexterity, manipulation and grasping.

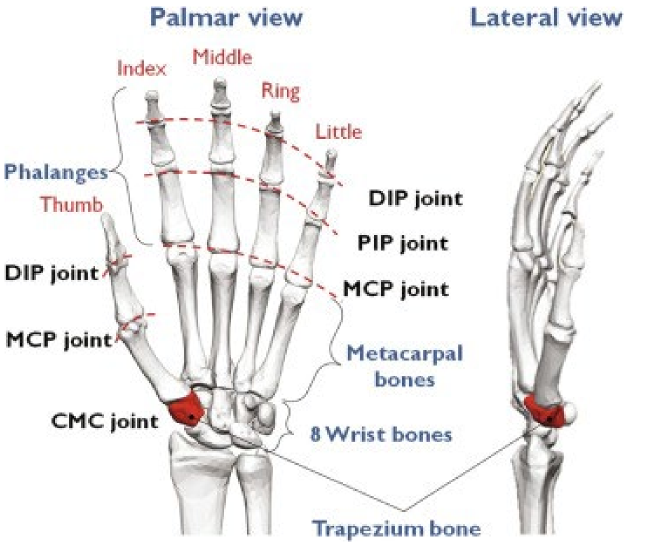

Figure 2. Skeletal joints of the human hand.

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, 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. These joints work together to provide the wrist with 2 DOF, namely flexion/extension (pitch) and ulnar/radial deviation (yaw) as shown in Figure 1. 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. These wrist movements are made around an instantaneous center connected to the forearm that would provide rotary motion.

2.2 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 3. They conducted an analysis method to investigate the evolution of motion in the whole underactuated grasping process. 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.

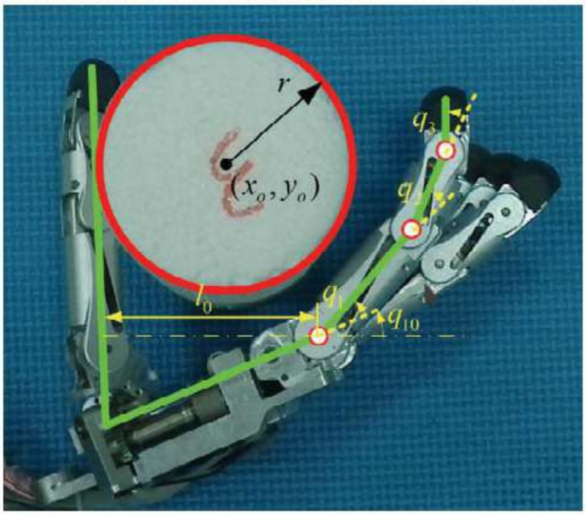

Figure 3. The grasping scenario of an underactuated animatronic hand.

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 performance. Their study allows for designing a prosthetic terminal; for deciding the number of actuators; 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 consists 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.

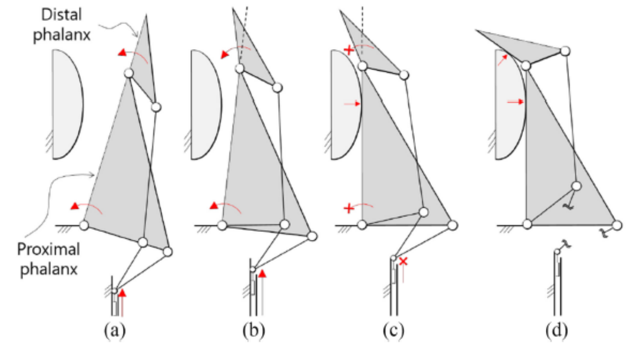

Figure 4. The concept of stackable four-bar linkages mechanism: (a) and (b) the human-like flexion sequence; (c) its main drawback that it can no longer move while in contact with the object; and (d) the self-adaptive grasping presented by Yoon and Choi.

Figure 5 shows the physical prototype created by Yoon and Choi for the robotic finger firstly as a 3D-CADmodel 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. 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.

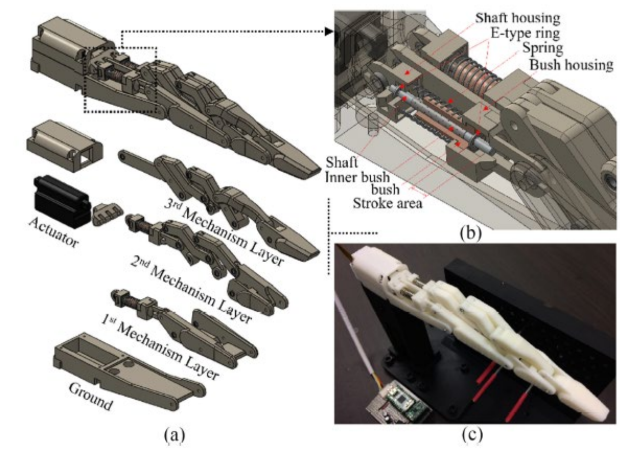

Figure 5. CAD 3D model of the finger prototype.

