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**DESIGN AND ACTUATION OF HUMANOID
HANDS FOR NATURAL GRASPING**

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School of Computer Science and Engineering

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A thesis submitted to the Nanyang Technological University in partial fulfilment of the
requirement for the degree of Doctor of Philosophy

2021

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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Tian Li

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

29 Sep 2021

Date _____

Prof. Zheng Jianmin

Authorship Attribution Statement

This thesis contains material from 9 papers published in the following peer-reviewed journals / from papers accepted at conferences in which I am listed as an author.

- 1) Chapter 2 (Section 2.1) is published as Tian, L., Thalmann, N. M., Thalmann, D., & Zheng, J. (2017). "The making of a 3D-printed, cable-driven, single-model, lightweight humanoid robotic hand." *Frontiers in Robotics and AI*, 4, 65.

The contributions of the co-authors are as follows:

- Prof N. Thalmann, Prof D. Thalmann and Prof Zheng provided the initial project direction and method and helped to edit the manuscript drafts.
- Tian Li developed and implemented the method, made the physical robotic hand, performed the test, and wrote the paper.

- 2) Chapter 3 (Section 3.2) is published as Thalmann, N. M, Tian, L., & Yao, F. (2017) "Nadine: A social robot that can localize objects and grasp them in a human way." *Frontiers in Electronic Technologies*. Springer, Singapore, 2017: 1-23.

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- Mr. Yao helped in the software part.

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- Tian Li developed and implemented the method, made the physical robotic finger, performed the test, and wrote the paper.
- Dr. Li helped to conduct the experiments, analyze the results, and revise the manuscript drafts.
- Mr. Halil helped in the design and making of the robotic hands.

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- Dr. Li helped to conduct the experiments, analyze the results, and revise the manuscript drafts.
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Abstract

Since the first prototype robot “WABOT-1” was created in 1973, how to build humanoid robots has been becoming an active research topic in the robotics area. Hands are one of the most articulated parts of humanoid robots. Natural grasping is a target that most humanoid robotic hands are pursuing. While a lot of research was done in the last 30 years for the simulation of human grasping, existing solutions for robotic hands to simulate the natural grasping of a human hand are still not satisfactory. For instance, it is observed that robotic hands are apparently different from human hands when moving or grasping due to the lack of kinematic ability and suitable motion plan. This thesis describes our research of designing robotic hands for social robots and enabling the robotic hands to function as human hands. The research is divided into four fundamental tasks: (i) designing visually pleasant customized robotic hands, (ii) equipping robotic hands with a human-like actuation mechanism, (iii) developing path planning method to simulate human hand grasping, and (iv) mimicking the complex in-hand manipulations.

The research started with studying the human hand anatomy biologically and mechanically. Based on the understanding of human hand’s structure and many rounds of prototype experiments, two designs of anthropomorphic robotic hands were proposed in this thesis. The first design is a 6 degrees-of-actuators (DOAs), 3D printable and customized robotic hand. This design retains more than 90% geometry information of a human hand surface, which is attained by utilizing 3D scanning techniques, and provides a simple, fast and low-cost solution to building a humanoid hand that is able to simulate major daily grasping gestures. The second design is a high-biometric multi-layer 3D printed robotic hand. This design focuses on the composition of human hands including bones, ligaments, tendons, tissues, and muscles. The multi-layer robotic hand shows great dexterity and deformability, for example, in the experiments of pinching a marble, a piece of Tofu, and a 2-millimeter screw cap.

Two methods were then developed to actuate the designed robotic hands. The first method uses soft nylon cables and six servo motors to build a system for direct actuation,

which can be used to actuate both the printable customized low-cost robotic hand and high-biometric multi-layer robotic hand. The grasping experiments show that the robotic hands are capable of performing all 33 grasping gestures under this actuation system. The second method is a full actuation system for actuating a high-biometric multi-layer robotic finger. The experiments show that this system is able to generate all 11 postures of the finger.

The research also incorporated the object detection software tool YOLO into the grasping control for object detection and localization. A path planning and motion control system was developed for natural grasping, including object perception, hand approaching and grasping. Two humanoid robots, the Nadine robot and the InMoov robot, were used for experiments, which verified the functionality of the proposed system.

