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Master-Slave Grasping Control for Enhanced Functionality in Under Actuated Prosthetic Hands for Upper Limb Amputees

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ABSTRACT

According to the International Classification of Functioning, Disability and Health (ICF), upper limb amputations constitute 16% of total amputations, significantly affecting an individual's ability to grasp objects. This paper proposes the development of an underactuated prosthetic hand tailored for upper limb amputees, introducing a Master-Slave Grasping Control system. The research involves meticulous study and development of suitable underactuated finger mechanisms, servo motors and controllers to enhance grasping and ungrasping activities. Employing SolidWorks and 3D printing technologies, the prosthetic hand is designed to seamlessly replace the lost limb, enabling users to grasp and ungrasp various objects. The innovative Master-Slave Grasping Control system facilitates intuitive and coordinated movements, enhancing the prosthetic hand's functionality. A series of tests is conducted to validate the proposed design, demonstrating its efficacy in achieving natural and versatile grasping motions. This research contributes to the advancement of upper limb prosthetics, addressing the unique challenges faced by amputees and promoting a more integrated and user-centric approach to prosthetic design.

1. Introduction

The landscape of prosthetic design has evolved significantly, transitioning from mere anatomical replication to creating functional and user-responsive devices. The Master-Slave Grasping Control system, an innovative addition to this trajectory, stands out for its capacity to bridge the gap between user intent and the prosthetic hand's actions, addressing the inherent challenges faced by upper limb amputees [1,2]. Recent literature highlights underactuated finger mechanisms as pivotal in mimicking the compliant and coordinated movements of the human hand. The Master-Slave

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Grasping Control system seamlessly integrates with underactuated designs, promising a leap forward in achieving a more intuitive and user-friendly prosthetic interface, particularly in the context of upper limb prosthetics [3].

The choice of servo motors and controllers plays a critical role in prosthetic design and in the context of a Master-Slave Grasping Control system, this takes on added significance. Literature emphasizes the need for components that can translate user commands into precise and coordinated movements. Our exploration goes beyond conventional considerations, focusing on compatibility with the Master-Slave paradigm to facilitate sophisticated and controlled grasping activities [4,5].

SolidWorks and 3D printing technologies have become integral tools in prosthetic design, enabling the realization of intricate and customized structures. The literature underscores the importance of these technologies in creating prosthetic hands that not only meet functional requirements but also align with the individual aesthetics and preferences of users. Our utilization of SolidWorks and 3D printing ensures a user-centric approach, making the prosthetic hand a personalized and adaptable extension for the user [6-8].

The synergy between under actuation and the Master-Slave approach promises enhanced functionality and adaptability. Studies on underactuated mechanisms highlight their capacity to reduce the complexity of traditional prosthetic hands while maintaining a high degree of functionality. The Master-Slave paradigm adds an extra layer of control sophistication, facilitating a more natural and responsive interaction between the user and the prosthetic device [9-11]. Advancements in prosthetics emphasize the importance of user-centric design principles. The Master-Slave Grasping Control system introduces a dynamic and adaptive mechanism for prosthetic hands, contributing to a more natural and responsive interaction. This shift towards user-centricity ensures that the prosthetic device not only restores lost functionalities but also empowers users with enhanced grasping capabilities, fostering a sense of normalcy and independence [12,13].

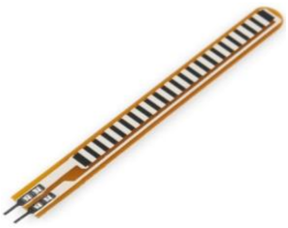
It is important to note that while underactuated finger mechanisms are mimicking compliant and coordinated movements of the human hand, there is a lack of literature specifically focusing on optimizing these mechanisms within the framework of the Master-Slave Grasping Control system. Addressing this gap would facilitate a deeper understanding of how underactuated designs can be tailored to seamlessly integrate with the Master-Slave paradigm, thereby enhancing functionality and responsiveness [14-16]. Hence, Master-Slave Grasping Control is essential in this study as it represents a pioneering approach to seamlessly integrate user intent with prosthetic hand actions, particularly crucial for enhancing functionality in underactuated prosthetic hands tailored for upper limb amputees [17-20]. In particular, this study incorporates flex sensors within the Arduino Control Glove and is instrumental in capturing the intricate movements and gestures of the user's hand. Flex sensors, which are bend-sensitive resistors, detect the degree of bending in the wearer's fingers and hand joints. As the user flexes or extends their fingers, the resistance of the flex sensors changes accordingly, providing real-time feedback on the hand's position and movements.

