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SharpShooters

Hand Exoskeleton

082100131, Design and Manufacturing II

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1 | Introduction

1.1 | Design Background

Rehabilitation plays a crucial role in assisting individuals with injuries or functional disabilities to regain their daily activities and enhance their quality of life. Hand impairments and diseases significantly impact a person's ability to perform tasks and engage in work. However, traditional rehabilitation methods may have limitations in fully restoring hand function. The emergence of hand exoskeletons offers an innovative solution by providing technological support and assistance, ultimately improving the quality of life for rehabilitation patients.

Hand exoskeletons serve multiple purposes in the rehabilitation process. Firstly, they assist patients in regaining hand functions such as grasping, gripping, and fine motor skills by providing strength support, motion assistance, and sensory feedback. This aids in enhancing patients' independence, social participation, and overall abilities in daily activities, leading to an improved quality of life.

Secondly, hand exoskeleton technology enables early and intensive rehabilitation interventions, expediting the recovery process. By offering accurate strength support and motion guidance, hand exoskeletons facilitate early motion training and functional recovery, thereby reducing rehabilitation time and improving outcomes.

Additionally, hand exoskeletons incorporate sensors and data logging capabilities to collect patients' motion data and track rehabilitation progress. This data holds significant value for rehabilitation professionals and researchers, as it assists in assessing rehabilitation outcomes, developing personalized rehabilitation plans, and advancing rehabilitation research.

Furthermore, hand exoskeletons play a vital role in the field of human-machine interaction. This interaction involves the exchange of information and modes of operation between humans and intelligent devices like computers or robots. Hand exoskeletons as a human-machine interaction technology strive for more natural and intuitive ways of interacting with machines. By combining the machine's strength and functionality with the human body's flexibility and sensory capabilities, hand exoskeletons extend users' hand functions and abilities, enabling them to accomplish tasks and activities beyond their own capabilities.

The human-machine interaction technology of hand exoskeletons finds applications in various domains. For instance, in virtual reality and augmented reality, hand exoskeletons facilitate user interaction with virtual worlds. In the medical field, hand exoskeletons' human-machine interaction technology can be employed in rehabilitation therapy, assistive surgery, and other areas.

1.2 | Design Targets and Requirements

For this project, our target is to design a cable-driven flexible hand exoskeleton that would assist people with hand impairments in grasping. It should provide natural and ergonomic assistance to hand movements through its lightweight, flexibility, and precise control. Our hand exoskeleton has the following basic requirements,

- Safety: Safety is the primary consideration in designing hand exoskeletons. The exoskeleton must have safety control systems, including emergency stop mechanisms and joint limiters, to prevent accidents and injuries.
- Actuation Range: Actuation range refers to the range of motion that the exoskeleton can achieve. The exoskeleton should have sufficient actuation range to enable a variety of hand movements and postures, such as whole hand bending and extending. For the cable-driven flexible hand exoskeleton, the actuator should be able to provide at least 50mm length variation of the finger internal thread.
- Grasping Force: Delivering sufficient force to enable users to grip and manipulate objects effectively, at least 15N.
- Degrees of Freedom: Drive at least three fingers.
- Weight: Designing the exoskeleton to be lightweight for improved user comfort. The weight of the directly worn part of the hand is no more than 0.5kg. The weight of the wearable part of the arm (such as the controller, sensor and power supply) is no more than 1kg. If all the electronic controls are integrated into the backpack, the weight of the backpack is no more than 1.5kg.
- Flexibility: Designing the thumb specifically can improve flexibility.

1.3 | Correlation Technique

Hand exoskeletons can be classified into rigid exoskeletons and flexible exoskeletons. Among the flexible exoskeletons, they can be further categorized based on their driving methods into pneumatic exoskeletons and motor-cable exoskeletons.

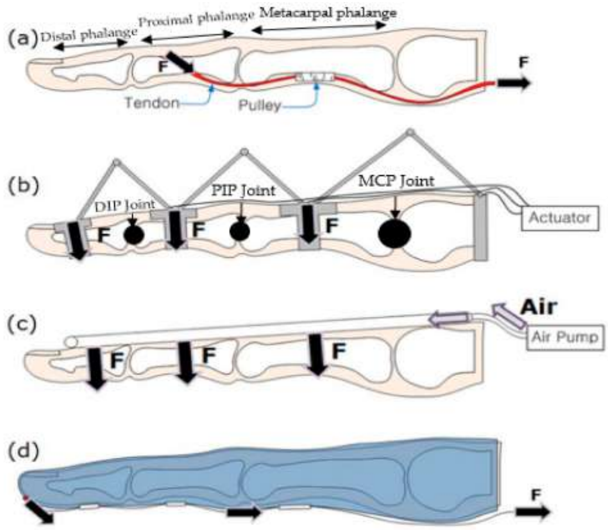


Figure 1.1: Internal bone structure of a human finger and finger exoskeleton robot, where 'F' is the actuation force applied in its respective direction (arrow head). (a) The natural skeletal structure of the human finger. (b) The rigid joint and link mechanism of a hand exoskeleton. (c) The pneumatically-actuated hand exoskeleton. (d) The tendon/cable–pulley system in a wearable glove.

1.3.1 | Advantages of Cable-driven Structure

- Simple mechanical structure: The cable-driven structure is relatively simple, consisting of cables, joint mechanisms, and frame structures. This simplicity makes it easier to design, manufacture, and maintain.
- Lightweight and flexibility: The cable-driven structure utilizes lightweight materials and components, resulting in a lighter overall exoskeleton. It also provides higher flexibility and freedom of movement, mimicking natural hand motions.
- Precise control: Cable tension can be adjusted to achieve precise control over hand movements, offering good control accuracy.
- Comfort: The lightweight and flexible nature of the cable-driven structure enhance the comfort of the hand exoskeleton, allowing it to better conform to the user's hand shape and movements.

1.3.2 | Limitation of Cable-driven Structure

Compared to pneumatic or rigid structures, the cable-driven structure typically has a lower torque and force output. This limitation may affect the exoskeleton's ability to provide sufficient assistive force for certain tasks that require high force or heavy lifting.

1.4 | Our Works

Our project has successfully designed a cable-driven hand exoskeleton, utilizing ten servos as the driving components. Each finger's flexion and extension are independently controlled by a dedicated servo. By accurately controlling the servo movements, our system can faithfully replicate the natural motion of the fingers, including bending and stretching. This enables users to maintain natural hand movements while using the exoskeleton. Our cable-driven hand exoskeleton also incorporates human-machine interaction capabilities. By strain sensors and control algorithms, our system can track the position and posture of the fingers in real-time. This allows users to interact with computers or virtual reality systems through finger movements.

2 | Concept Design

2.1 | Design Philosophies

Our design goal is to develop a safe, reliable, and practical cable-driven hand exoskeleton with human-machine interaction capabilities. We strive to provide users with an innovative solution that can assist and enhance hand functionality. Here is our design concept:

- Safety and Reliability: We prioritize safety and ensure that the exoskeleton device does not cause any harm or discomfort to the user during its use. We employ reliable materials and structural designs, equipped with safety protection mechanisms, to ensure user safety throughout the usage.
- Practicality: We emphasize practical value and aim to design a comprehensive and user-friendly hand exoskeleton. We focus on the range of motion and force requirements of each hand joint, ensuring that the exoskeleton can provide accurate and natural hand movement assistance. Additionally, we consider the weight and comfort of the exoskeleton, allowing users to wear it for extended periods and engage in daily activities.
- Human-Machine Interaction: We value the ability for human-machine interaction, enabling the exoskeleton to perceive user hand movements and interact with computers or other devices. We integrate sensors and control algorithms to achieve real-time hand motion tracking and data collection and analysis, meeting the user's needs for interaction in areas such as virtual reality, game control, or remote operation.

2.2 | Design Content and Design Plan

2.2.1 | Tendon-driven Hand Exoskeleton

The objective of this project is to design a hand exoskeleton system that provides assistance and support for individuals with hand impairments or disabilities. The system incorporates anchor points and tendon sheaths on the surface of a glove, allowing for flexible finger movement through the use of strings connected to the anchor points. The design focuses on determining the appropriate string material and positioning of the anchor points to achieve optimal functionality and usability.

Design Content

- Design overview

  The hand exoskeleton system is designed to assist individuals with hand impairments or disabilities in regaining hand functions and improving their quality of life. The system incorporates anchor points and tendon sheaths on the surface of a glove, along with strings connected to the anchor points. By contracting and pulling the anchor points, the fingers can be bent flexibly and freely. The design focuses on determining the appropriate string material and positioning of the anchor points to ensure optimal functionality and usability.

- Design Objectives

  First, enable users to perform grasping, gripping, and fine motor skills by providing strength support, motion assistance, and sensory feedback. Second, enhance users' abilities in performing daily tasks. Third, incorporate sensors and data logging capabilities to collect motion data and track rehabilitation progress for assessment and personalized rehabilitation plans.

- Design Considerations

  At first, choose suitable materials for the strings that provide flexibility, durability, and comfortable wear. Second, determine the optimal locations for the anchor points on the glove surface to ensure effective finger movement and support. Third, implement safety mechanisms to prevent over-extension and protect the wearer's hand during movement. Fourth, prioritize ergonomic design principles to ensure user comfort and minimize discomfort or fatigue during prolonged use.

Design Plan

- Research and Analysis

  Conduct a comprehensive study of hand bio-mechanics, user requirements, and existing hand exoskeleton technologies.

- Conceptual and Detailed Design

  Generate multiple design concepts based on the identified requirements and evaluate their feasibility and potential benefits. Besides, select the most suitable design concept and develop detailed specifications, including the material selection for the strings, anchor point positioning, and safety mechanisms.

- Prototyping and Testing

  Build prototypes of the hand exoskeleton system and conduct rigorous testing to evaluate its functionality, comfort, and safety.

2.2.2 | Gesture Sensing

In an assistive hand exoskeleton system, gesture sensing refers to the ability of the system to detect and interpret hand and finger movements made by the wearer, in order to provide appropriate assistance or mimicry. The system can incorporate gesture sensing technology, such as flex sensors or other motion sensors, to accurately detect the wearer's finger movements and translate them into commands for the exoskeleton motors. This allows the exoskeleton to assist the wearer in performing tasks that require hand dexterity, such as gripping objects or manipulating tools. Aiming at utilizing this gesture sensing technology in our design, we designate a detailed design content and design plan.

Design Content

- Design Overview

  First, this design aims to develop a wearable device that accurately senses and tracks the shape and flexion of a human finger. Second, this design will enable intuitive control of digital systems, virtual reality applications, or prosthetic devices.

- Design Specifications

  First, the flex sensor should have a suitable range and sensitivity to detect the varying degrees of finger flexion. Second, the device should provide real-time data on changes in finger shape. Third, it should be comfortable to wear, lightweight, and non-intrusive to ensure user convenience.

- Design Goals

  First, develop a finger tracking device that provides precise and reliable measurements of finger flexion. Second, ensure a seamless and intuitive user experience, allowing for natural and responsive interaction with digital systems. Third, design a cost-effective and manufacturable solution with limited budget.

- Design Constraints

  First, the device should be small enough to fit comfortably on the finger without hindering normal movement. Second, it should be battery-powered and have low power consumption for extended usage. Third, the device should be compatible with existing digital interfaces or provide necessary connectivity options.