To achieve complex in-hand manipulation, a new gesture-based approach was proposed. The approach divides the complex manipulation into multiple basic gestures and adapts the key-frame interpolation method to complete the task. Each complex manipulation is represented by a set of continuously changed stages of 20 finger joint rotation angles. High-biometric multi-layer robotic hands are used to mimic the human hand. The experimental results demonstrate that with the developed method, the robotic hand is able to mimic human-like in-hand manipulation and other complex motions, which is important for natural grasping.

List of Acronyms

DOF	Degree of freedom
ROM	Range of motion
FDM	Fused deposition modeling
PIP	Proximal interphalangeal joints
DIP	Distal interphalangeal joints
MCP	Metacarpophalangeal joints
TM	Trapeziometacarpal
FDP	Flexor digitorum profundus
CMC	Carpometacarpal
CAD	Computer-Aided Design
3D	3 Dimensions
SLA	Stereolithography

List of Symbols

No.	Notation	Description (identified from palmar side view)
1	P _T	Thumb's tip
2	P _I	Index finger's tip
3	P _M	Middle finger's tip
4	P _R	Ring finger's tip
5	P _L	Little finger's tip
6	P ₁	Midpoint of the middle crease line at palmar side of the MCP of the thumb
7	P ₂	Midpoint of the middle crease line at palmar side of the IP line of the thumb
8	P ₃	Midpoint of the middle crease line at palmar side of the MCP line of the index finger
9	P ₄	Midpoint of the middle crease line at palmar side of the PIP line of the index finger
10	P ₅	Midpoint of the middle crease line at palmar side of the DIP line of the index finger
11	P ₆	Midpoint of the middle crease line at palmar side of the MCP line of the middle finger
12	P ₇	Midpoint of the middle crease line at palmar side of the PIP of the middle finger
13	P ₈	Midpoint of the middle crease line at palmar side of the DIP line of the middle finger
14	P ₉	Midpoint of the middle crease line at palmar side of the MCP line of the ring finger
15	P ₁₀	Midpoint of the middle crease line at palmar side of the PIP line of the ring finger
16	P ₁₁	Midpoint of the middle crease line at palmar side of the DIP line of the ring finger

17	P ₁₂	Midpoint of the middle crease line at palmar side of the MCP line of the little finger
18	P ₁₃	Midpoint of the middle crease line at palmar side of the PIP line of the little finger
19	P ₁₄	Midpoint of the middle crease line at palmar side of the DIP line of the little finger
20	P _{w1}	Endpoint (ulnar side) of the middle wrist baseline
21	P _{w2}	Endpoint (radius side) of the middle wrist baseline
22	P _O	The midpoint of Pw1 and Pw2
23	P ₁₅	The midpoint of the rotation axis of the TM of the thumb
24	P ₁₆	The midpoint of the rotation axis of the MCP of the index finger
25	P ₁₇	The midpoint of the rotation axis of the MCP of the middle finger
26	P ₁₈	The midpoint of the rotation axis of the MCP of the ring finger
27	P ₁₉	The midpoint of the rotation axis of the MCP of the little finger
28	HLT	Hand length total measurement
29	Rxy	The ratio of finger segments x = T,I,M,R,T to represent Thumb, Index, Middle, Ring and little fingers y= M,P,I,D,W to represent Metacarpal, Proximal, and Intermediate, Distal Phalanges and web height from MCP joint
30	AFP _x	Angles cause by the flexion/extension motion P _x =The root point of the motion (one of 15 movable joints)
31	AAP _x	Angles cause by the adduction/abduction motion P _x =The root point of the motion (one of 15 movable joints)
32	AM _x	Angles of metacarpals of each fingers x = T,I,M,R,T to represent Thumb, Index, Middle, Ring and little fingers
33	CVL	Capitate bone's vertical length
34	xLy	Knuckles' length of each fingers x = T,I,M,R,T to represent Thumb, Index, Middle, Ring and little fingers y= M,P,I,D,W to represent Metacarpal, Proximal, Intermediate, Distal Phalanges and web height from MCP joint
35	ATO	Angles of the segment of TM joint to Original point