2. Methodology

In this paper, a detailed methodology encompassing the key components utilized in the development of this system is presented, elucidating their roles and interactions. The subsequent sections will delve into the design principles, operational workflows and integration strategies employed to realize the Arduino Control Glove and Prosthetic Hand system, highlighting its potential to redefine the paradigm of assistive technology.

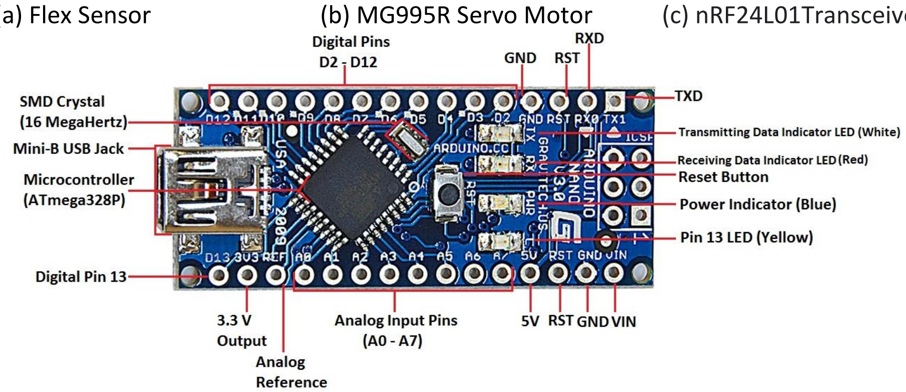
2.1 Components

Figure 1 illustrates the key components used in this research, the components include a Flex Sensor, a thin and flexible device detecting bending through changes in resistance; MG995R Servo Motors serving as actuators with high torque for precise angular motion; the Arduino Nano, a compact microcontroller board designed for small-scale projects; a 9V battery as a power supply for the MG995R Servo Motors; nRF24L01 Transceiver Module for wireless communication in the 2.4GHz range; and resistors forming a voltage divider circuit with the Flex Sensor to measure changes in resistance as it bends. Each component plays a crucial role in the overall functionality of the system, contributing to the seamless integration of the Arduino Control Glove and the Prosthetic Hand. See Figure 1 for an example of each component used in this research.

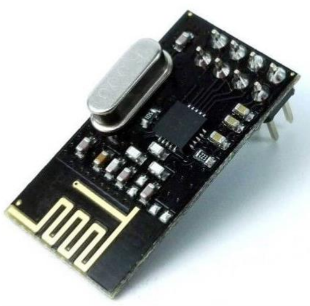

(a) Flex Sensor

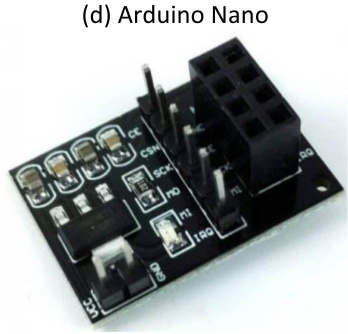
(b) MG995R Servo Motor

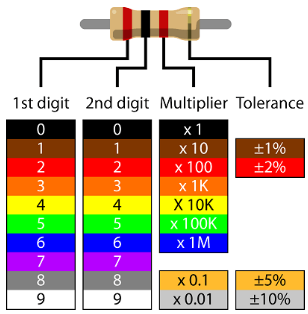
(c) nRF24L01Transceiver Module



(d) Arduino Nano


(e) nRF24L01 transceiver module


(f) Breakout board for NRF24L01



(g) Resistor with colour code

Fig. 1. Components used in this project [21-23]

More specifically, the Flex Sensor acts as a nimble and responsive detective, capable of detecting and measuring the extent of bending through changes in resistance. It serves as the interface between the user's hand movements and the project, akin to a stretchy wire that communicates the hand's actions. The project's musculature is represented by the MG995R Servo Motors—strong movers with high torque capabilities, ensuring precise angular motion for the prosthetic hand. Powered by a 9V battery, these motors become the powerhouse of the project, executing movements with accuracy. The Arduino Nano functions as the brain, a compact yet intelligent microcontroller board designed for small-scale projects. It orchestrates seamless communication among the components, ensuring efficient coordination. Facilitating wireless communication is the nRF24L01 Transceiver Module, acting like a radio that allows different parts of the research to communicate without physical connections. Lastly, resistors serve as traffic controllers for the Flex Sensor, working in tandem to measure bending accurately. Each component plays a distinct and indispensable role, contributing to the overall functionality and harmonious integration of the Arduino Control Glove and the Prosthetic Hand. Together, they form a cohesive team, translating the user's hand movements into precise actions with efficiency and responsiveness.