- User Experience (UX) Considerations

  First, prioritize user comfort and ergonomic design to ensure the device is wearable for extended periods. Second, consider intuitive calibration processes and user-friendly interfaces for ease of use. Third, strive for accurate and responsive data capture to enhance the user's sense of control and immersion.

Design Plan

- Research and Concept Development

  First, conduct market research to understand existing finger tracking solutions, their limitations, and potential areas for improvement. Second, explore various design concepts, including sensor placement, sensor types, and form factors. Third, evaluate the design concepts based on criteria such as accuracy, comfort, manufacturability, and user experience. Fourth, select the most suitable concept for further development and refinement.

- Prototype Development and Testing

  First, build prototypes using appropriate materials and manufacturing techniques. Second, conduct extensive testing to validate the accuracy, responsiveness, and comfort of the device. Third, develop a detailed design that includes a compact housing for the flex sensor, microcontroller, and battery. Fourth, design a circuit that measures and processes the sensor's output signal accurately.

- Evaluation and Iteration

  First, continuously evaluate the device's performance through user feedback and real-world testing. Second, incorporate improvements based on user needs, market demands, and technological advancements.

2.2.3 | Dynamic Hand Motion Tracking

In the context of the hand exoskeleton system, motion tracking refers to the ability of the system to sense and interpret the wearer's finger movements using flex sensors or other motion sensors and drive . The system can then use this data to provide appropriate assistance or mimicry through the motor-driven tendon mechanism, enabling the wearer to perform tasks that require hand dexterity, such as gripping objects or manipulating tools.

Design Content

- Design Overview

  The hand motion tracking system utilizing flex sensors is designed to accurately capture and interpret the bending motion of the wearer's fingers. By incorporating flex sensors on both the hand glove and the hand exoskeleton system, the system aims to provide real-time feedback and control for precise finger motion tracking. The flex sensors are strategically placed on the finger joints to detect and measure the degree of finger bending. The hand glove is worn by the user, and its flex sensors serve as the input signals for the tracking system. These signals are transmitted to the hand exoskeleton, which utilizes the data to drive its own hand and replicate the wearer's finger movements.

- Flex Sensor Placement

  The flex sensors are positioned on the hand glove and hand exoskeleton system at specific locations corresponding to the finger joints. This ensures accurate and reliable measurement of finger bending angles.

- Signal Transmission and Processing

  The flex sensors on the hand glove capture the finger bending information and transmit the signals to the hand exoskeleton system. The transmission method can be wired or wireless, depending on the design requirements. As for the signal processing, the flex sensors on the hand glove capture the finger bending information and transmit the signals to the hand exoskeleton system. The transmission method can be wired or wireless, depending on the design requirements.

- System Identification and Control

  The processed flex sensor signals are mapped to the corresponding finger joints of the hand exoskeleton. The mapping algorithm translates the input signals into control commands that drive the hand exoskeleton to mimic the wearer's finger movements.

- Feedback and Calibration

  The tracking system incorporates feedback mechanisms to continuously monitor and calibrate the flex sensor measurements. This ensures that the hand exoskeleton accurately tracks the finger motion and provides a seamless and responsive user experience.

Design Plan

- Sensor Integration

  Integrate the flex sensors into the hand glove and hand exoskeleton system, ensuring secure attachment and proper alignment with the finger joints.

- Signal Conditioning

  First, implement signal conditioning techniques, such as amplification and noise filtering, to enhance the accuracy and reliability of the flex sensor signals. Second, Develop algorithms for real-time signal processing, including data smoothing and calibration, to improve the tracking system's performance.

- System Identification and Control

  First, design a mapping algorithm to translate the flex sensor signals into control commands for the hand exoskeleton system. Second, Design a mapping algorithm to translate the flex sensor signals into control commands for the hand exoskeleton system.

- Feedback and Calibration

  First, incorporate feedback mechanisms to continuously monitor and calibrate the flex sensor measurements. Second, develop calibration procedures to ensure accurate tracking and minimize any drift or error in the system.

2.2.4 | System Assembly Box

This system assembly is designated to assembly and contain all components needed in this project, e.g., motors, batteries, microcontroller, motor driver and so on.

Design Content

- Design Overview

  The project aims to develop a system assembly box for housing the actuators and control board of the hand exoskeleton system. The design of the box should ensure proper placement of each motor to avoid any interference. Additionally, the size and internal structure of the box need to be carefully designed to accommodate ten motors and the control board effectively.

- Assembly Box Design

  First, determine the appropriate dimensions for the box, considering the size of the actuators and control board. Second, design the internal structure of the box to provide secure and organized placement for the motors and control board. Third, ensure sufficient space between the components to prevent any unwanted contact or interference. Fourth, consider the material selection for the box to ensure durability and proper protection for the internal components.

- Motor Placement

  First, conduct a thorough analysis of the dimensions and specifications of the actuators. Second, determine the optimal positioning of each motor within the assembly box to prevent any mechanical conflicts. Third, ensure that the motor placement allows for smooth movement and operation of the hand exoskeleton system. Fourth, consider the alignment of the motors with the corresponding tendons to facilitate efficient tendon-driven motion.

- Control Board Installation

  First, design a secure and accessible location within the assembly box to install the control board. Second, ensure proper mounting and fastening of the control board to prevent any movement or disconnection during operation. Third, provide necessary openings or interfaces on the box for connecting external power and communication cables to the control board. Fourth, consider heat dissipation requirements and incorporate appropriate ventilation or cooling mechanisms, if necessary.

Design Plan

- Requirements Gathering

  Gather detailed specifications of the actuators, control board, and other components to determine the space and structural requirements for the system assembly box.

- Conceptual and Detailed Design

  First, develop initial concepts for the system assembly box, considering factors such as size, internal structure, and material selection. Second, Use CAD software or similar tools to create 3D models of the box, allowing for visual evaluation and potential modifications. Third, refine the selected design concept, incorporating considerations for motor placement, control board installation, and overall functionality. Fourth, ensure that the box design aligns with safety standards and ergonomic principles. Fifth, verify that the selected materials provide sufficient strength, rigidity, and protection for the internal components.

- Prototyping and Testing

  First, create a physical prototype of the system assembly box using the finalized design. Second, Conduct thorough testing to evaluate the fit, functionality, and reliability of the box design. Third, Make necessary adjustments or improvements based on the testing results.

3 | Manufacturing

3.1 | Tendon-driven Hand Exoskeleton

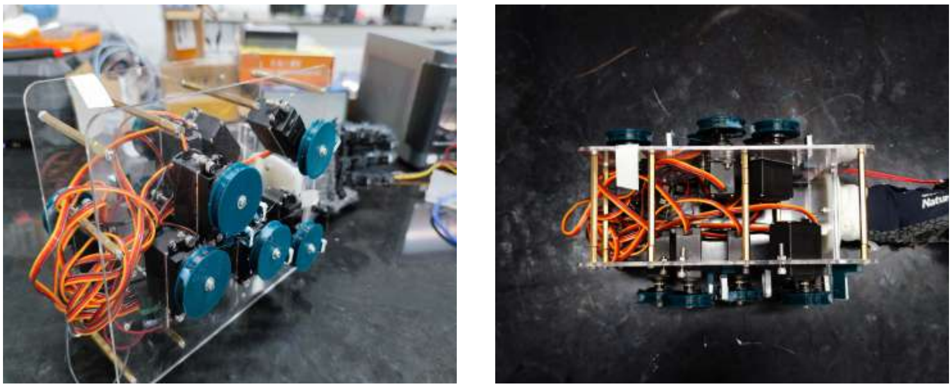
Figure 3.1: Detailed arrangements on the prosthetic hand, including the tendon sheath, anchor, string and flex sensor.

In the hand exoskeleton system, all the strings, anchor points, and the tendon sheath are integrated into a glove. The strings play a vital role in bending the fingers. Each string is connected to an anchor point fixed near the joint on the glove. When a string is pulled, it creates tension that is transmitted to the finger joint through the anchor points. The fixed position of the anchor point causes a specific section of the string to bend, resulting in the desired curvature of the finger.
By adjusting the length and position of the string, the tension and direction can be controlled, thereby regulating the angle and force of the finger bend. Tightening the string applies a constricting force that guides the finger joints to bend, enabling the formation of a holding position. Releasing the string and tightening it in the opposite direction allows the finger joint to return to its original straight position.

Each finger is equipped with two sets of strings and anchor points, enabling both flexion and extension movements.
The position of the anchor point significantly affects the range of finger movement and sensitivity. When the anchor point is located far from the joint, contracting the string generates a larger torque, leading to increased finger bending. Conversely, if the anchor point is positioned near the joint, it may limit the range of finger flexion.
Moreover, the position of the anchor point influences the force transmission between the string and the finger. Placing the anchor point directly on the joint allows the force applied to the string to directly affect the bending movement of the finger. If the anchor point is situated elsewhere on the finger, additional leverage may be required, potentially impacting the strength and control of the fingers.
The sensitivity and accuracy of the system are also affected by the anchor point's position. A closer position to the joint enhances movement sensitivity but requires higher control precision.
During the testing phase, multiple anchor point positions were evaluated to achieve optimal results. Ultimately, the anchor point was fixed at the midpoint between two joints, striking a balance between sensitivity and control difficulty.
The anchor points are made of TPU (Thermoplastic Polyurethane) using 3D printing technology. TPU as the material for the anchor points enhances durability due to its flexibility, elasticity, and toughness. The low friction factor of TPU ensures smoother movement between the string and the anchor points, facilitating easier and more efficient operation.
The tendon sheath plays a crucial role in the system's structure. Placing the strings inside the tendon sheath reduces friction, resulting in improved sensitivity and smoothness of finger movements. The tendon sheath provides a smooth surface that minimizes friction as the strings move internally. This reduces energy loss, minimizes wear on the ropes, and enhances the overall efficiency and service life of the exoskeleton. The placement of the tendon sheath is primarily centered on the palm, guiding the strings effectively.
By incorporating these design considerations, the hand exoskeleton system achieves precise finger movements, enhanced sensitivity, and improved user experience.

3.2 | System Assembly Box

Using a steering motor and a wheel can make a simple winder. By rotating the steering motor, the wheel can be wound or unwound, allowing the string to be tightened and loosened, achieving finger bending and extension. By controlling the direction and speed of the steering motor, it can achieve precise control over the tightening and loosening of the string. This provides the exoskeleton with flexible finger movements and allows adjustment and customization as needed. The wheel was designed with a dip in the middle to ensure that the string remained inside the wheel while it was rotating. The wheel was made of PLA material ensuring it was strong enough to withstand the pull of the string.
Because there were ten winders of the control system, the internal structure of the box was designed carefully to follow the direction of the strings and avoid the interference between the winder and the other one.



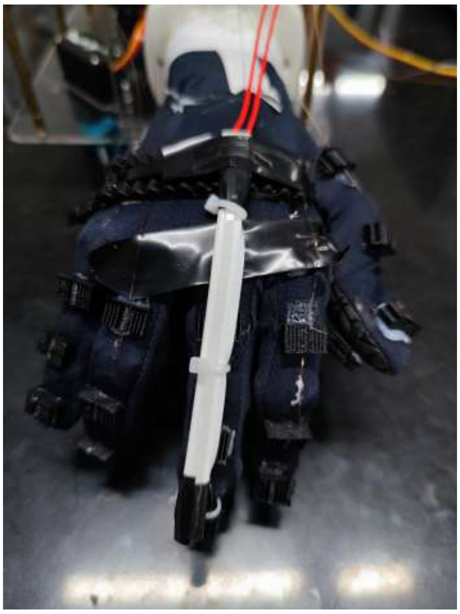
(a) Front view of the system assembly box **(b)** Top view of the system assembly box

Figure 3.2: System assembly box at different angles of view.