List of Video link

1. 3D Model process - <https://youtu.be/elCcCl9o0vo>
2. Grasping test with Nadine robot - <https://youtu.be/7r29Z69nbiY>
3. Fully actuated robotic finger test - <https://youtu.be/kMEjhcXsOf8>
4. Deformation test - <https://youtu.be/NCbKIyAAHSs>
5. Grasping test - <https://youtu.be/9qqFD83CDJM>
6. Ablation study on tissue - <https://youtu.be/o51H04AWq60>
7. Deformable hand 3D Model Process - <https://youtu.be/Xfddw24eDkc>
8. Assembly - <https://youtu.be/wIs2iSjRBk4>
9. Grasping test with Nadine robot (2) - <https://youtu.be/o1Kpb2Rs-AI>
10. Grasping test with Nadine robot (3) - <https://youtu.be/ndwsruEvmFY>
11. Grasping test with InMoov robot - https://youtu.be/_ktm98wDwC0
12. Manipulation test - https://www.youtube.com/watch?v=iZ0FznwMG_o

List of Publication

1. Thalmann, N. M, Tian, L., & Yao, F. (2017) “Nadine: A social robot that can localize objects and grasp them in a human way.” *Frontiers in Electronic Technologies*. Springer, Singapore, 2017: 1-23.
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6. Tian, L., Thalmann, N. M., Zheng, J., & Thalmann, D. (2019). “Design of a Highly Biomimetic and Fully-Actuated Robotic Finger.” In *2019 IEEE Symposium Series on Computational Intelligence (SSCI)* (pp. 2382-2387). IEEE.
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Chapter 1 Introduction

1.1 Background

The human-like robotic hand belongs to mechanical hands, usually programmable, with similar functions as a human hand. The links of such a manipulator are connected by joints allowing either rotational motion (such as in an articulated robot) or translational (linear) displacement. The most considerable portions of the robotic hands are industrial robotic hands which be deployed in the factories. Compared to human hands, their shortcomings are that the robotic hands are usually heavy and unlike the human hand. In recent years, human-like (or anthropomorphic) robotic hands, which are a sub-category of robotic hands and closely mimic the appearance and functionality of human hands, are developing rapidly [1]. The anthropomorphic robotic hands are mainly required in general-purpose robotic arms and humanoid robots. The general-purpose robotic arms are designed for the unconstructed environment, for example, picking up the different sizes of objects in a daily environment. Humanoid robots are specially designed robots with their body shape built to resemble the human body. Some of them are also called “Androids” if they aesthetically resemble humans [2]. A couple of articulated anthropomorphic hands will significantly improve the appearance and functionality of a humanoid robot.

In the robotics area, the uncanny valley is the hypothesis that human replicas that appear almost but not exactly like real human beings elicit eeriness and revulsion among some observers. Unfortunately, most humanoid machines fall into the uncanny valley as they are not like humans (Figure 1-1) [2-7]. The uncanny valley is the region of negative emotional response towards robots that seem “almost” human [8]. Movement amplifies the emotional response. Humanlike behaviors, such as grasping and manipulating, are vital to solving this problem. Previous researchers have done many works on robot grasping, but they usually focus on industrial robot hands. Most hands designed for industrial robots are very different from natural human hands [9, 10]. Industrial robot hands are usually more straightforward and may have only two or three fingers, but real humans interact with objects by all fingers most of the time. Prosthetic hands are designed in low DOF for high robustness. Therefore, human-like hands for social robots are more complicated. Besides work on a humanoid robot, the research on the humanoid robotic hand is also meaningful in the development of robotic arms, studies of human

grasping, and medical rehabilitation.

