

Robotic Hand Solution for Impaired Hands

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ABSTRACT– Hand disabilities can limit individuals from achieving the full range of finger movements seen in typical human hands, rendering some unable to grasp objects effectively. In response, this project introduces a portable 5 Degree of Freedom (DOF) robotic hand. It serves to amplify the limited flexion range of an impaired hand, expanding it to match the completely normal range of motion found in a robotic hand. This innovative solution is designed to attach to the palm of the impaired hand and is controlled by a glove equipped with five flex sensors. These sensors precisely measure the angles of finger bends and translate them into appropriate servo motor angles, facilitating enhanced dexterity for the user.

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Introduction

Robotics have become more common in our lives these days, not only in human-robot cooperative environments such as surgical robotics or in isolated robot environments where the robot takes human place, such as in some military applications, but also in being part of our daily tasks or to be more specific, part of our human body such in the robotic applications that are used to solve or compensate human disability which is the main theme of this project.

The motivation behind this project stems from an encounter with a former student who presented a specific hand disability. In his case, a profound weakness in his fingers hindered him from effectively grasping objects. His condition resulted in an inability to achieve complete closure of his hand, as observed in typically functioning human hands. However, it is important to note that his hand was not entirely incapacitated; rather, it exhibited limited articulation capacity. This limitation was characterized by a reduced angular range of finger movement compared to the typical range observed in unimpaired human hands, as in Figures 1, 2, & 3.

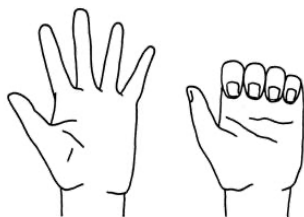


Figure 1. Abnormal finger flexion range [1].

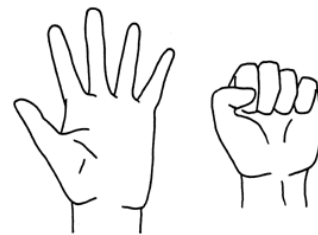


Figure 2. Normal finger flexion range [1].



Figure 3. Human's maximum flexion with a similar case [2].

Hand weakness or lost grip strength can be a result of several different conditions, and the reason can be diverse based on the condition, where the damage could be in the muscles, tendons, or nerves [3].

Most of the hand issue cases are usually treated by rehabilitation, where already there are some robotic solutions for that, such as exoskeleton robotics hands as in Figure 4. However, still some cases that can't be cured, or the hand can't restore its full movement range due to the permanent damage.

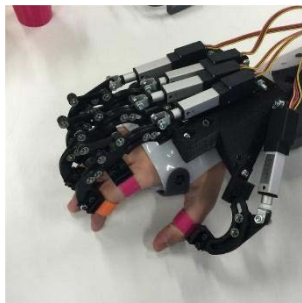


Figure 4. Exoskeleton robotic hand for rehabilitation [4]

An informal visit has been conducted to the Physiotherapy department in R.A.K hospital (with specialist C. G. the head of the department) to clarify more about the issue and similar cases as well as to have an expert opinion about the feasibility of the investigated solutions. A significant point was highlighted, where some cases would feel pain if the fingers flexed more than the patient could do by himself, which makes the exoskeleton solution not applicable in such cases.

The aim of this project is to find a solution that allows people with similar disability or with impaired hands to use their hands again, even if to grasp light objects such as carrying a cup of water.

The targeted cases are the cases that have the ability to move or bend their fingers partially, not the cases that can't move their fingers at all.

Related research and similar solutions

A. Hand weakness

Some people are born with hand disabilities. However, so many factors can cause hand disability, including disease, work environment, aging, and hand injuries, which can be considered very popular due to the functionality of hands in daily life activities. In the US, hand and arm injuries are classified as the 2nd most common injury with a percentage of 28.3%, almost equal to the first common injury that occurs to the neck and head (29.5%) [5], and these injuries may lead to long-term disability, or permanent disability and in both cases, the person may not be able to do the same job again [6]. Before considering any solution, some important points need to be highlighted about hand injuries where the patients may experience limited hand motion, stiffness, or pain [5].