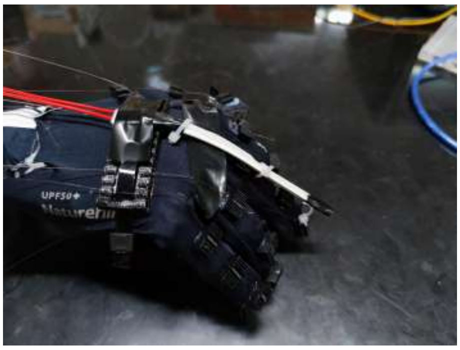
3.3 | Gesture Sensing

3.3.1 | Sensor Integration and Calibration

Since the flex sensors are very fragile and can be easily broken, we use white electrical tape to wrap around their surface. Moreover, this wrapping protects the flex sensor from localized bending by spreading the bending evenly. In addition, two layers of smooth ties are arranged on the surface of the white electrical tape to reduce friction during the back and forth movement of the flex sensor. The reading of the flex sensor will change over time, so it needs to be calibrated each time it is used.



(a) Front view of the flex sensor arrangement



(b) Side view of the flex sensor arrangement

Figure 3.3: Arrangement of flex sensor on the prosthetic at different angles of view.

3.4 | Dynamic Motion Tracking

3.4.1 | Flex Sensor Installation

As shown in Figure 3.4, the flex sensor is mounted on the back of the finger and fixed by several rolling bands, because the flex sensor can only detect the degree of bending and does not have ductility. The measurement data from the flex sensor is sent back to the PC through Serial Communication.

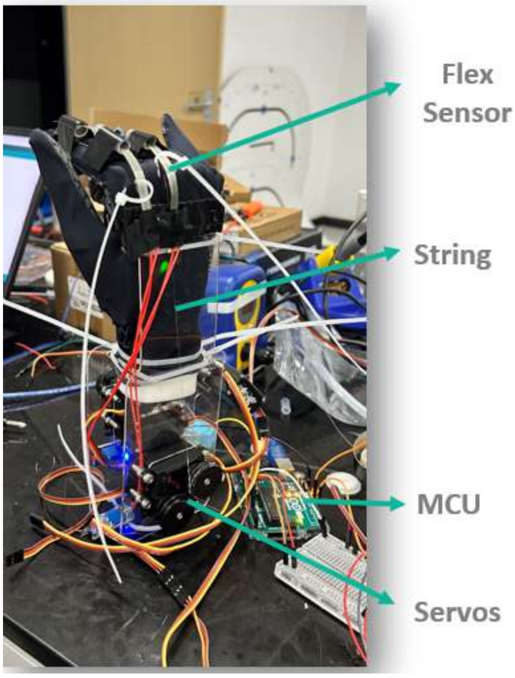


Figure 3.4: Overview of the arrangement of the dynamic tracking system

	Servo angle		Flex sensor reading	
	θ_1 (palm)	θ_2 (dorsum)	y1 (Flexion)	y2 (Extension)
1	100	100	2370	2090
2	120	90	2170	1990
3	135	80	2100	1940
4	150	70	2040	1870
5	165	60	1990	1835
6	170	50	1935	1830
7	200	40	1860	1685
8	225	30	1680	1650
9	250	20	1630	1580
10	275	10	1580	1530
11	300	0	1540	1540
	tighten	predefined	read through serial port	

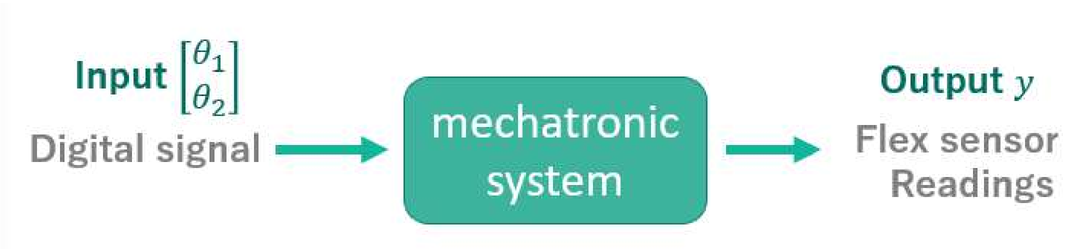
Figure 3.5: Experiment data used to conduct system identification.

3.4.2 | System Identification

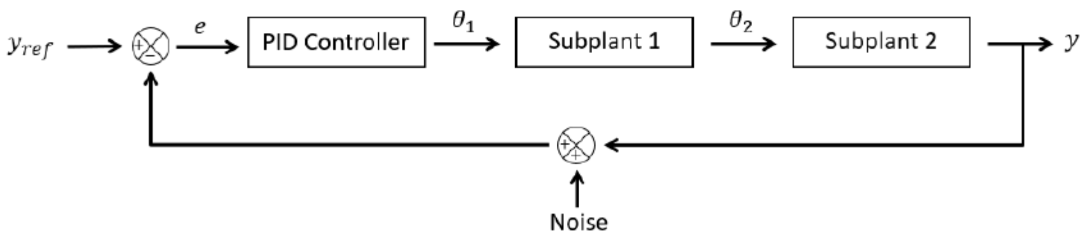
To achieve the hand motion tracking task, we need to model the hand exoskeleton system mathematically. Considering the complexity and difficulty in directly modeling system using mathematical formula, we use the system identification method to model the system. As shown in the Figure 3.5, we've conducted experiments on our hand exoskeleton system. We drive two motors to flex and extend the prosthetic hand and collect the corresponding flex sensor data. There exists difference during the flexion and extension process, which should be paid additional attention in the following control-strategy designing process.

3.4.3 | Control Strategy

Since the hand motion tracking system of each finger is a MISO system and we plan to design a PID controller to achieve the tracking task, we need to transform the MISO system into a SISO system, which means we need to decouple the two simultaneous input into two cascaded input, as shown in Figure 3.6a. Hence, we add an assumption where the two input values are dependent and the flex sensor data can be extensively determined by one of the input value. With this assumption, the decoupled cascaded system shown in Figure 3.6b can be obtained.



(a) MISO system block diagram



(b) Decoupled cascaded SISO system block diagram

Figure 3.6: System block diagrams for the hand motion tracking system

With the experiment data shown in Figure 3.7 and 3.8, we assume that both relationships are linear, which is reasonable implied in the data plot.

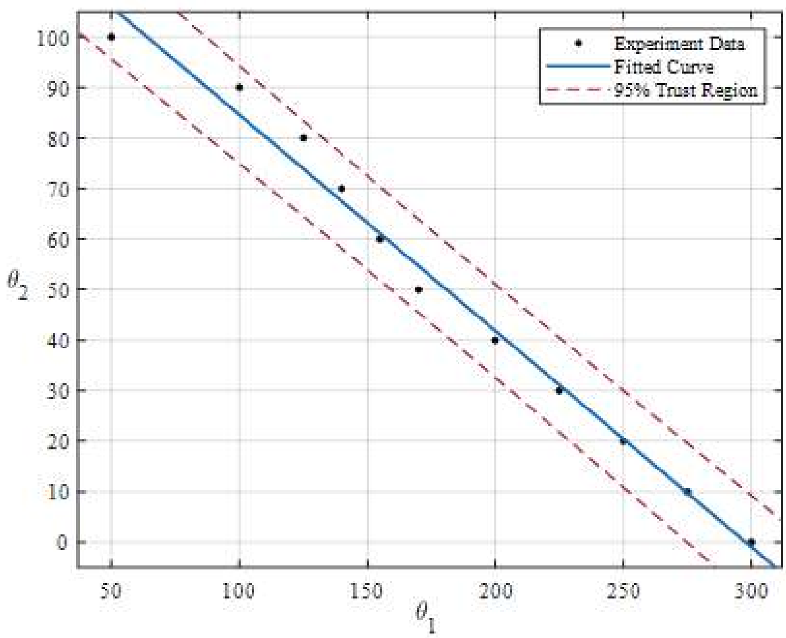


Figure 3.7: Fitted relationship of the angle of two motors

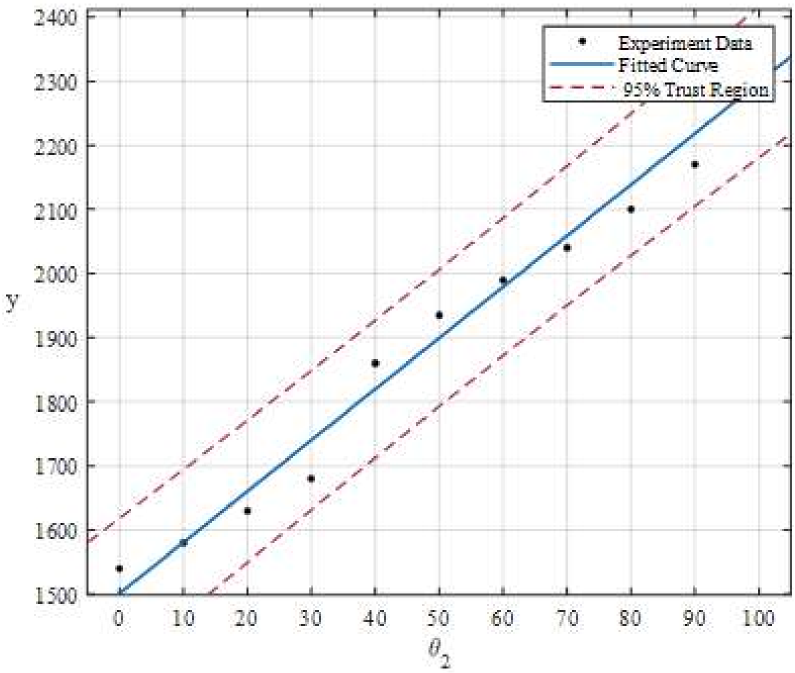


Figure 3.8: Fitted relationship between the flex sensor data and the angle of one motor

With the decoupled cascaded system, we can design our PID controller to achieve our desired task. The designed PID controller block diagram is shown in Figure 3.9. This is a kind of adaptive PID controller, which has embedded two different PID block aiming to solve the problem we've mentioned in the system identification section, where the flex sensor data is different in the process of flexion and extension.