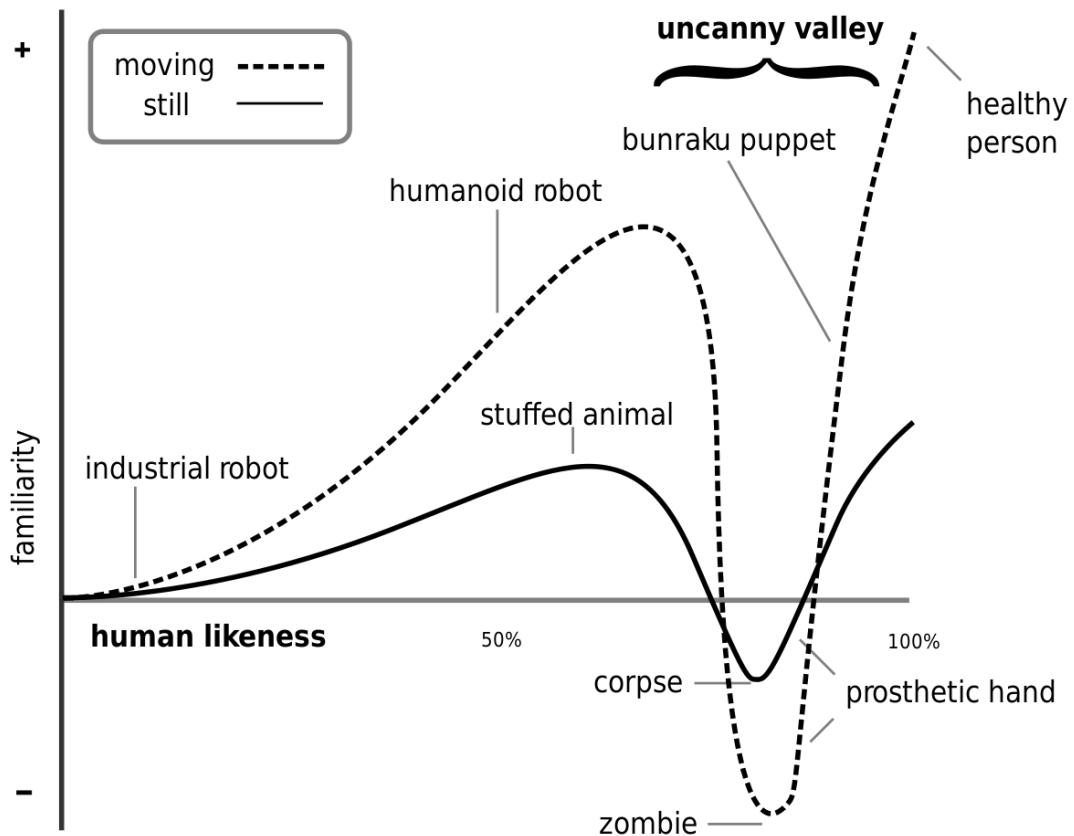


Figure 1-1 Uncanny valley - Proper hypothesized emotional response of subjects is plotted against anthropomorphism of a robot, following Mori's statements [8]

Since the first dexterous robotic hand, the Stanford/JPL hand was invented in 1983 [11], researchers have continuously pushed the boundaries to increasingly lifelike robotic hands [12]. The application of robotic hands has also been greatly expanded according to its features. For example, in a disease pandemic, a general-purpose robotic hand that can grasp different objects can help reduce physical contact among people. However, one of the most significant drawbacks of existing robots is that they have difficulty accomplishing physical interactions in daily settings. Specifically, robots cannot grasp and manipulate objects in unstructured environments or environments for which they have not been designed [1]. To sum up, it is essential to design a human-like and general-purpose robotic hand. A human hand has a complex system and contains many naturally evolved organs, making it challenging to model and mimic its joint structure, force transmission, and actuator synergy. The difficulty comes from duplicating the human hand kinematics from a robotic hand made from suitable material corresponding to hand bones and tissues.

1.2 Problem statement, scope and objectives

Due to the robotic hand's complexity, the price of the traditional anthropomorphic robotic hands is usually very high, and the developing cycle is time-consuming. More importantly, no robotic hand can fully mimic human-hand dexterity while keeping a neat and light actuation system. These constraints cause existing robotic hands always to have rigid and unnatural grasping. This research aims to investigate cost-effective techniques for building visually pleasant, articulated, and customized robotic hands for social robots or research purposes and make them function as a human hand. In particular, the research is focused on the three aspects outlined below.

The first aspect imitates a human hand mechanical structure. The human hand has 21 DOFs from the finger and 6 DOFs from the wrist. Five out of 15 finger joints have multiple DOFs. The human hand also has elastic tendons, ligaments tissues and deformable tissues and skin. Creating a mechanism that closely imitates the human hand's structure and DOFs is still an unsolved question. With the fast development of 3D printing technology, people can quickly produce physical models from digital models. It is thus helpful to introduce a complete technological process for rapidly making customized anthropomorphic robotic hands at a low cost. This research aims to use the latest 3D scanning and automatic 3D modeling techniques to 3D model robotic hands. Several designs have been 3D printed out and assembled.

Another related problem is how to build a small but efficient actuation system that functions as muscles to actuate the hand. Most existing anthropomorphic robotic hands have much less motion ability due to a lack of sufficient DOFs or range of motion (ROM). The human hand is a golden example of actuation system design. However, fully duplicating human hand's 21 DOF and ROM will lead to a heavy and expensive actuation system. This research aims to design actuation systems for the proposed robotic hands with various usages by studying the human hand kinematic.