Away from injuries and congenital disability, some people may experience sudden and persistent weakness or heaviness in their hands, which makes gripping things difficult, and that can occur due to a variety of medical conditions, some of them are common conditions such as diabetes, stroke, and herniated disc, others are advanced medical issues caused by different factors such as Carpal Tunnel Syndrome where work environment is a major reason of causing this condition [7]. Carpal Tunnel Syndrome is one of the most common conditions that causes pain in hands and weakness [8]. Carpal Tunnel Syndrome can lead to permanent hand dysfunction as well as loss of sensation in fingers. Studies show that older people and women tend to develop it more because pregnancy is one of the reasons that

can cause it; however, the most common reason is the repetitive use of the hand, like doing the same wrist and hand movements over a prolonged period such as typing or machine operating [9].

B. Exoskeleton hand

A robotic device can be worn in hand to provide kinetic feeding to human fingers in order to assist them in completing their range of motion, rehabilitate impaired hands, amplify power, or as haptic feedback to be used in teleoperation or virtual applications [10]. Many hand exoskeleton studies have been published and systems developed with different design aspects like mobility where some have five fingers, such as human hands as in Figure 5 [11], and others with four fingers where the little finger is not included as in Figure 6. [12], three fingers exoskeleton where ring and little fingers are excluded as in Figure 7 [13], two fingers which thumb and index fingers only controlled as in Figure 8 [14], or one finger exoskeleton as in Figure 9 [15]. Some of the reduced fingers exoskeletons (4 or 3 fingers exoskeletons) are designed based on the fact that the middle, ring, and little fingers are highly coupled in healthy hands, which make them usable in activities of daily life (ADLs) [16].



Figure 5. Exoskeleton with five fingers.

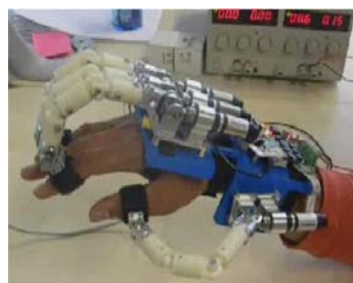


Figure 6. Exoskeleton with four fingers.

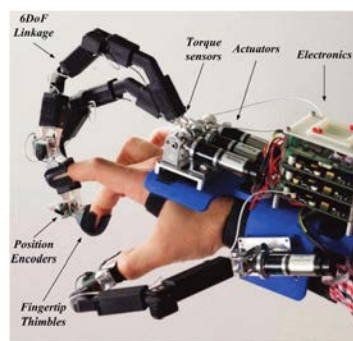


Figure 7. Exoskeleton with three fingers.



Figure 8. Exoskeleton with two fingers.

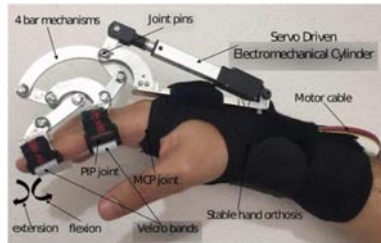


Figure 9. One-finger exoskeleton.

Another design aspect is actuation and sensing methods, where some exoskeletons use electric motors as actuators [17] while others use pneumatic system to exert the force that moves the fingers [11]. As a sensing method, a variety of sensors have been used in exoskeletons including flex sensor [18], potentiometer [19], encoder [13], electromyography sensor (EMG) [20] and electroencephalogram sensor (EEG) [21].

Exoskeleton hands can be classified based on the function where certain design requirements need to be considered to suit their purpose [22].

Rehabilitation hand exoskeletons are designed to help people with hand disabilities restore or improve their hand usage and assist the therapists in treating patients by doing repetitive tasks mimicking the ADLs, which makes it mostly used in medical or clinical environments [16].

Reference [20] is the design and development of a 3D-printed rehabilitation exoskeleton that is designed to be self-used without any need for the clinical setting. It has five fingers, each finger driven by a servo motor coupled with an EMG signals sensor that detects muscle intention to simple open-close tasks as in Figure 10., a case was attached on the dorsal side of the forearm and the wrist to contain all the electronics and the actuators (Figure 11) where strings used as transmission between the motors and the fingers.