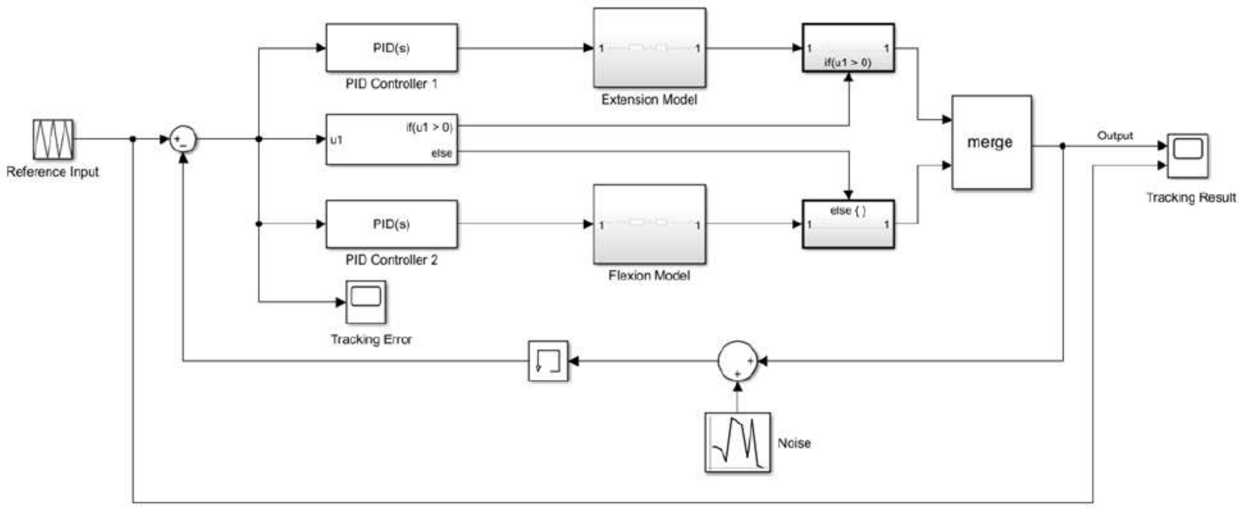
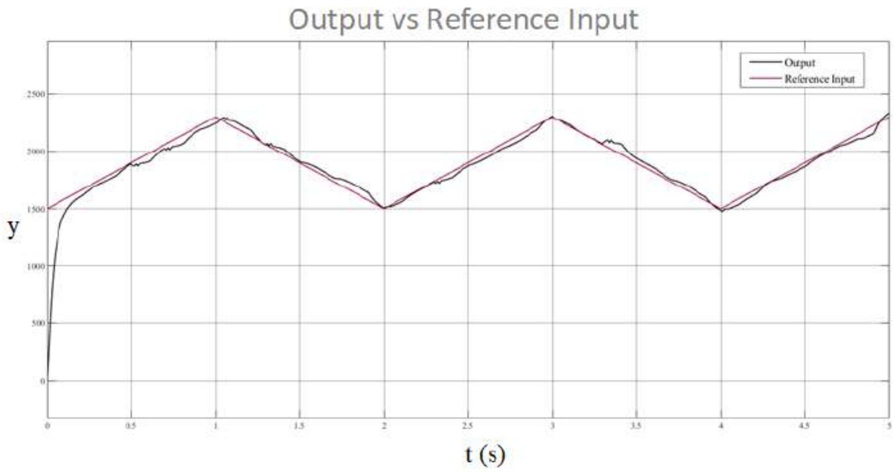
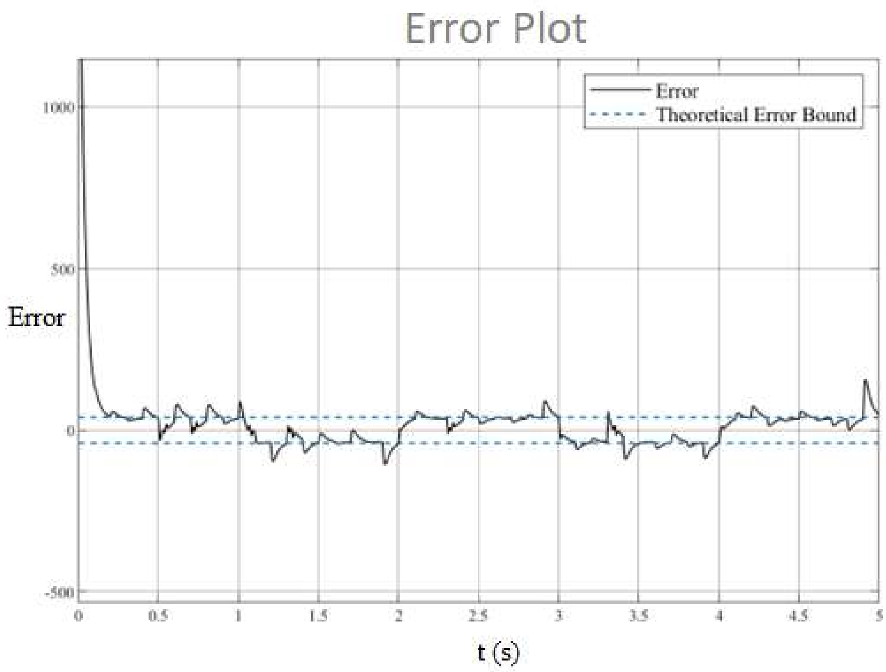


Figure 3.9: Front view of the flex sensor arrangement

The simulation results are shown in the Figure 3.10a and 3.10b, both of which are satisfying and capable of achieving the hand motion tracking task with low latency and low steady-state error.



(a) Tracking result in simulation.



(b) Tracking error in simulation

Figure 3.10: Tracking results in simulation

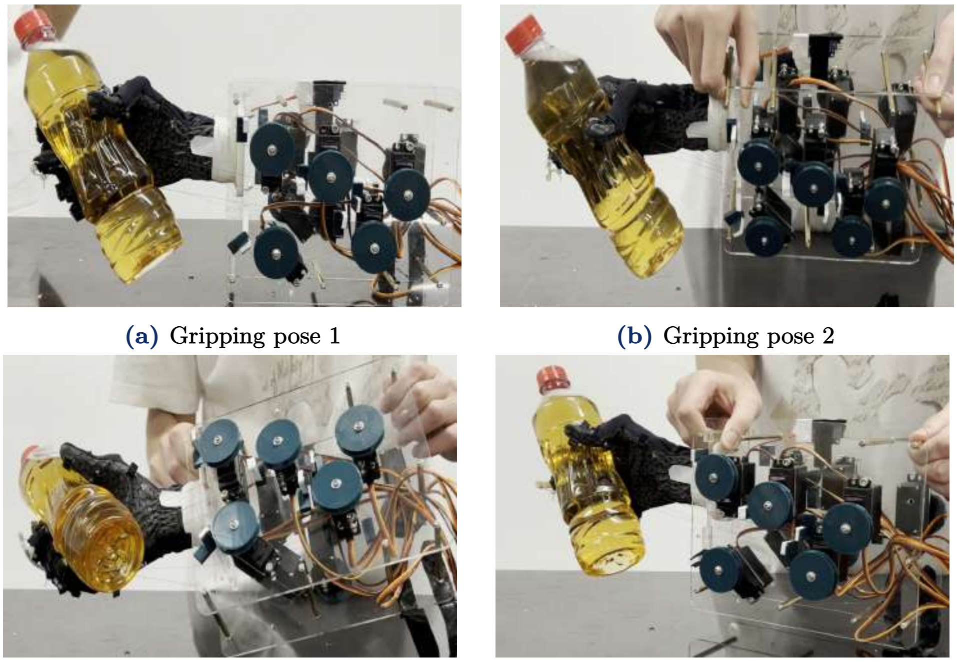
4 | Results and Discussion

After manufacturing our prototype of the whole system, we conduct several experiments to test the characteristics of our prototype from different aspects. All basic requirements are well satisfied and verified in the experiments. More importantly, the motion tracking system proposed before also achieves desirable outcome, which is a closed-loop controlled system, incorporating finger shape sensing, with safety insurance embedded in the tracking algorithm.

4.1 | Experimental Results

4.1.1 | Gripping Test

The 15 N grip strength is the basic grip strength that meets the daily activities of human life. We designed a grip experiment, if our hand exoskeleton system can grasp a 500 ml bottle of water in any direction, it shows that it meets the basic requirements of grip strength above 15 N. The result was satisfactory, our hand exoskeleton grabbed the 500ml bottle of water successfully.



(a) Gripping pose 1 **(b)** Gripping pose 2

(c) Gripping pose 3 **(d)** Gripping pose 4

Figure 4.1: Experiments of gripping test. These experiments show that our hand exoskeleton system can drive the prosthetic hand to grip one 500 ml bottle of beverage with an arbitrary pose, which demonstrates that the grip strength in all directions provided by our hand exoskeleton system is larger than the required baseline, 15 N. And this baseline is regarded as the minimum gripping strength for daily life[4].

4.1.2 | Freedom And Actuation Range Test

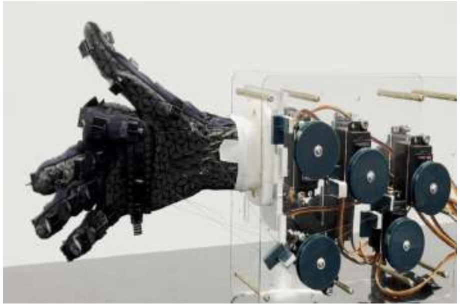
The hand exoskeleton needs to have enough freedom and drive stroke so that the user can move the hand freely. We drive finger by finger to see if each finger can achieve full flexion and extend. The result was positive, we achieved complete flexion and extend of each finger, meeting the requirements of freedom and actuation range. The results are shown in Figure 4.2.

4.1.3 | Flexibility Test

The hand exoskeleton needs to be able to move flexibly to meet the needs of various hand posture in users' lives. We control the hand exoskeleton to make a variety of postures, proving that it has a high degree of flexibility and can meet the daily needs of users. The results are shown in Figure 4.3.

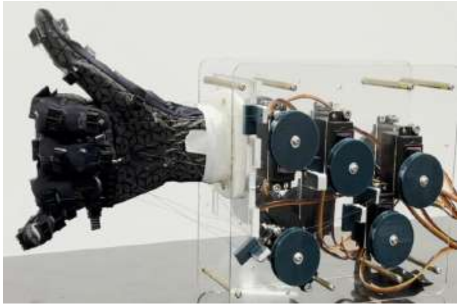
4.1.4 | Multidimensional Gripping Test

The hand exoskeleton should have good adaptability and be able to cope with different grasping conditions. We controlled it to grasp a number of different shapes of water bottles filled with water, it can steadily grasp the water bottles, which proves that our hand exoskeleton has good adaptability, can cope with different grasping conditions in life. The results are shown in Figure 4.4.

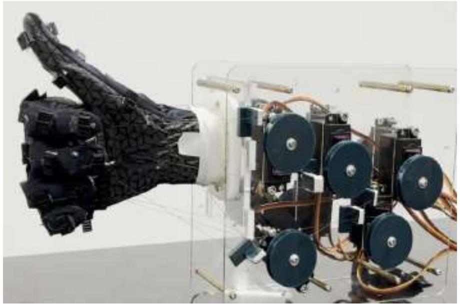


(a) Flexion with only index finger

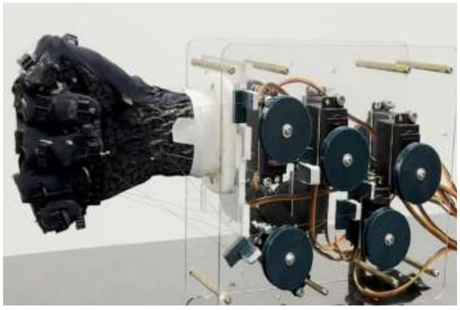
(b) Flexion with index and middle finger



(c) Flexion with three fingers



(d) Flexion with four fingers



(e) Flexion with five fingers

Figure 4.2: Experiments of controlling each finger independently. Figures 4.2a to 4.2e show the flexion process of the prosthetic hand driven by the hand exoskeleton system. These experiments demonstrate that each finger is able to be driven to flex independently, from index, middle, ring, little to thumb finger respectively. Hence, each finger is equipped with 1 degree-of-freedom and totally 5 degree-of-freedom of the prosthetic hand, which enables the flexibility in practice.