2.3 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. 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.

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.

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.

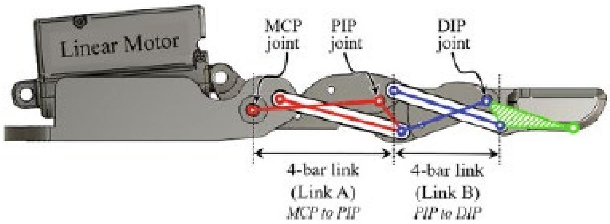

Figure 6. Design of the figure module.

3 DESIGN AND FABRICATION

The teleoperated anthropomorphic hand system consists of the several major parts. The sensory glove (master manipulator) collects the user finger and wrist positions using flex pressure sensors 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.

3.1 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 servomotors 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.

In order to overcome and fulfil the first criteria Park and Kim (2020) underactuated finger design was adopted then further modified to suit the current application. 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 in combination with a lever and linkage mechanism to convert the rotary motion into linear motion.

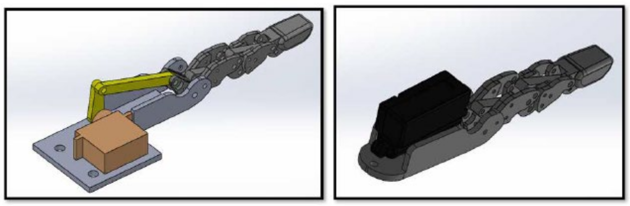

Figure 7. "MyHand" figure module design.

3.2 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 utilized, it needs a location to be secured to allowing it to detect the motion of the wrist.

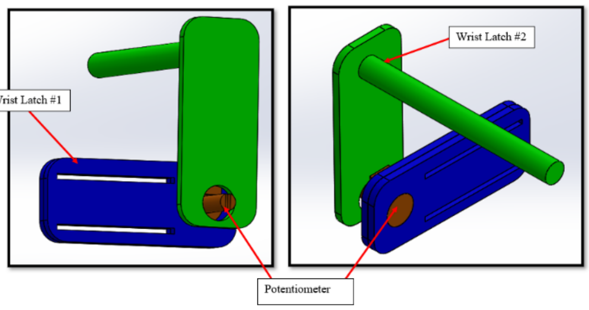

Figure 8. The exoskeleton wrist that would be worn alongside the sensory glove.

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 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.

3.3 Electrical Design

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. The TinkerCAD application was used to simulate and design the electrical components involved for the sensory glove, wrist exoskeleton and servomotors.

Table 1. List of 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 Flex Sensor	Finger Sensor	A3
Ring Flex Sensor	Finger Sensor	A4
Pinky Flex Sensor	Finger Sensor	A5
Servomotor 0	Wrist Actuator	13
Servomotor 1	Finger Actuator	12
Servomotor 2	Finger Actuator	11
Servomotor 3	Finger Actuator	10
Servomotor 4	Finger Actuator	9
Servomotor 5	Finger Actuator	8

3.4 Firmware

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

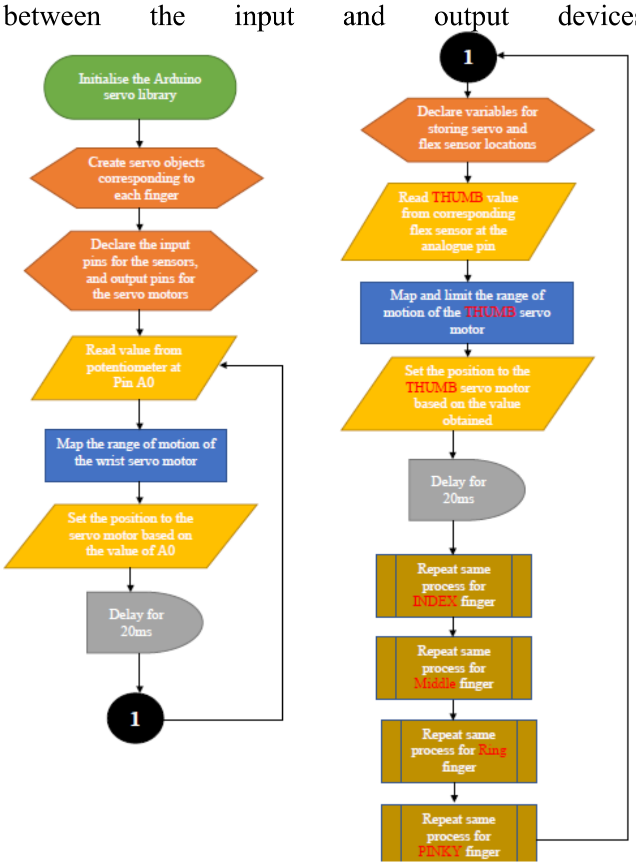

Figure 9. Flowchart for the program flow process.