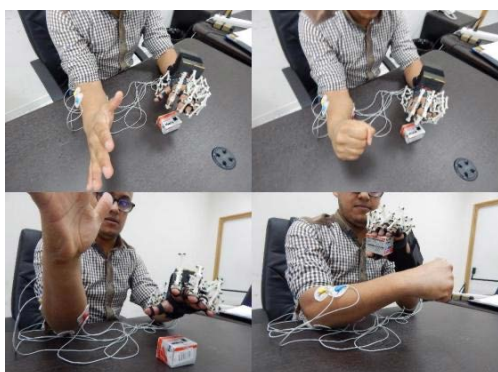


Figure 10. Open-close tasks for the developed exoskeleton.

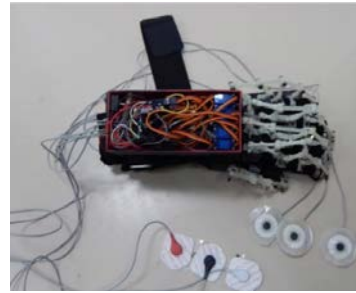


Figure 11. The wrist-forearm case.

Assistive hand exoskeletons are designed to aid people with hand disabilities in their daily lives by achieving ADLs such as eating or holding a key, which makes one of the important aspects in developing such exoskeleton is to be portable since it will be worn all the time and everywhere, so it is crucial to be lightweight and easily wearable [16].

Reference [23] is a design and development of a 3D printed portable and wearable hand exoskeleton that has four fingers, the thumb is excluded, and the actuation system mainly motors in addition to cable transmission mechanism to transfer the power from motors to fingers. The first prototype basically used four servomotors connected with fingers through pulling cables, triggered by two buttons, one for opening and one for closing. This is impractical because the buttons will open and close the four servos together, and that makes using four servos unnecessary because it defeats the purpose of moving each finger independently. In addition to that, using a button trigger system will keep the other hand busy to push the buttons, and that became a burden on the user; however, the last prototype was much way better where a specific transmission system used with cables and different pulleys actuated by a single servo motor, also instead of using buttons, a specific EMG control architecture developed to collect signals from forearm muscles which make it more compact, lighter and controlled without forcing the other hand to be engaged. Figure 12 shows the first and last prototypes.



Figure 12. a) First prototype, b) Last prototype.

Augmentation hand exoskeletons are designed for healthy people. This type of exoskeleton aims to amplify the user's power, generally developed for military applications. Also, it is used in space applications to assist astronauts in moving their fingers in the stiff spacesuit glove in order to prevent any hand fatigue that can be caused by the pressurized extravehicular activities (EVA) gloves [24].

Reference [25] is a development of a five-finger augmented hand exoskeleton called RoboGlove. It is a mutual

work between NASA and General Motors. This exoskeleton is designed to be integrated with an EVA glove. As shown in Figure 13, it is fabricated from elastic, flexible fabric material. The forearm section contains the actuators, in addition to a ruggedized case, which contains the drive electronics and the microprocessor. The linear actuation system consists of three small brushless DC motors coupled with small ball screws that actuate a total of five artificial tendons pass from the forearm set to the glove through small flexible conduits to flex and extend the fingers. For triggering the movement, thin film piezoresistive force sensitive resistors (FSRs) are embedded in the fingertips of the gloves to measure the human force interaction with the objects.

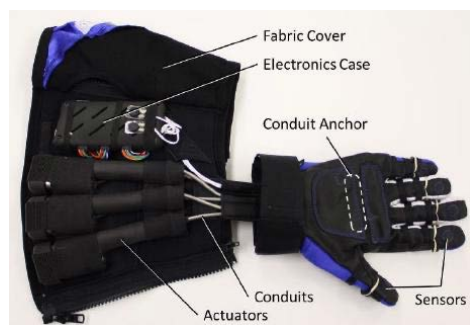


Figure 13. RoboGlove forearm set and the glove.

Haptic hand exoskeletons are designed for healthy users to simulate the interaction with the virtual environment and teleoperation applications in addition to giving virtual reality haptic feedback, and that means it is crucial in this type of exoskeletons to track the fingers efficiently [16].