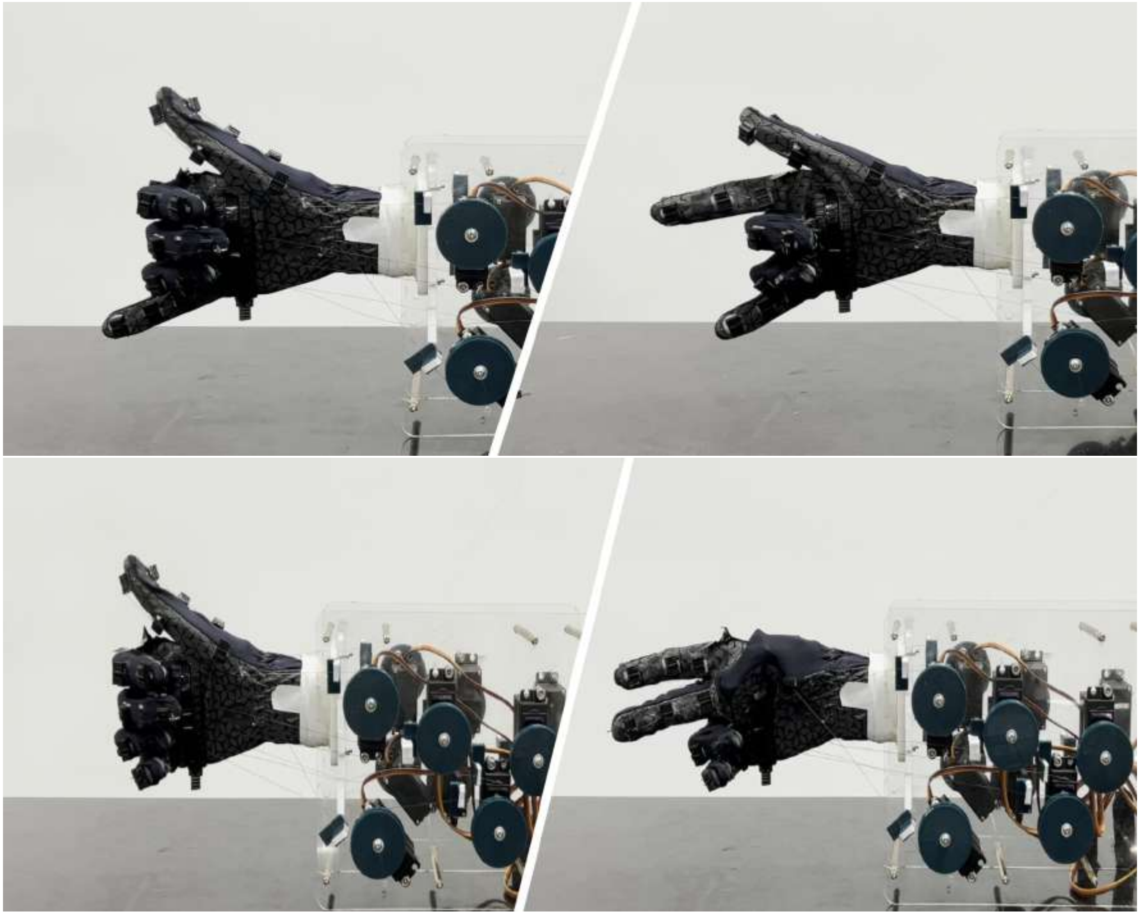


Figure 4.3: Experiments for the demonstration of the flexibility of the driven prosthetic hand. Four kinds of gesture driven by the hand exoskeleton system are shown in this figure, which verifies the flexibility and totally 5 degree-of-freedom of motion of the driven prosthetic hand.

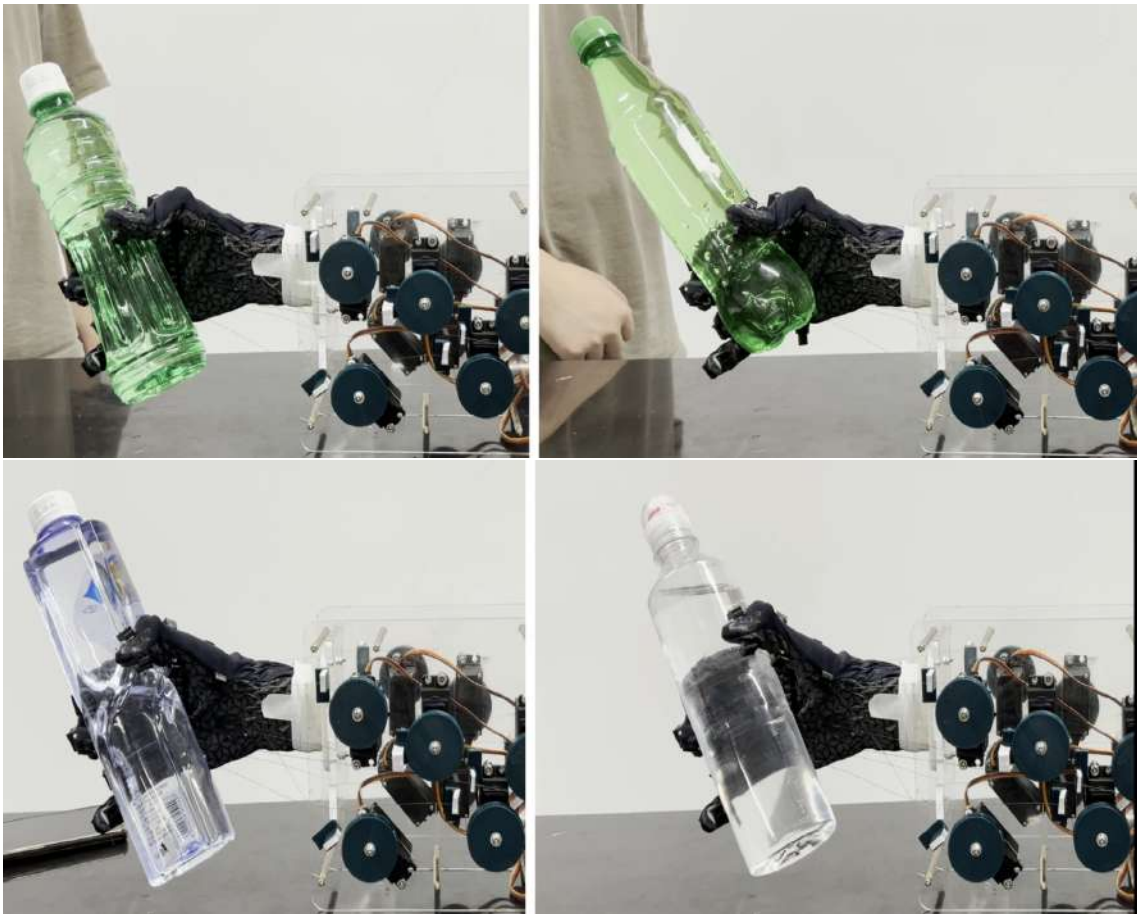


Figure 4.4: Experiments for the demonstration of the gripping strength. Four bottles of beverage with different container profile are stably gripped by the prosthetic hand driven by the hand exoskeleton system, which also shows the great adaptability of our hand exoskeleton system for different gripping tasks in daily life.

4.1.5 | Tracking Test

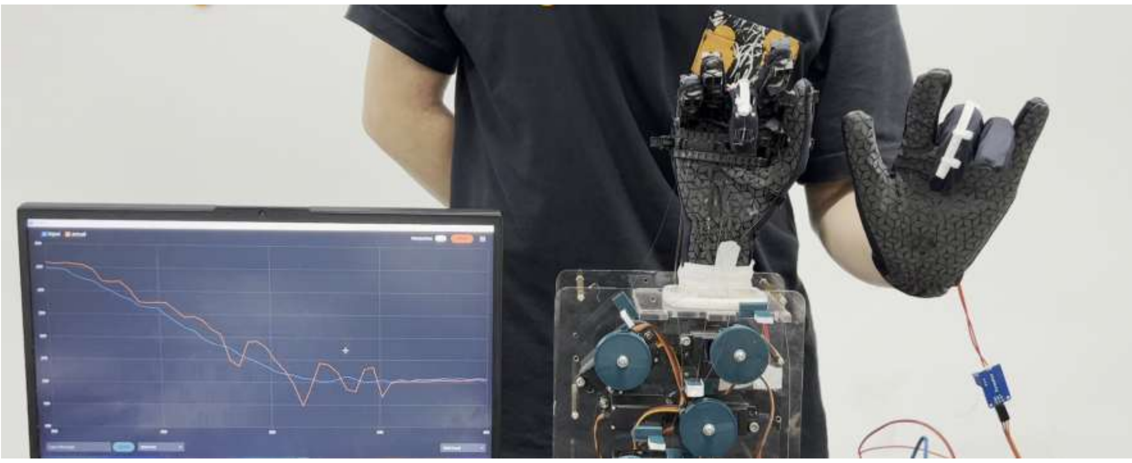
Our hand exoskeleton also has a unique human-machine interaction function. It can track the user's hand posture and realize the function of remote control of the manipulator. We controlled it to track the user's middle finger, and the curve between the two is shown here. It can be seen that our hand exoskeleton can quickly track users' movements and realize human-machine interaction. The experimental tracking results are shown in Figure 4.5.

4.1.6 | Other Basic Requirement

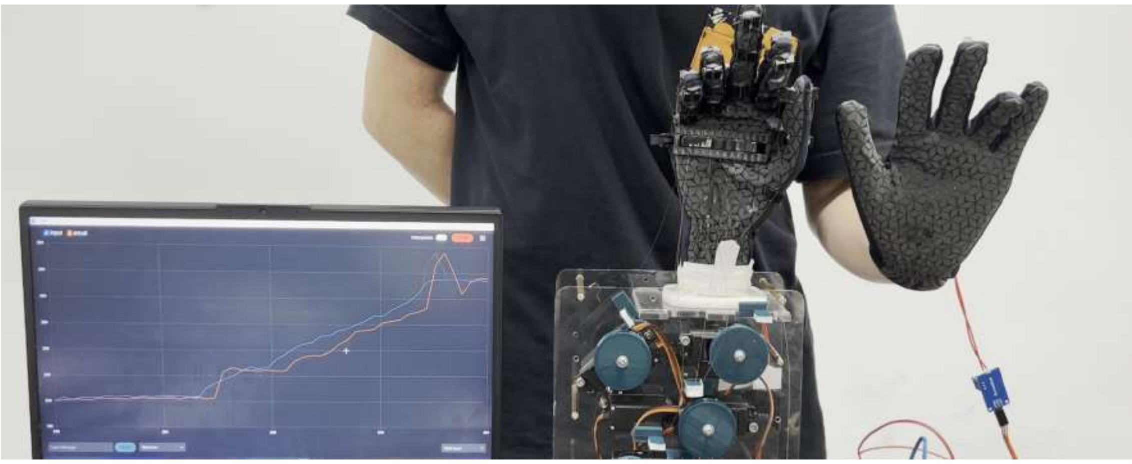
The weight and safety of the hand exoskeleton are also essential requirements. As for the weight of the wearable part of the arm, the steering gear accounts for the majority. We use ten steering gear, which is about 0.6kg. After adding the rest of the gear, the total weight is no more than 1kg. The weight of the wearable part of the hand is mainly gloves, which do not exceed 0.5kg. For safety, we limited the rotation angle of the steering gear at the software level, so as to limit the motion range of the hand exoskeleton, avoid it to drive the hand over-stroke and anti-joint motion, and ensure the safety of the hand exoskeleton. So our hand exoskeleton meets the basic needs of weight and safety.