2.2 System Block Diagram

The schematic representation of complex systems often provides a clearer understanding of their functionalities. Figure 2 presents a comprehensive view of both the Master (Controlling Glove) and Slave (Prosthetic Hand) systems. Figure 2(a) shows the components within the Master system, featuring a Flex sensor as input, Arduino Nano as the controller and Transmitter as the output. Meanwhile, Figure 2(b) captures the intricate processes within the Slave system, highlighting a Receiver as input, Arduino Nano as the microcontroller and Servo Motor as the output in the slave control environment. This visual breakdown sets the stage for a detailed exploration of the inner workings of these interconnected systems.

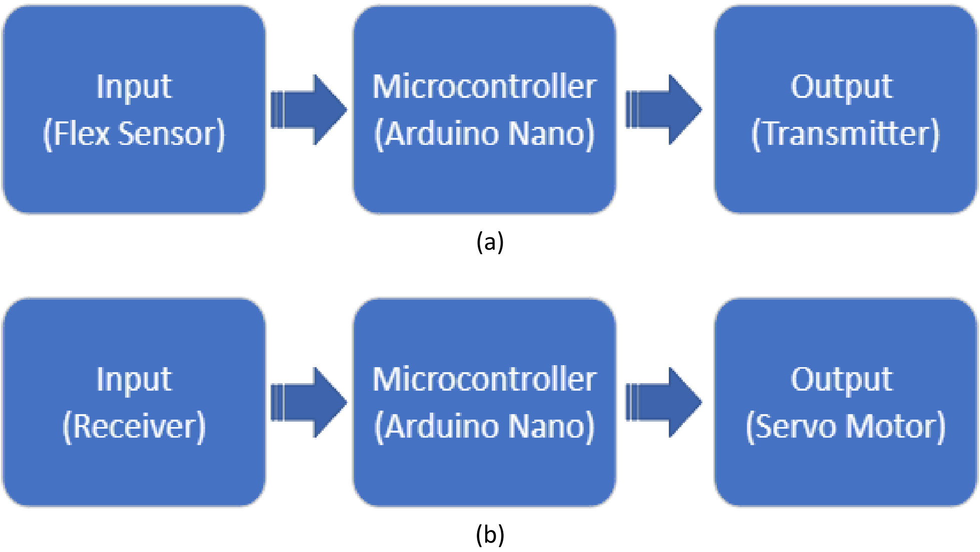


Fig. 2. System description (a) Block diagram of Arduino control glove; (b) Block diagram of prosthetic hand

2.3 System Flowchart

The process of Master and Slave control shown in Figure 1 can be further detailed as depicted in Figure 2. Figure 2(a) illustrates the operational sequence of the Arduino Control Glove. It initiates with the user activating the system ('Switch On') and the subsequent detection of hand movement through a Flex Sensor. The Arduino Nano, functioning as the microcontroller, processes this input, determining the nature and extent of the gesture ('Movement'). At a decision point, if movement is confirmed ('Yes'), the system proceeds to transmit the information via a Transmitter. In the absence of detected movement ('No'), the process loops back to monitoring the Flex Sensor. The culmination of this process is denoted by the 'Transmit Complete and Ready' point. In essence, the flow chart encapsulates the glove's capacity to recognize and respond to user gestures, showcasing the seamless integration of hardware components for an interactive and intuitive wearable technology experience. Meanwhile, Figure 2(b) illustrates the seamless collaboration between the Arduino Control Glove and the Prosthetic Hand. The process initiates with the 'Signal from Transmitter,' showcasing the smooth transmission of information from the controlling glove (Master) to the prosthetic hand (Slave). The 'Switch On' command activates the prosthetic hand, while the 'Receiver' comprehends and decodes the signal, paving the way for the 'Microcontroller (Arduino Nano)' to analyse the intended movement. During the 'Movement' phase, an important decision is made – whether to mimic the gesture ('Yes') or await further instructions ('No'). If 'Yes,' 'Prosthetic Hand Move' animates the hand in synchronization with the user's gestures. The cycle then returns to the 'Receiver' for additional input in case of a 'No,' ensuring continuous adaptability.