Reference [13] is a design of a three-finger hand exoskeleton (shown in Figure 7) used for haptic interaction, and to suit the purpose, accurate tracking needs to be provided for each finger. Each finger consists of 6 DOF driven by a DC motor and six magnetic position encoders used to calculate the kinematic of the fingertip. Moreover, for controlling and measuring the interaction force on the fingertip, torque sensors are used, and each torque sensor is a cantilever beam whose deflection is measured by a pair of bilaterally bonded strain gauges in a half bridge configuration.

C. Robotic hand

One of the suggested solutions for this reported issue is a robotic hand, which means adding a robotic system or an extra hand with extra fingers instead of wearing an exoskeleton over the human fingers to support them, as in the previous solution.

Some published papers suggested a similar solution, but with a different concept where extra fingers were added to support the patient in grasping objects such as [26]; the suggested design was a five fingers wearable glove that carries another two robotic fingers controlled by the glove itself where the movement of 2 robotic fingers depends on the posture of the glove fingers as in Figure 14.

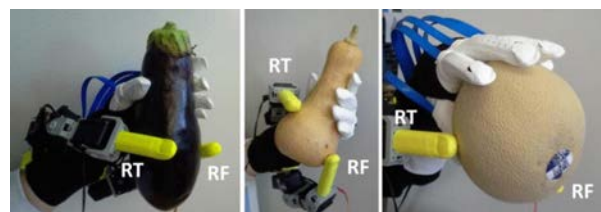


Figure 14. Grasping posture of various objects.

A similar solution was suggested by [27]. However, an AI model was added. The two fingers were actuated through flex sensors and IMU attached to the glove, although not in a direct way where sensor readings were fed to a machine learning model that was trained to predict the gestures like carrying a bottle, a tablet, or manipulating big objects, as in Figure 15.

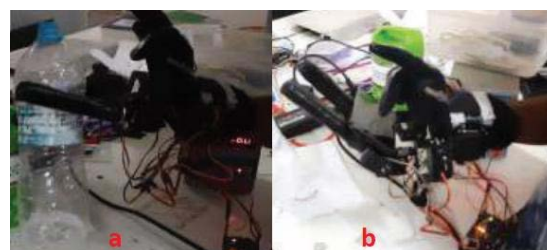


Figure 15. a) Bottle grabbing mode, b) Tablet mode.

Another published solution was adding an extra finger instead of using a glove, as in [28] and [29], where both have the same concept, and both used a control button to flex and extend the finger. Figures 16 & 17 show various grasped objects for both solutions.

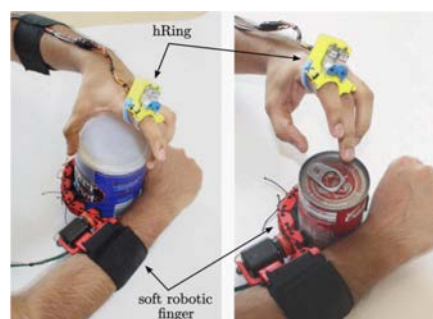


Figure 16. The proposed solution from [28] is controlled by a button mounted on hRing.

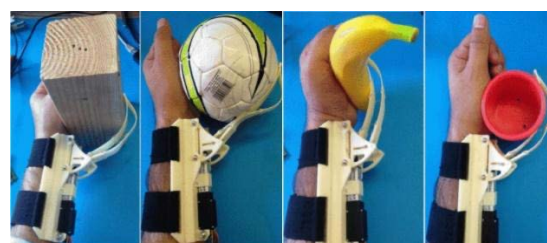


Figure 17. Various objects with different sizes are grasped by the proposed solution in [29].

Such solutions might be easy, simple solutions to increase the independence of the patients, but still lack flexibility and dexterity. Moreover, the solution [26] is kind of complicated because the user needs some time to train his/her hand to the

suitable posture for grasping objects, which might be confusing; add to that the ability of the user's fingers to do these postures considering the impaired fingers and the disability. In [27], the gesture prediction solved using a machine learning model; however, that means more computational power and more consumed power need to be solved using extra hardware, and that's affects the wearability and the portability, which are fundamental aspects in the solution design. In solutions [28] and [29], besides the lack of flexibility mentioned earlier, controlling the extra finger using buttons needs to be pressed by the other hand, which is a burden on the other hand and needs to be avoided.