4.2 | Strengths and Innovations

Our hand exoskeleton is controlled by a total of ten steering gear, and the flexion and extend of each finger are controlled by one steering gear, which greatly improves the accuracy and flexibility of the hand exoskeleton. In addition, we used the resistive flex sensors to detect the degree of finger curvature and



(a) Motion tracking in flexion process



(b) Motion tracking in extension process

Figure 4.5: Experiments for the demonstration of the motion tracking function. With two flex sensors attached to the glove on human hand and the glove on prosthetic hand individually, the bent extent of the human finger and the prosthetic finger are measured. And the bent extent of the human finger is used as input signal represented by the blue line on the PC screen while the bent extent of the prosthetic finger is represented by the orange line. Both in the flexion and extension process of the human finger, the prosthetic finger driven by the hand exoskeleton system can track the motion of the human finger, due to the utilizing of closed-loop controller.

paired with the closed-loop control algorithm to enable the hand exoskeleton to track the human finger so that it could interact with the computer innovatively.

4.3 | Further Improvement

At this present stage, our hand exoskeleton still has many deficiencies and worthy of improvement, such as the thumb movement stroke is small, not flexible enough; can only track the middle finger, not the whole five fingers, etc. In the future, we can adjust the position of the anchor point to control the thumb more precisely; Second, we can put flex sensors on each finger to track all five fingers.

5 | Cost Estimation

As shown in the Table 5.1 below, all costs of this project are enumerated. The total cost is around 1599.36 RMB, which is in the range of budget while lots of money has been invested in the trial and error process.

Table 5.1: Materials and costs used in this project

Item	Unit Price	Quantity	Cost
Nuts and screws	121.56	many	121.56
Acrylic sheet	63	many	63.00
Hand model	69.00	1	69.00
Glove	39.00	1	39.00
Arduino Uno	40.00	1	40.00
Resistive flex sensor	89	4	356.00
Steering gear drive plate PCA9685	19.20	2	38.40
Steering gear MG996R	32.00	10	320.00
Linear motor	190.00	1	190.00
3D Printing	362.40	many	362.40
Total Cost			1599.36

6 | Conclusion

As for the tasks listed in Section 1.2 required by the project, our final prototype is capable of completing all tasks successfully. How these tasks are completed and the corresponding section talked about the results are summarized as follows.

- Our tendon-driven hand exoskeleton system is capable of assisting human to achieve the gripping task in daily life, which is demonstrated in experiments. The flexibility and
- Flex sensor is utilized as the key component to quantitatively measure the bent extent of fingers. And this flex data is successfully used to enable the human hand dynamic tracking task.
- Human hand dynamic motion tracking system is successfully developed, through real-world physical model identification, controller, simulation verification and experimental demonstration. This system empower the intelligence development of traditional hand exoskeleton system.

Finished this project, we've progressed a lot, not only our personal skills in many aspects, e.g. mechanical design and manufacturing, controller design, real-world modeling, but also the team coherence. Better performance in future could be expected.

7 | Acknowledgement

All work of this project is finished by the team *SharpShooters*, supported by SHIEN-MING WU SCHOOL OF INTELLIGENT ENGINEERING, Dr. Jincheng Lei, and Dr.Yitong Zhou, and all people who provided valuable assistance. Lots of online open-source websites provides useful materials, e.g. CSDN[1], Stack Overflow[3]. The photos of this report are mainly from Google Images[2].

8 | References

[1] CSDN. Csdn. https://www.csdn.net/, 1999.

[2] Google Images. Google images. https://images.google.com/, 2001.

[3] Stack Overflow. Stack overflow. https://stackoverflow.com/?products, 2008.

[4] Mir Muneeb Ullah, Uzair Hafeez, M. Naeem Shehzad, M. Naeem Awais, and Haroon Elahi. A soft robotic glove for assistance and rehabilitation of stroke affected patients. In *2019 International Conference on Frontiers of Information Technology (FIT)*, pages 110–1105, 2019.