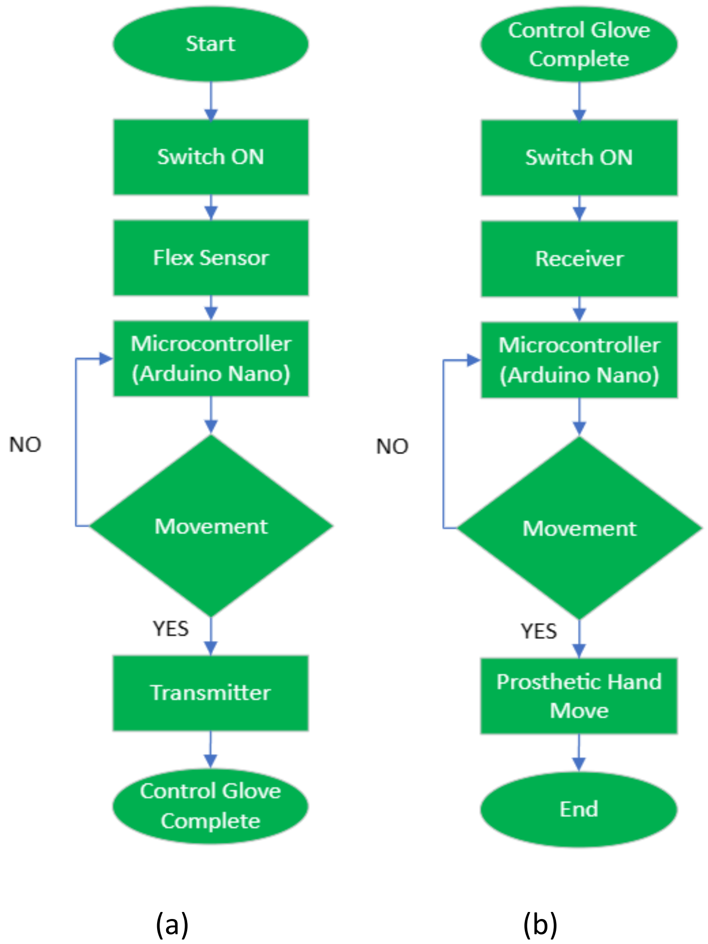


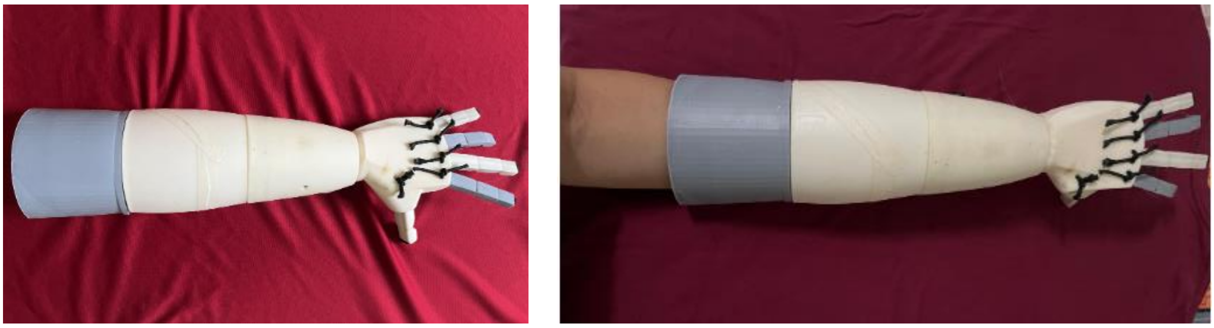
Fig. 3. Figure description (a) Flowchart of Arduino control glove (b) Flowchart of prosthetic hand (slave)

3. Results

The results of the project are presented, encompassing the design, implementation, testing and performance evaluation of the Arduino control glove and prosthetic hand system.