Apart from this kind of solution, a full robotic hand solution was published in [30]. The proposed robotic supernumerary limb can be divided into five sub-parts, as in Figure 18 (1) is a robotic hand actuated by one DC motor to open and close the hand in addition to a magnetic encoder used to read motor position. (2) is a passive gravity compensator used to support the weight of the robotic hand and the arm interface in order to reduce muscular fatigue. (3) is a human arm interface used to place the robotic hand and to support the arm of the patient in addition to controlling the hand. (4) a finger glove is also used to control the hand. (5) is a remote trigger used to control the hand.



Figure 18. The five sub-parts of the robotic hand solution.

As was mentioned in the sub-parts, there are three different ways to control the robotic hand. **The first way** is using a grasp handle mounted on the arm interface (Figure 18-3), and inside this handle, there are two force sensors (Figure 19) fixed at both extreme ends of the handle to avoid any issues if the user's hand was not centered on the handle. The amount of grasp strength exerted by the user's hand and measured by the integrated force sensors determine the grasping robotic hand status (Figure 19) [30].

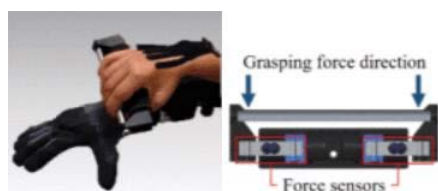


Figure 19. On the left, the control handle and on the right, the force sensors placing.

The second way is a finger glove (Figure 18-4) worn on the middle finger that has an embedded flex sensor that controls the hand closure based on the bend angle (Figure 20) [30].



Figure 20: The finger glove that controls the hand.

The Third way is a remote trigger (Figure 18-5) that has a knob connected to an electromagnetic encoder that measures the rotation angle and control hand closure based on measured reading (Figure 21) [30].



Figure 21. On the left is the remote trigger, and on the right is an example of a knob angle.

As a manipulation range of motion, Figure 22 [30] shows that the arm interface allows the forearm to rotate, which also rotates the robotic hand; however, the gravity compensator kind of limits the range that the user can work in; moreover, it creates a mobility issue and making the wearability of the hand everywhere is difficult.



Figure 22. The robotic hand axial movement.

Having various controlling ways is supposed to give the user some flexibility; however, the second and the third ways need to be controlled by the unaffected hand where the finger glove will prevent the user from using the second hand freely without affecting the robotic hand, and the remote trigger also needs continuous press which will keep the second hand busy. Therefore both ways can be considered a burden on the user. The first way is more practical than the other ways, where the busy hand is the same impaired hand. Nevertheless, the fingers lack independence, where the five fingers open and close together, although the solution size is considered big to cover this point.

D. Discussion

Designing a generic hand exoskeleton is challenging, and as shown from the published and developed skeletons, the

essential properties to design an exoskeleton differ based on the application, where some of these properties can be dropped in some applications but not in others. Table 1 summarizes some of the design properties that are essential for the four exoskeleton classifications (Rehabilitation, Assistive, Augmentation & Haptic).

Table 1. Some Properties and its fundamentality for each exoskeleton type.

Design property	Exo. Type			
	Reh	Ast	Aug	Hap
Finger independency	✗	✓	✗	✓
Finger position tracking	✗	✗	✗	✓
Wearable easily	✓	✓	✗	✗
Ability to grasp various objects shapes	✗	✓	✗	✓
High output force	✓	✓	✓	✗
Interaction with real objects	✗	✓	✓	✗
Portability	✗	✓	✓	✗
Weight lightness	✓	✓	✗	✓

*Augmentation exoskeleton can differs based on the used application

For example table 1 shows that easiness of wearing the exoskeleton is unnecessary for haptic and augmentation since both are for healthy hands compared with the other two types where wearing complicated system might be painful and difficult for impaired hands, also some exoskeleton need to be in a certain environment setting like haptic (limited work place) and rehabilitation (clinic or medical environment) which make the portability is unessential however for assistive exoskeleton it needs to be worn for longer periods and different places. In general, these properties are generic, but it might be changed due to the circumstances, for instance some of the publications suggested that in some cases the doctors need finger tracking to measure patients progress, but the others considered that the purpose of rehabilitation exoskeleton is to motivate fingers movement without any need to track finger position.