9 | Appendix I

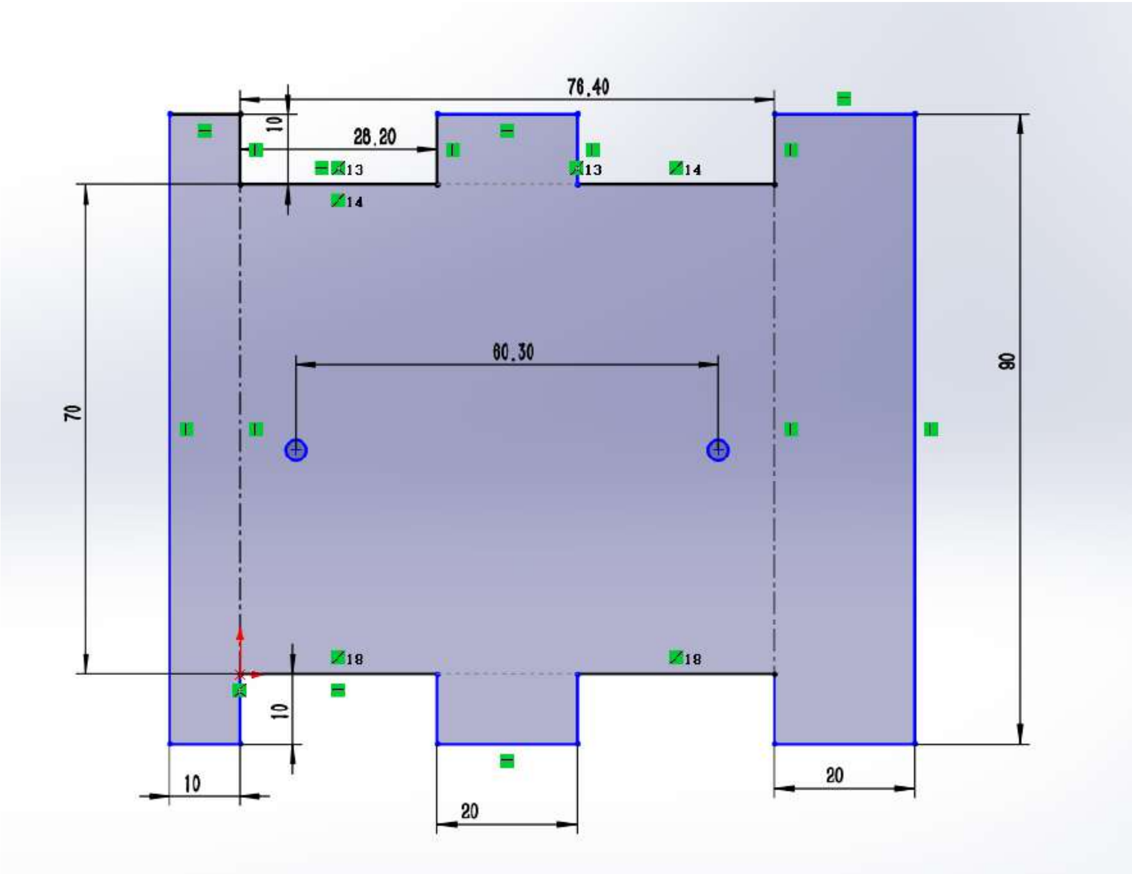


Figure 9.1: Front board CAD

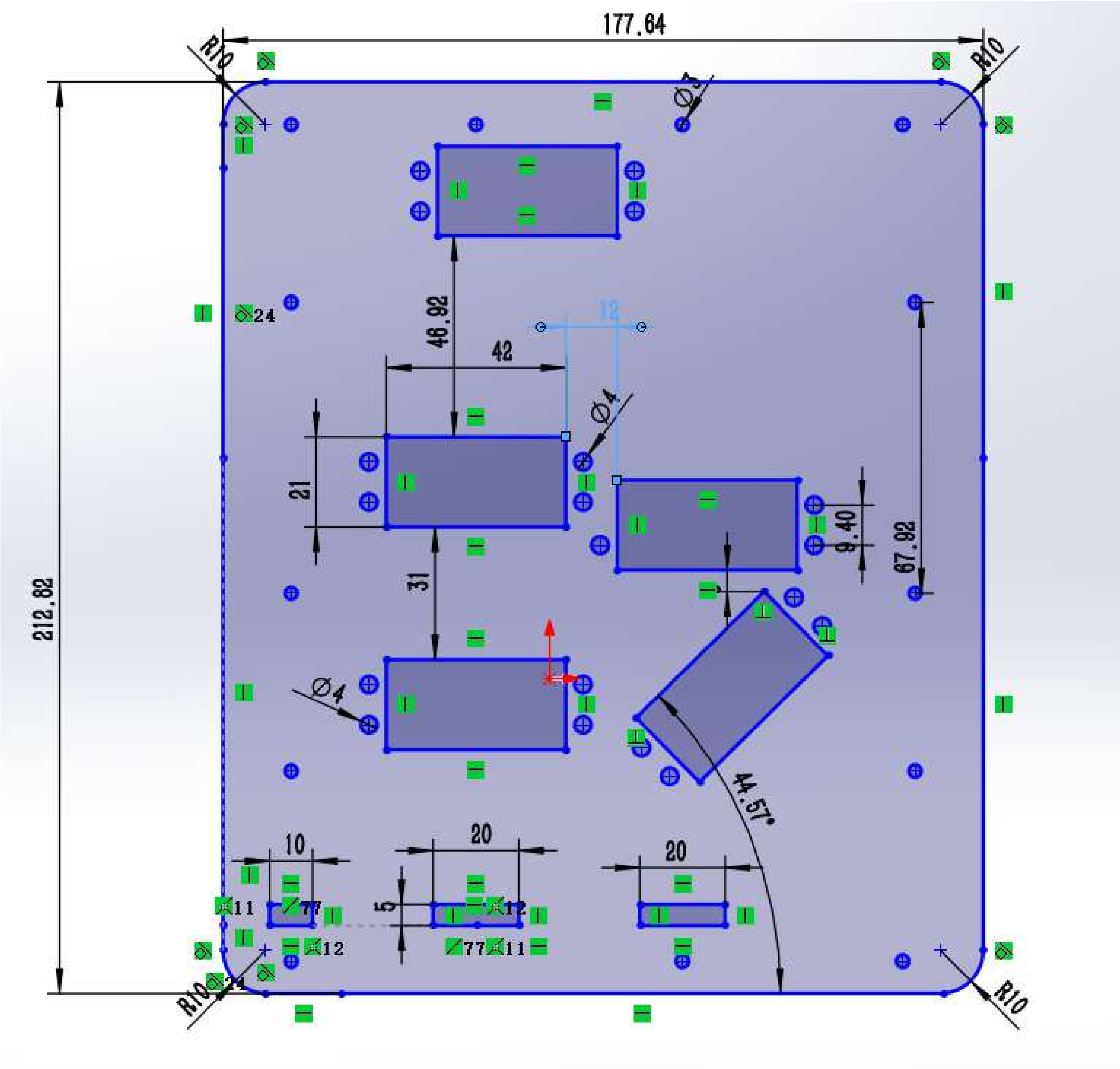


Figure 9.2: Left board CAD

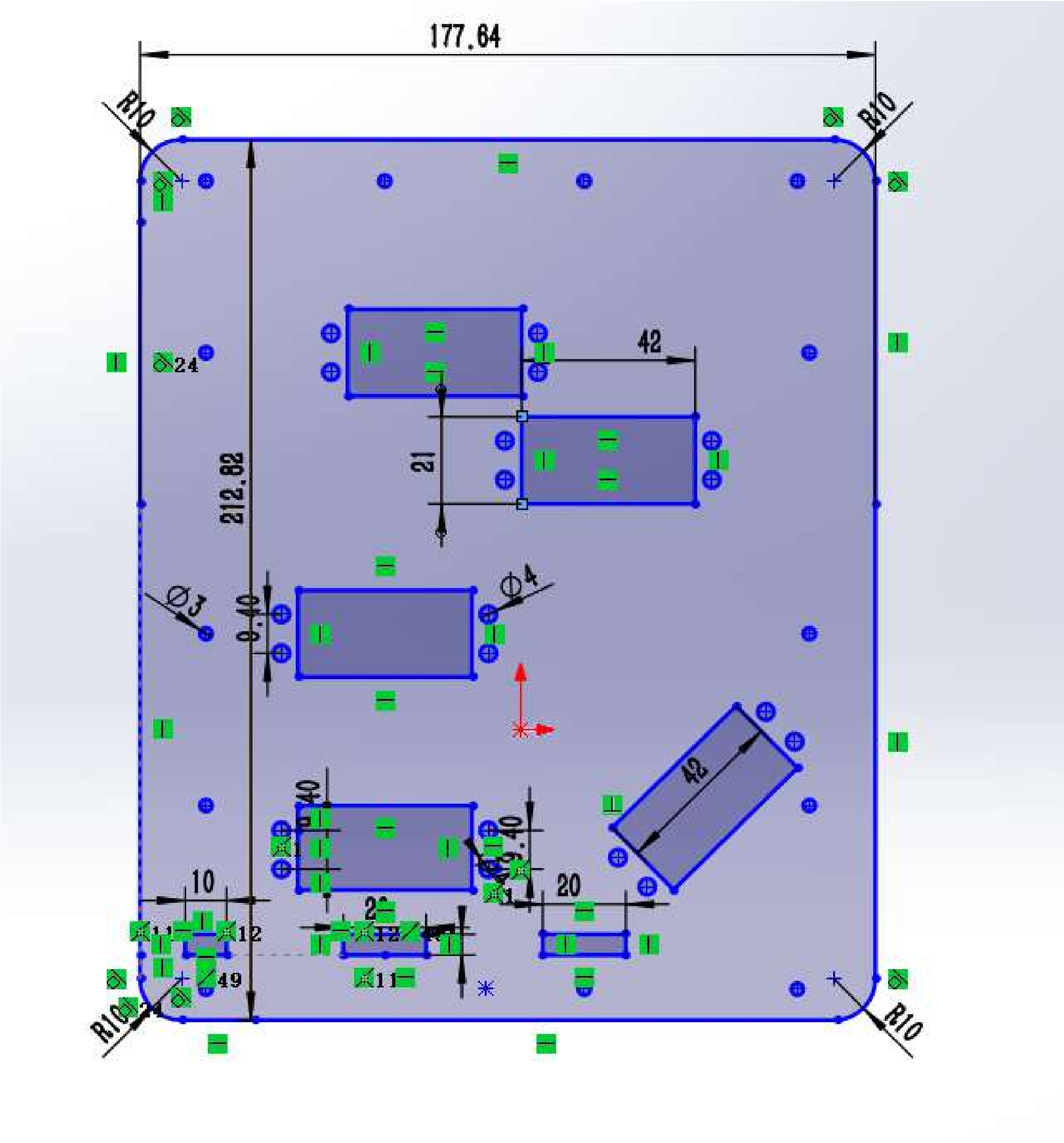


Figure 9.3: Right board CAD

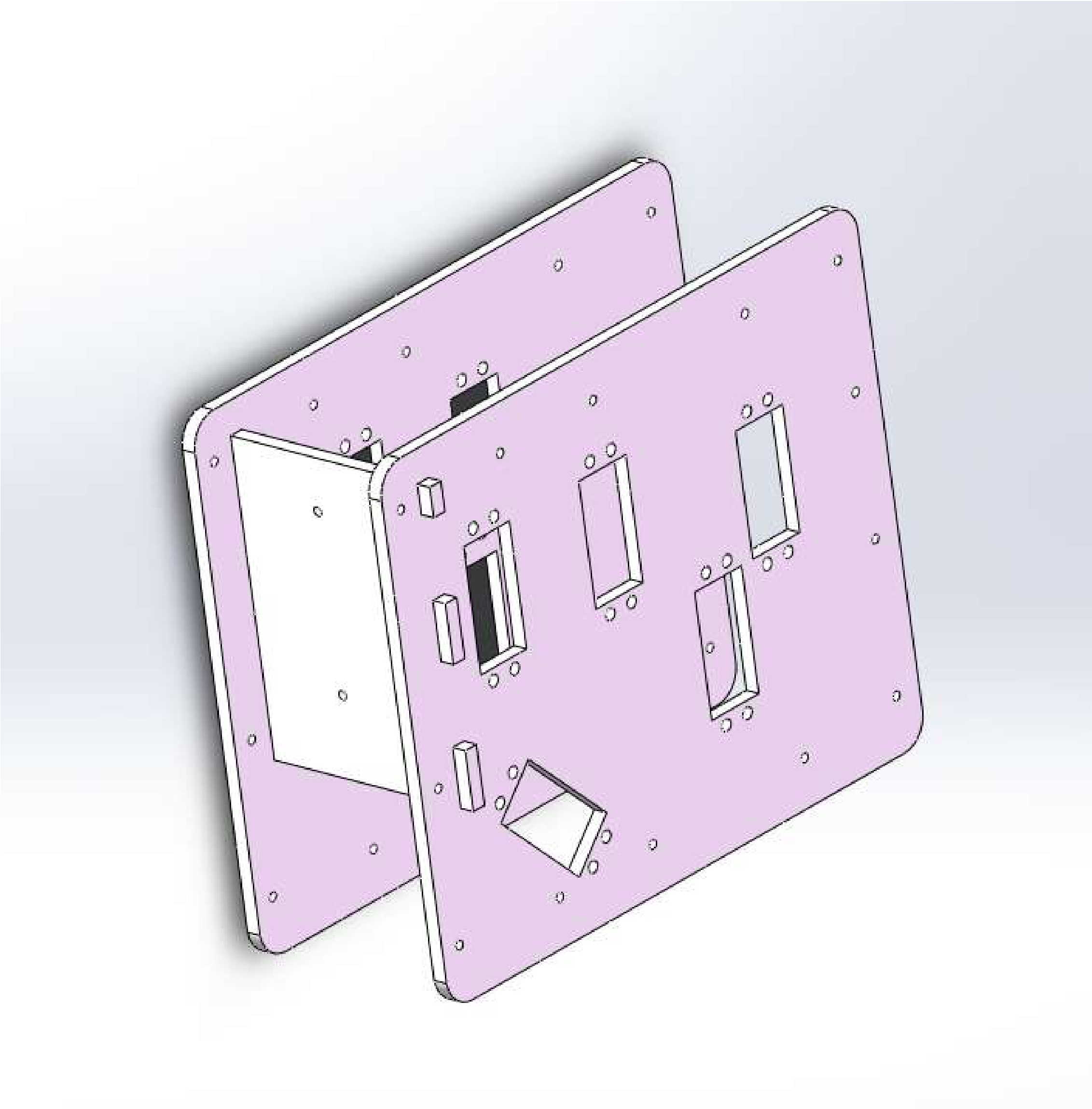


Figure 9.4: Total support structural 3D model

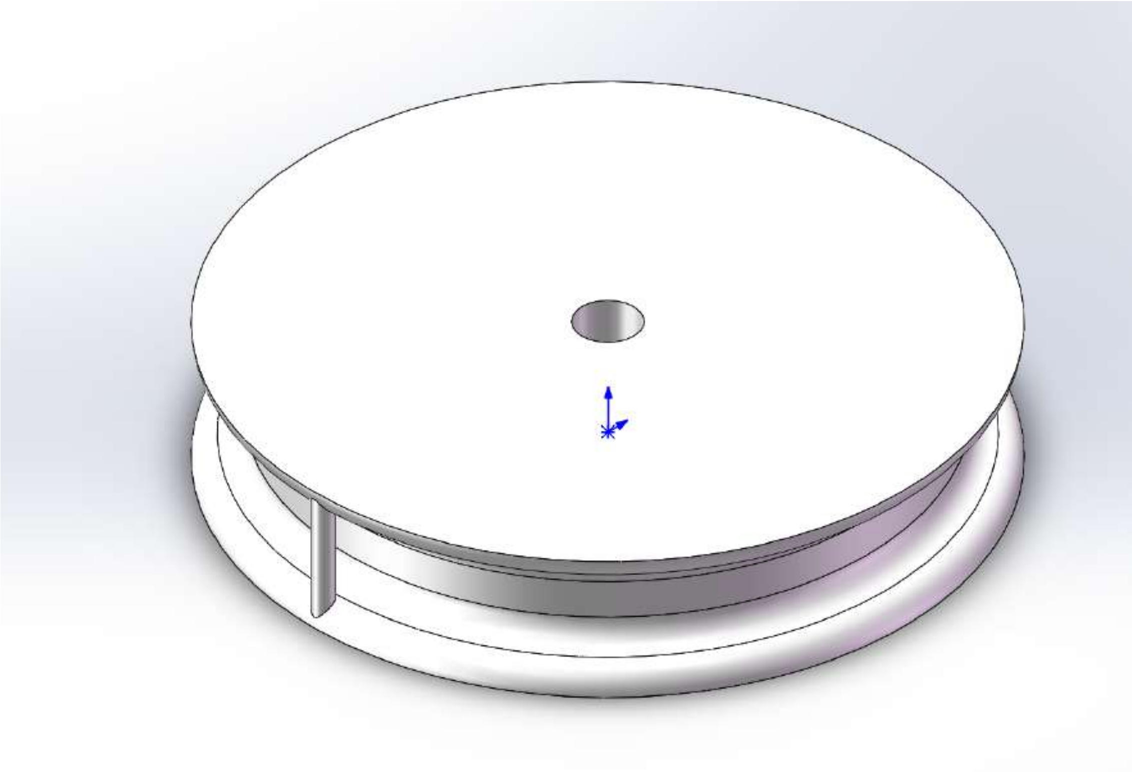


Figure 9.5: Turntable 3D model

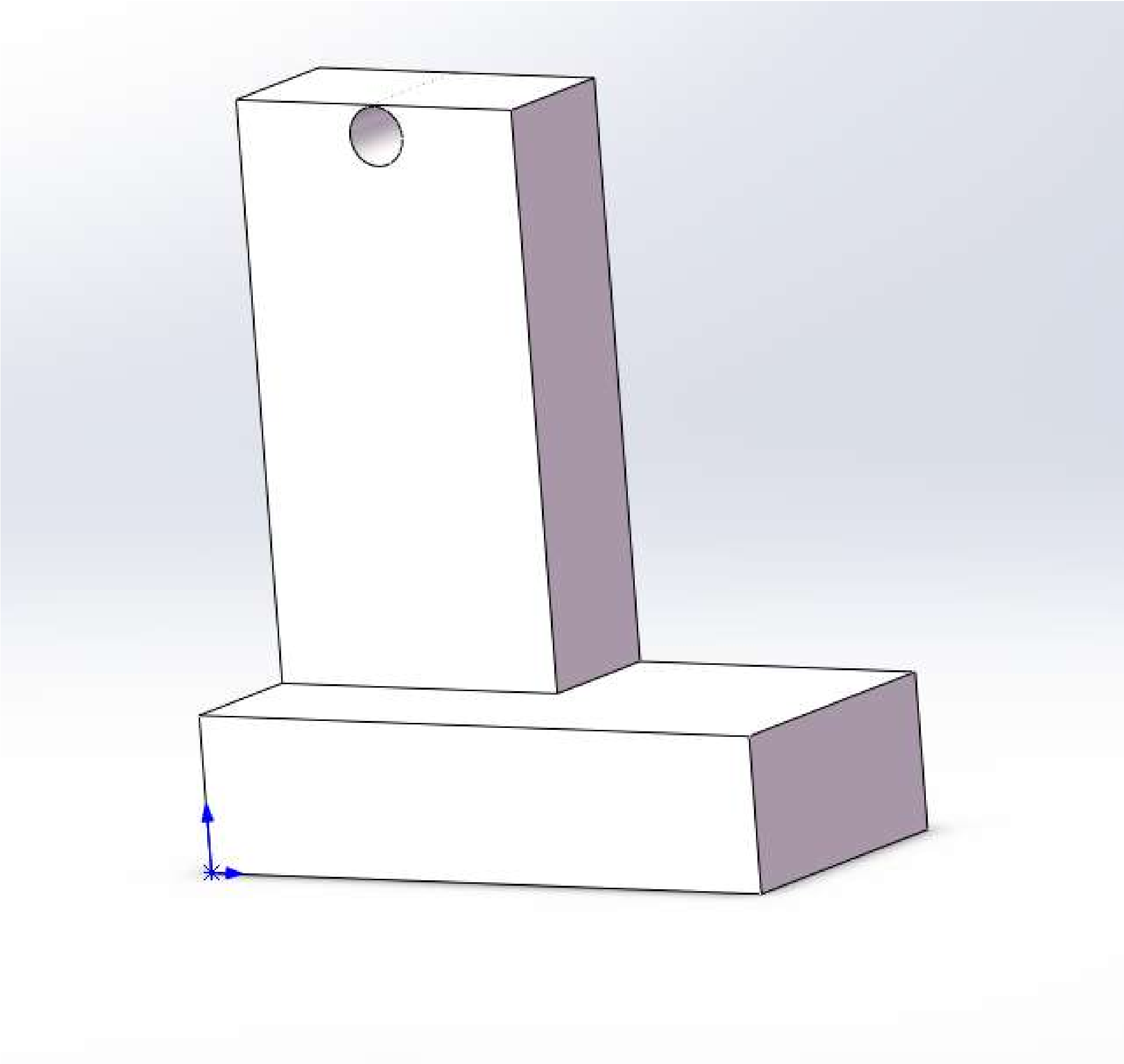


Figure 9.6: Line support 3D model

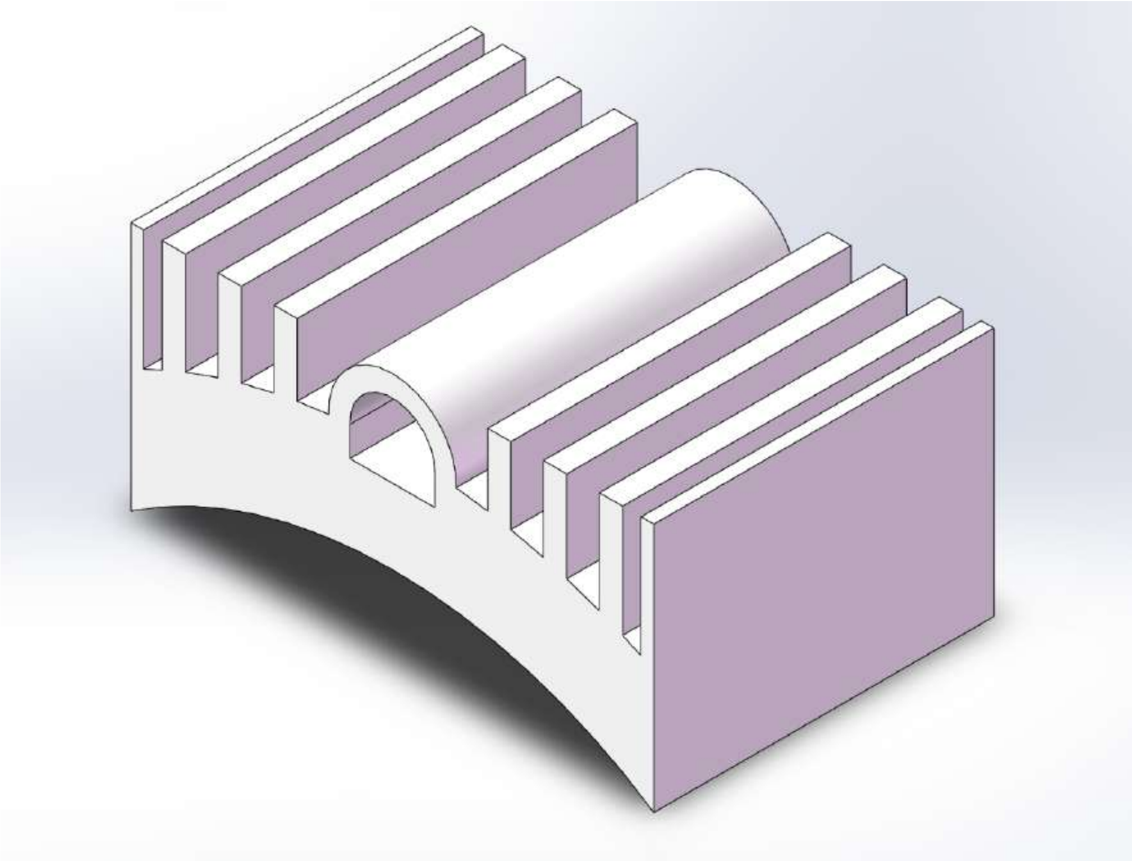


Figure 9.7: Tendon sheath 3D model

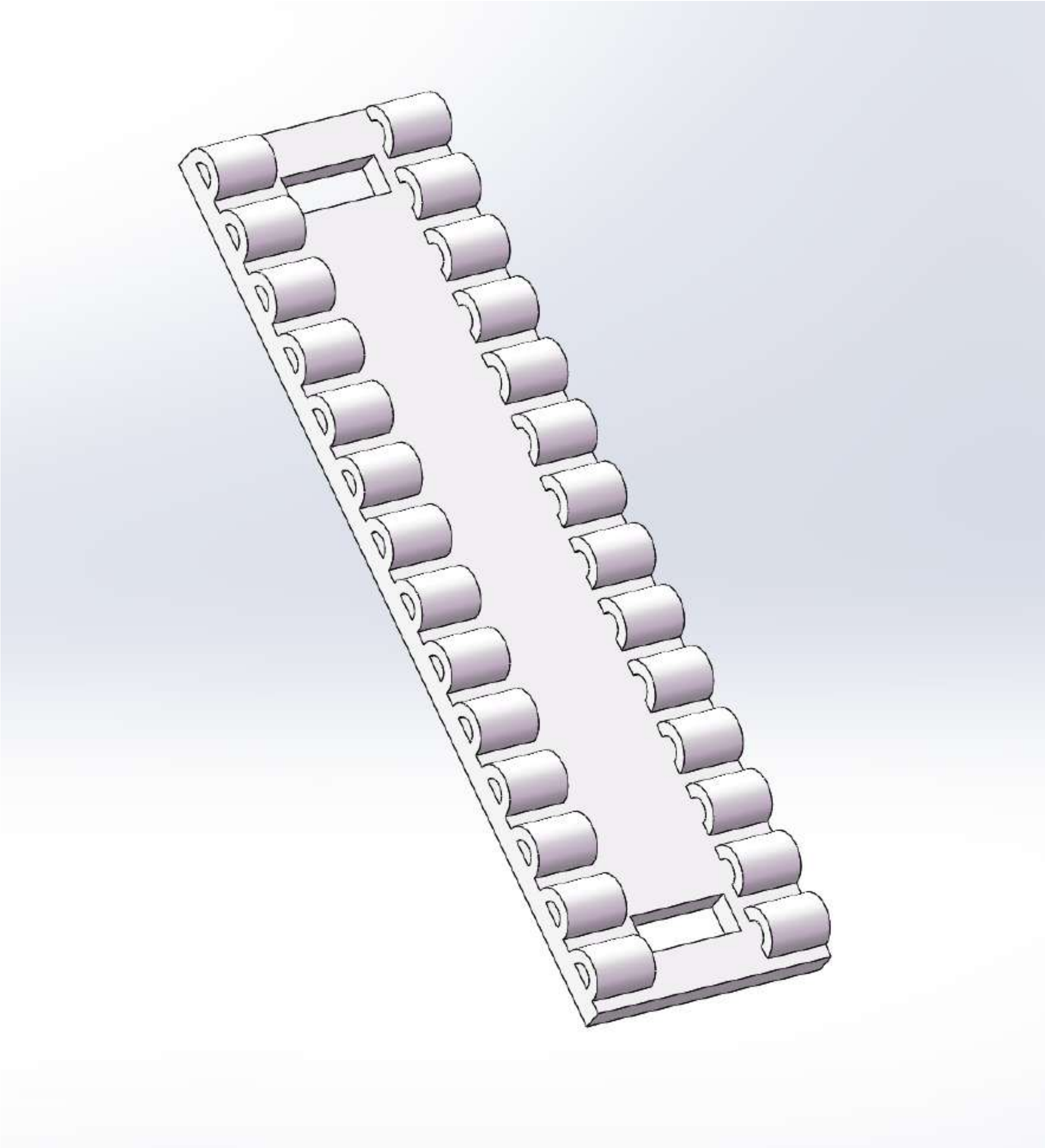


Figure 9.8: Netlist 3D model

10 | Appendix II

Table 10.1: Specification Parameter

Item	Parameter
Weight (except hand model)	800g
Length (except hand model)	213mm
Width	116mm
Height	178mm
Nominal voltage	5V
Control voltage	8V

Table 10.2: Bill of materials

Major parts	Quantity	Note
MG996R steering engine	10	Nominal voltage 5V
3D print turntable	10	Radius 20mm
Arduion uno	1	Nominal voltage 5V
Acrylic plate	3	Thickness 5mm
16 channel PWM Servo Steering gear drive plate module	1	None
Glove	1	None
FLEX sensor	1	None

11 | Appendix III

Notice:

- Use the product under nominal voltage.
- Do not shrink two steering engines on one finger at same time.
- Do not contact water.