3.1 Prosthetic Hand and Socket Design

Figure 4 illustrates the design of a prosthetic hand, illustrating two configurations: one with a socket (Figure 3(a)) and the other with a real hand attachment (Figure 3(b)). The modelling process employed SolidWorks CAD to realize 19 distinct hand components. Each finger, including the index, middle, ring and thumb, comprises a tip segment, a middle segment and a base segment seamlessly connecting to the palm. Subsequently, the palm is affixed to an arm piece, culminating in the assembly of a fully realized prosthetic hand. Significantly, a socket tailored for upper limb amputees is a focal point of this project. The intricacies of the socket design involve meticulous considerations encompassing functionality, comfort and aesthetics. Given its attachment to the user's hand, we prioritize ensuring its ergonomic comfort.

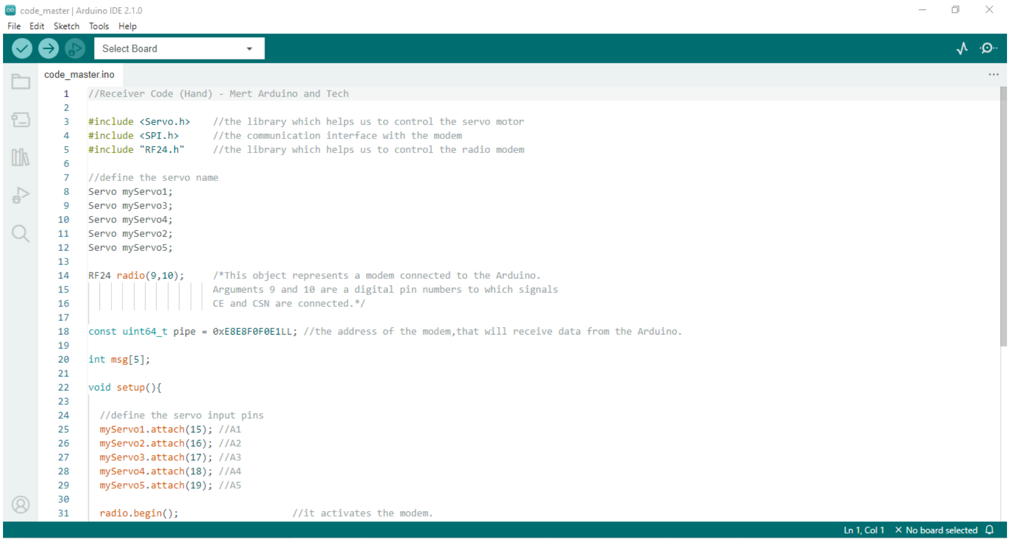


(a) (b)

Fig. 4. Figure description (a) Prosthetic hand with socket (b) Prosthetic hand attach on hand

3.2 Arduino IDE

The Arduino IDE as seen in Figure 5 is used to create programmable code and the Arduino code will be uploaded into the Arduino Nano. Writing code and uploading it to the board is simple with the open-source Arduino software. The code for both the Proteus simulation and the Arduino Nano that are used in the prosthetic arm. In Arduino IDE, testing the flex sensor to obtain its values is a crucial step in incorporating it into the project. The flex sensor is a type of sensor whose resistance changes based on the degree of bending or flexing it experiences. By testing and reading the values from the flex sensor, can gather information about the degree of bend, which can be used as input in various applications. In the test, the result is counted in tolerance of 5 counts, so the values are 763 counts and 888 counts for maximum and minimum value respectively (see Table 1). The tolerance of 5 counts refers to the allowable range of variation in the recorded values from the flex sensor during testing. This tolerance is imposed to account for minor fluctuations or noise in the sensor readings, which can occur due to factors such as electrical interference, sensor imperfections or environmental conditions. Moreover, these values establish a reference range for interpreting the flex sensor's output, facilitating its effective utilization in controlling the prosthetic arm's movements and functions.



(a) Arduino coding for master (controlling hand)

(b) Arduino coding for slave (prosthetic hand)

Fig. 5. (a) Arduino codes for Arduino control glove (master) and (b) Arduino codes for slave (prosthetic hand)