Regarding robotic hand solutions, several solutions that just add finger/s, which might be simple and easy solutions to increase patient's independency but that's not what is sought in this project. Human hands have five fingers that allow flexible manipulation for different shaped objects and increase the dexterity level which is what needs to be compensated in this project.

A quick comparison between the exoskeleton hand and the robotic hand gives preference to the robotic hand in terms of avoiding the medical issue that mentioned earlier about the pain that can be caused to some cases if the fingers bended

more than the range that the person can do by himself, however the appearance might not be aesthetically pleasing in comparison with exoskeleton hand.

Solution

The implemented solution is a 5 DoF robotic hand attached on the disabled hand, driven by 5 servo motors arranged within the robotic hand where each servo motor actuates a finger and controlled by 2.2" flex sensor attached on a glove that will be worn beneath the robotic hand, the glove finger sensors will read the bend angle and map it with robotic hand as follow: the maximum angle that the finger can reach in the disabled hand will be mapped to be a fully closed finger in the robotic hand as well as the maximum extended angle of the fingers will be mapped to a fully open robotic hand, in other words the small finger flexion range will be magnified in the robotic hand to meet the full flexion range.

The solution is divided into 3 parts (Figure 23).

- The glove that contains all the 5 flex sensors and all the wires arranged and crimped to a JST connector that can plugged/ unplugged easily to/ from the control unit.
- The robotic hand that contains all the servo, also all the wires arranged and crimped to a JST connector can be easily plugged/ unplugged to/ from the control unit.
- The control unit which is a small bag will be worn on forearm and includes an Arduino Nano as a controller, power bank and small circuit that has 2 JST connectors as an output to be connected to the previous 2 parts.

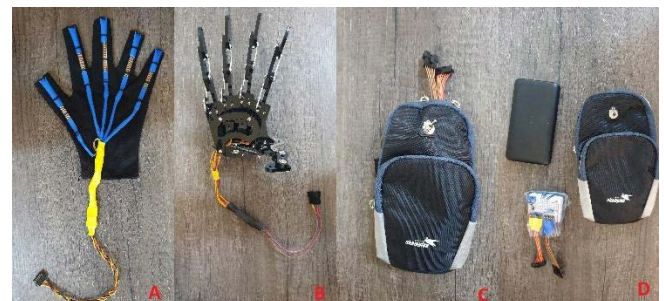


Figure 23. A) Control Glove, B) Robotic Hand, C) Control Unit, D) Control Unit components including Arduino board, power bank and forearm bag.

Material and Methods

A. Material

The listed below material are the main material that has been in this solution.

- Arduino Nano: is a small and compact microcontroller.
- 2.2 "Flex sensors: (Figure 24) used to measure fingers angles where the resistance across the sensor increases as the sensor flexed.



Figure 24. Flex Sensor.

- Glove: a soft breathable cloth glove used to control the robotic hand through the flex sensors attached on it.
- 5 DOF robotic hand will be attached to the palm [31].



Figure 25. 5 DOF Robotic Hand.

- MG90S micro servo motors that have metallic gear and produce high out power to actuate the fingers.
- 20000 mAh 5v power bank with 2 Amps USB port, which is enough to run the system at full load, continuously for at least 8 hours.

B. Wiring and connections

Figure 26 shows the general connection between all components however in implementing the work, the wiring done in a way that minimize the number of wires going from control unit to the glove and the robotic hand.

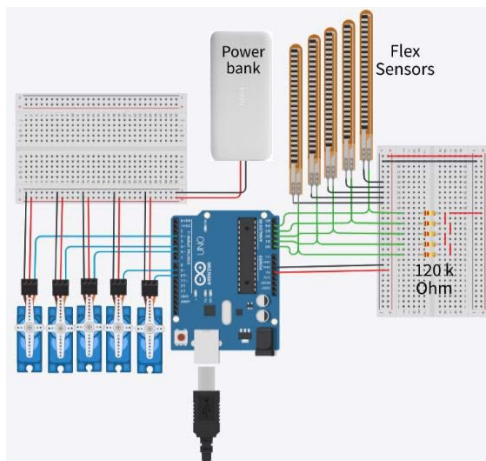


Figure 26. Wiring Diagram for all components.