4 RESULTS AND DISCUSSION

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 10 and 11 showcase 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.

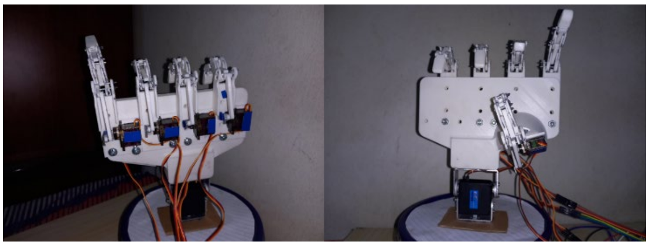

Figure 10. The front and back view of the entire hand assembly.

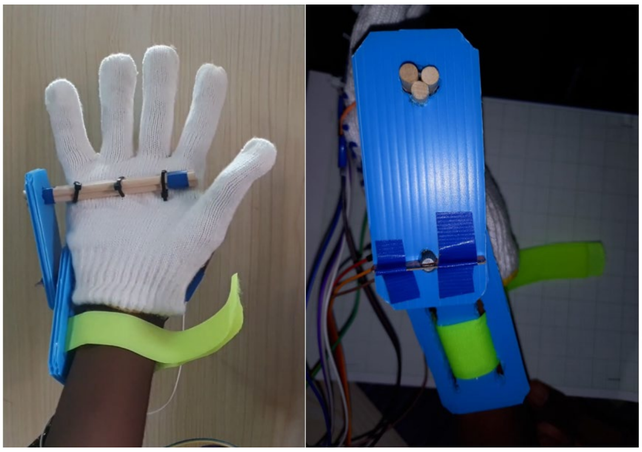

Figure 11. The sensory glove and wrist exoskeleton.

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.

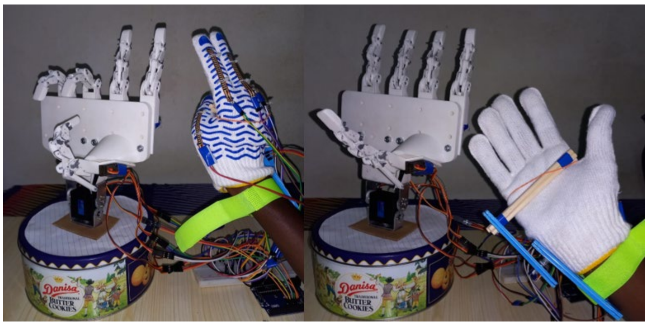

Figure 12. Demonstration of the mimicry of "MyHand" animatronic hand of the human hand

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 behaviour 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.

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 behaviour 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 cannot be grasped by the fingers.

Figure 12. Grasping capabilities of the anthropomorphic hand.

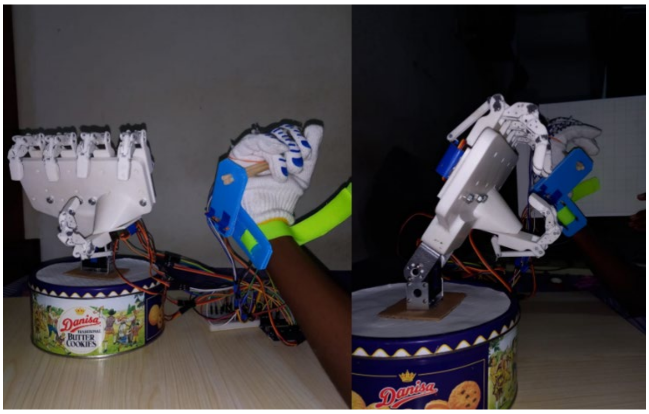

Figure 13. Demonstration of the wrist mimicry of the "MyHand" animatronic hand.

4.1 Limitations

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 led 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.

5 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 utilized 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 performance 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 up to 120 degrees of motion. The grasping capability of the robotic hand was tested and demonstrated and it was found that cylindrical object was firmly grasped whereas other objects of different sizes are either loosely held by the fingers or sometimes cannot be grabbed.

ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to my supervisor Dr. Chiew Tsung Heng as well as Dr. Ong Jia Jan for their invaluable knowledge, expertise and feedback. I would also like to thank our university technicians for guiding me in regards to how properly utilize the 3D printing machines and other useful tools that aided in construction of my project.

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