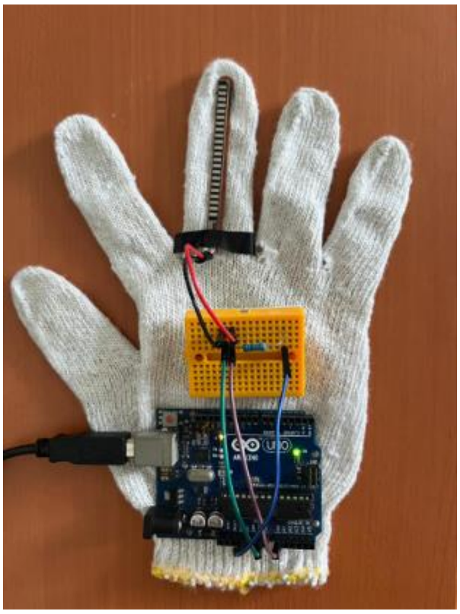
Next, testing a flex sensor with a servo motor provides valuable information about how the sensor responds to changes in its resistance due to bending and how that information can be translated into servo motor movement. the servo motor used is 180 degrees, so the value should set from 0 to 180 degree, due to the tolerance, it can also set from 10 to 170 degree to rotate servo motors more smoothly. Besides, testing the nRF24l01 wireless transceiver before installation is a crucial step to ensure that the communication between devices using the transceiver works correctly. By conducting thorough testing before installation, it can minimize the risk of encountering issues once the nRF24l01 transceiver is integrated into the project system. It ensures a smoother deployment and helps achieve the desired performance and reliability in wireless communication. Lastly, all the codes are successfully compiled and uploaded to the Arduino Nano board, both the process of testing each component and the final coding for the project.

Table 1
Data set of Flex Sensor at initial test

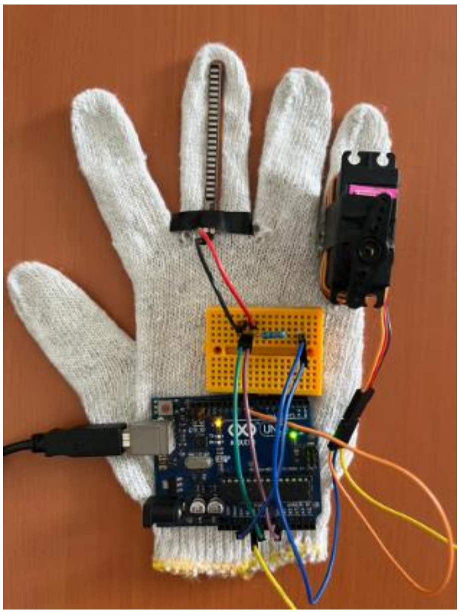
No.	Number of Count Open	Number of Count Close
1	767	833
2	768	877
3	771	874
4	768	873
5	768	869
6	769	868
7	775	873
8	775	873
9	775	875
10	771	870

3.3 Hardware Installation

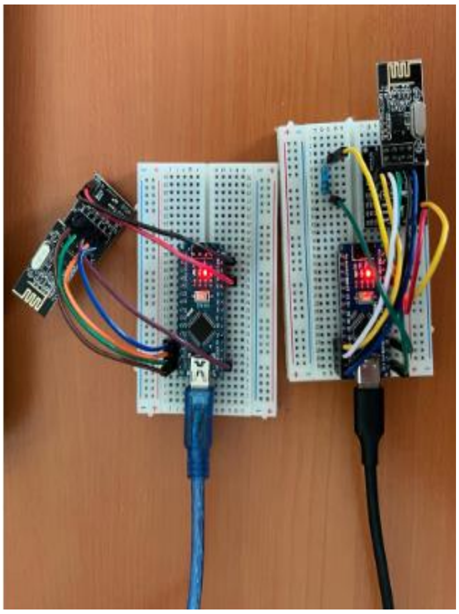
The process of hardware installation, illustrated in Figure 6, serves as the culmination of academic studies in this project. This phase involves establishing electrical connections or wiring among various electronic components, ensuring their seamless communication and intended functionality. The correctness of wiring installation is essential for research success, aligning the hardware with the project's objectives. Figure 6 comprehensively portrays each step of the hardware installation, depicting critical stages in the project's development.