Table 2. Arduino used pins and their connections.

Pin	Connection	Pin	Connection
3	Thumb servo motor	A0	Thumb flex sensor
5	Index finger servo	A1	Index finger flex sensor
6	Middle finger servo motor	A2	Middle finger flex sensor
9	Ring finger servo motor	A3	Ring finger flex sensor
10	Little finger servo motor	A4	Little finger flex sensor

C. Code Flow chart

The code basically read the maximum flexion finger angle and map it with 0° in servo as well as the maximum extension finger angle and map it with 150° . 150° used instead of 180° because normal human fingers usually flexed a little bit and not fully straight extended. In Figure 27 that shows code flow, the first process is a flag where in the code, the ranges values assumed to be half bended and by changing the flag to 1, the code will only print on serial monitor a 5 columns table arranged from thumb to little finger without moving the robotic hand to study an individual case fingers motion ranges as in Figure 28.

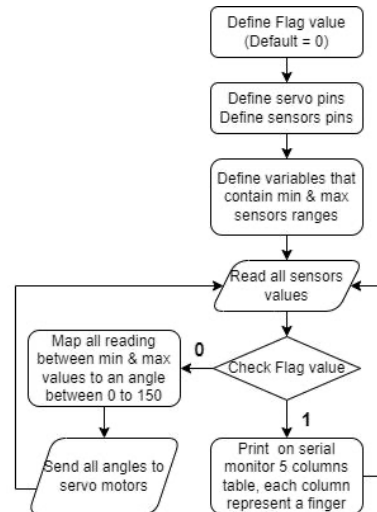


Figure 27. Code flow chart.

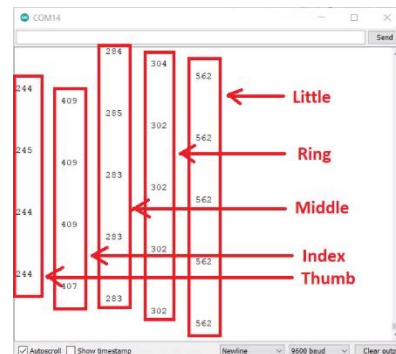


Figure 28. Each column represents a finger reading.

D. Implementation

After researching similar robotic solutions and related projects, one of the most important aspects in designing a solution for similar issues is portability, where the solution must be light assumed that the user would wear it for long periods and everywhere as well as need to be easy to wear and take off considering that the user will do it on his/her own frequently and without any need to a specific setup before that.

Since the control unit will be on forearm, and all the wires need to pass from the glove and the robotic hand to the forearm which may reduce the freeness of arm movement, so the number of wires has been reduced as in Figure (29) and gathered into 2 cords of wires (one cord 7 wires and the other 6 wires) crimped at the end with JST connector to make

plugging and unplugging the cords easy and practical. The reduction in wires done in GND and power wires where sets of wires connected through connectors with one output wire as in Figure (29).

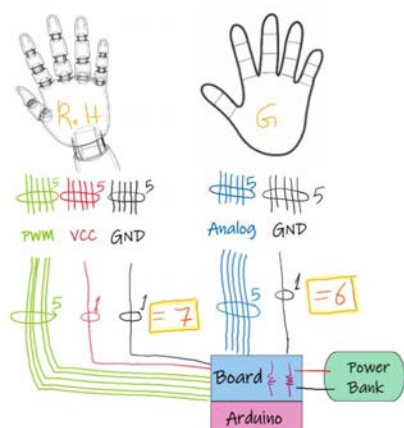


Figure 29. Number of wires for both glove and robotic hand.

Results and Discussion

Since the system can be disassembled into 3 parts easily, it allows the user to set it by his own without any need to an external assistance. Figure 30 shows different angles of the solution after being set up.

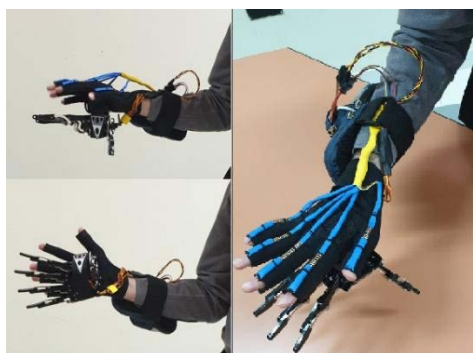


Figure 30. Different angles and views for the solution.