a) Hardware of Initial Testing for Max and Min Value of Flex Sensor



(b) Hardware of Testing Flex Sensor with Servo Motor



(c) Hardware of Testing nRF24l01 Wireless Transceiver

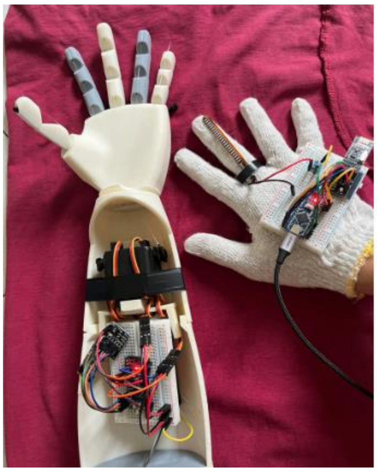
(d) Complete Project

Fig. 6. Hardware installation

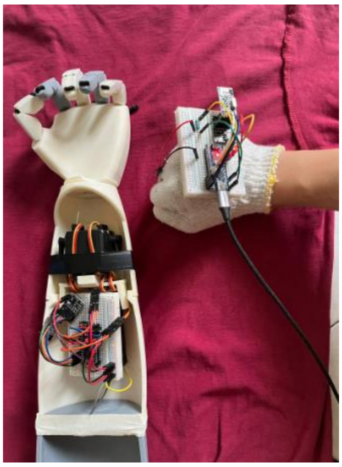
More specifically, Figure 6(a) illustrates the initial testing phase for the Flex Sensor involves assessing its maximum and minimum values, a crucial step in calibrating the sensor's response. Subsequently, Figure 6(b) illustrates the hardware setup transitions to testing the Flex Sensor with the Servo Motor, ensuring their effective collaboration in translating hand movements into precise actions. Meanwhile Figure 6(b) depicts the hardware installation further progresses to testing the nRF24L01 Wireless Transceiver. This is a key component for wireless communication in the project, ensuring its seamless integration. Finally, Figure 6(d) encapsulates the completed project, showcasing the intricate hardware installation that forms the backbone of the Arduino Control Glove and Prosthetic Hand system. This visual representation provides a comprehensive overview of the meticulous process undertaken to establish robust electrical connections, validating the successful execution of the project's objectives.

3.4 Grasping Tests

A set of grasping tests has been conducted to evaluate the performance of both the developed Master and Slave Hand. Beyond assessing the effectiveness of grasping and ungrasping manoeuvres, the tests involve two distinct objects: an orange and a phone, as depicted in Figure 7.



(a) Ungrasping



(b) Grasping

(c) Grasping Orange

(d) Grasping Phone

Fig. 7. Grasping tests

The results of each grasping trial are comprehensively presented in Table 2, Table 3, Table 4 and Table 5, offering insights into the system's proficiency in handling different objects and showcasing its overall performance.

Table 2 presents the specific angles of the finger joints during the ungrasping process in the developed Master and Slave Hand system. The angles are categorized into three joints: Joint 1, Joint 2 and Joint 3 for each finger type, namely Thumb, Index, Middle, Ring and Small. For the Thumb, during the ungrasping manoeuvre, Joint 1 maintains a position of 0°, Joint 2 is at 9° and Joint 3 does not have a specified angle, suggesting a static position. Similarly, the Index finger exhibits angles of 0°, 5° and 2° for Joint 1, Joint 2 and Joint 3, respectively. The Middle finger follows with 0°, 4° and 5° for the same joints. The Ring finger maintains angles of 0°, 3° and 3°, while the Small finger presents 0°, 5° and 10° for Joint 1, Joint 2 and Joint 3, respectively. These detailed joint angles provide a comprehensive insight into the nuanced finger movements executed during the ungrasping process, highlighting the precision and control achieved by the Master and Slave Hand system for different finger types.

Table 3 outlines the angles of the finger joints involved in the grasping process of the developed Master and Slave Hand system. Each finger type (Thumb, Index, Middle, Ring and Small) exhibits distinct joint angles at Joint 1, Joint 2 and Joint 3 during the grasping manoeuvre. For the Thumb, the grasping sequence involves angles of 10°, 70° and no specified angle for Joint 1, Joint 2 and Joint 3, respectively. The Index finger highlights angles of 20°, 70° and 30° for the corresponding joints. The

Middle finger adopts angles of 50°, 60° and 30°, while the Ring finger presents angles of 55°, 60° and 30°. Lastly, the small finger demonstrates angles of 70°, 65° and 45° for Joint 1, Joint 2 and Joint 3, respectively.

Table 2
Angle of fingers for ungrasping process

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	0°	9°	-
Index	0°	5°	2°
Middle	0°	4°	5°
Ring	0°	3°	3°
Small	0°	5°	10°

Table 3
Angle of fingers for grasping process

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	10°	70°	-
Index	20°	70°	30°
Middle	50°	60°	30°
Ring	55°	60°	30°
Small	70°	65°	45°

Table 4 outlines the specific angles of the finger joints during the grasping process of an orange in the developed Master and Slave Hand system. Each finger type, including Thumb, Index, Middle, Ring and Small, displays distinct joint angles at Joint 1, Joint 2 and Joint 3 during the grasping manoeuvre. For the Thumb, the grasping sequence involves angles of 10°, 55° and no specified angle for Joint 1, Joint 2 and Joint 3, respectively. The Index and Middle fingers highlight angles of 5°, 55° and 15° for the corresponding joints. The Ring finger adopts angles of 8°, 50° and 15°, while the small finger demonstrates angles of 8°, 60° and 20° for Joint 1, Joint 2 and Joint 3, respectively.

Table 4
Angle of fingers for grasping orange

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	10°	55°	-
Index	5°	55°	15°
Middle	5°	55°	15°
Ring	8°	50°	15°
Small	8°	60°	20°

Table 5 delineates the specific angles of the finger joints during the grasping process of a phone. Each finger type (Thumb, Index, Middle, Ring and Small) displays distinct joint angles at Joint 1, Joint 2 and Joint 3 during the grasping manoeuvre. For the Thumb, the grasping sequence involves angles of 10°, 60° and no specified angle (-) for Joint 1, Joint 2 and Joint 3, respectively. The Index finger exhibits angles of 0°, 5° and 25° for the corresponding joints. The Middle finger maintains angles of 0°, 45° and 10°, while the Ring finger presents angles of 0°, 40° and 10°. Lastly, the small finger demonstrates angles of 10°, 35° and 25° for Joint 1, Joint 2 and Joint 3, respectively.

Table 5
Angle of fingers for grasping phone

Finger Type	Joint 1	Joint 2	Joint 3
Thumb	10°	60°	-
Index	0°	5°	25°
Middle	0°	45°	10°
Ring	0°	40°	10°
Small	10°	35°	25°

In summary, Table 2, Table 3, Table 4 and Table 5 collectively illustrate the intricate finger joint angles during the ungrasping and grasping processes for different objects in the developed Master and Slave Hand system. In Table 2, detailing the ungrasping process, each finger type demonstrates specific joint angles, providing a comprehensive overview of the precise movements during this manoeuvre. Meanwhile Table 3, which outlines the finger angles during the grasping process, distinct joint configurations for various finger types reveal the system's ability to delicately control finger movements. These measurements shed light on the nuanced motion executed during the grasping sequence, highlighting the system's precision. Moreover, Table 4 and Table 5 specify finger joint angles during the grasping process for an orange and a phone, respectively. Notably, the system adapts its finger movements based on the object, highlighting a versatile design. These tables offer a detailed glimpse into the tailored control of the Master and Slave Hand system when interacting with specific objects. The specific joint angles during ungrasping and grasping manoeuvres demonstrate the system's ability to cater to diverse objects, highlighting a sophisticated and precise integration of hardware and control algorithms in the context of prosthetic hand functionality.

4. Conclusions

The development of an underactuated prosthetic hand has successfully been crafted tailored for upper limb amputees, designed using SolidWorks and 3D printing technologies. The underactuated prosthetic hand enable users to grasp and ungrasp various objects. Introduction of a Master-Slave Grasping Control system that facilitates intuitive and coordinated movements, enhancing the prosthetic hand's functionality. Validation of the proposed design through a series of tests, demonstrating its efficacy in achieving natural and versatile grasping motions. Utilization of SolidWorks and 3D printing to ensure a user-centric approach, making the prosthetic hand personalized and adaptable for the user. Introduction of a dynamic and adaptive mechanism for prosthetic hands, contributing to a more natural and responsive interaction. Nevertheless, this research can be further enhanced by integrating advanced hardware with precise control algorithms. Exploring advanced materials and manufacturing techniques for the prosthetic hand components can contribute to increased durability and functionality. Additionally, integrating sensory feedback mechanisms, such as pressure or temperature sensors, could provide users with a more immersive and interactive experience. Further research into machine learning and artificial intelligence applications can potentially enable the system to adapt and learn from user behaviour, improving its responsiveness over time. Collaboration with healthcare professionals and end-users for continuous feedback and user-centred design iterations is crucial. This ensures that future developments align with the specific needs and preferences of prosthetic users. Moreover, exploring miniaturization and energy-efficient solutions for components can contribute to a more lightweight and energy-efficient design.

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