To test the system, different pick-up postures on various objects has been conducted including cup, bottle of water and apple as well as gripping a door handle as in Figure 31.

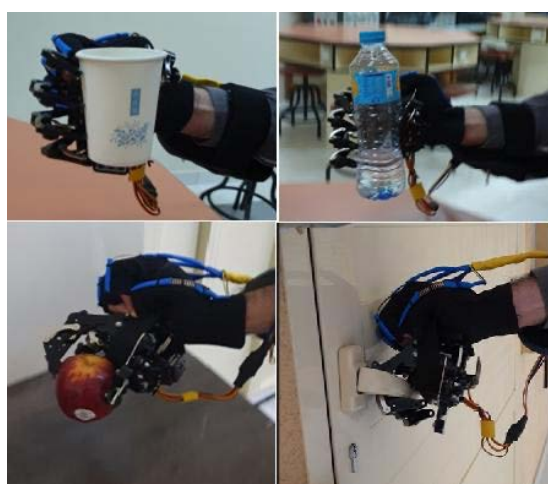


Figure 31. Testing the robotic hand on different objects.

As a result, the robotic hand managed to grab these objects and successfully mimics the user's hand movements. When the user bends their fingers, the flex sensors in the glove detect the finger angles and transmit the data to the robotic hand, causing it to replicate the motion. This allows the user to control the robotic hand and grasp objects with their impaired hand.

The implemented solution addresses the need for individuals with hand disabilities to regain partial control and independence in performing everyday tasks. The robotic hand offers a promising approach to assist users in grasping objects by replicating their finger movements. However there some points to discuss regarding the implemented solution:

1. **Portability and Wearability:** The solution prioritizes portability and wearability, ensuring that users can wear the robotic hand comfortably and without significant hindrance to their arm movements as well as without any need to an external help. The reduction in wires and the use of a lightweight control unit contribute to this goal
2. **Control Mechanism:** The flex sensors embedded in the glove provide a practical and user-friendly control mechanism. The mapping of finger angles to robotic hand movements allows for intuitive control.
3. **Thumb DOF:** Human hand movements poses a considerable challenge, primarily due to the intricate nature of human fingers, particularly the thumb. Human fingers can be likened to ball joints, and this characteristic presents a substantial constraint in projects of this kind. Introducing an additional Degree of Freedom (DOF) to the thumb could yield a significant enhancement, especially in terms of grasping various small objects such as pins and keys. This potential addition stands as a promising avenue for future project improvements.
4. **Range of Motion:** The solution maps the maximum flexion and extension angles of the user's fingers to the robotic hand. This range of motion is tailored to accommodate the user's capabilities and limitations, preventing discomfort or pain.
5. **User Training:** The solution may require users to adapt to specific postures for grasping objects effectively. User training and familiarization with the system could help users maximize its benefits.
6. **Robotic Hand Material:** Another point needs to be highlighted is smooth objects, the material that robotic hand made of makes carrying objects with smooth surface difficult. For example, when the bottle of water as full, it kept slipping and to be able to lift it, half of the bottle need to be emptied.
7. **Future Improvements:** Future iterations of the solution could focus on exploring alternative control methods, such as Electromyography (EMG) or Electroencephalography (EEG), holds substantial promise. Implementing these advanced control techniques could broaden the range of potential users and expand the usability of the system.

Conclusion

In conclusion, the implemented solution, a 5 DoF robotic hand controlled by flex sensors in a glove, holds promise in assisting individuals with hand disabilities in regaining partial control over their hand movements. The system prioritizes portability and wearability, making it practical for everyday use.

While the solution successfully mimics user finger movements and offers a degree of independence, there is room for improvement in terms of finger dexterity and appearance. Future enhancements could include achieving greater finger DOF especially for the thumb.

This project represents a significant step towards addressing the needs of individuals with such kind of hand disabilities, and it opens the door to further developments in the field of assistive robotics. The ability to provide individuals with more independence in their daily lives is a valuable contribution to improving their overall quality of life.

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