Third, motion planning for the robotic hand to perform the grasping and complex in-hand manipulations. Humanoid robot grasping is an interaction between the robotic hand and the target object. In order to give the robot artificial intelligence (AI) to grasp an object naturally, the robot must first understand the object with the help of perception hardware and then plan the path for the motion of the hand. The autonomous grasping problem is an active research topic in the robotics area. The objective of autonomous grasping is to grasp the target firmly in hand and grasp the target in a natural and human-

like way. This research also aims to solve in-hand complex manipulation and autonomous grasping.

This research uses the Nadine robot (Figure 1-2) as a case study, where several factors such as the weight of the robotic hand, the compatibility with the Nadine robot and the cost of time and money are also considered.



Figure 1-2 The Nadine robot at the Institute for Media Innovation (IMI), NTU

In summary, this is an interdisciplinary research that involves three tasks in different areas: (1) in mechatronics, design a method to make articulated anthropomorphic

robotic hands that closely mimic the human hand structure; (2) in kinematics, design and implement the actuation system for the robotic hand (3) in grasping and manipulation, detect the target object and make the motion plan.

1.3 Contributions

In order to find out methods for designing human-like anthropomorphic robotic hands, this research starts with the exploration of the human hand structure and how the human hand functions, followed by replicating the critical features of the natural hand from the 3D hand model. This thesis has described the detailed methods to create two different versions of robotic hands and actuate them to naturally grasp.

The first method is proposed to design a low-cost and customizable 3D printed robotic hand. This method significantly shortens the 3D modeling and fabricate duration to produce a customizable robotic hand. It provides a cost-effective solution that could be implemented in a humanoid robot to achieve 16 grasping gestures.

The second method is used to design an anthropomorphic multi-layer 3D printed robotic hand. This method closely mimics the human hand multi-layer structure by hybrid materials including silicon artificial hand skin, deformable tissue, rigid bones, and tendons. It closely reproduces the deformation of the human hand when grasping unique objects such as marble balls and Tofu.

The methods of design actuation systems for these two robotic hands are also introduced. These methods provide straightforward ways to create compact and feasible actuation systems for different robotic hands.

In order to solve the autonomous grasping problem, the proposed robotic hands are tested with two humanoid robots (Nadine and InMoov) for verifying the ability of nature grasping. For the object detection part, this research implemented the YOLO [13] to the autonomous grasping system to detect the position and shape of the target object. For the arm path planning part, this research implemented the algorithm based on the inverse kinematic method.

In order to solve the robotic hand's in-hand manipulation problem, this research proposed a new approach for robotic hand motion control. The concept of "Continuous and Composed Manipulation" (CCM) is proposed and tested. This approach significantly improves the robotic hand's dexterity when dealing with complex in-hand

manipulation.

This research has also provided a completed pipeline for designing and actuating a robotic hand, including mechanical design, fabrication, assembling, actuation, and grasping. The proposed methods are helpful in the area of reducing the gap of functionality from robotic hand to human hand. The applications of this research may include dexterity robotic hands for humanoid robots, low-cost robotic hands for the robotic arms, and prosthetic robotic hands for medical usage.

1.4 Organization of the thesis

The rest of the thesis is organized as follows. Chapter 2 reviews the related work. It shows the latest related work of robotic hand designs, automatic design methods, actuation methods and object detection and grasping. Chapter 3 presents methods for the design and making of a low-cost 3D-printable customized robotic hand. The robotic hand is printed out and tested with the Nadine robot. It is capable of human-like grasping with 16 different grasping gestures. Chapter 4 describes another method for designing an anthropomorphic robotic hand based on a multi-layer deformable design. The robotic hand showed excellent deformability like the human hand during the grasping test. Chapter 5 shows the autonomous grasping system on a humanoid robot. The experiment showed that the robotic hand could grasp different objects autonomously based on the object detection result. Chapter 6 explains a new solution to duplicate in-hand complex manipulation. Some complex manipulations such as spinning a pen, rotating a Rubik's cube are demonstrated with the proposed method. The conclusion and future work are given in Chapter 7.

Chapter 2 Related Work

2.1 Robotic hands

A robotic hand can be designed and evaluated based on many criteria, such as DOFs, motion ranges of each joint, accuracy, speed, grasping trajectory, grasping force, weight, appearance. It is a challenge to make a robotic hand with excellent features in all areas. However, researchers can focus on essential features for specific users based on the pre-established design purpose of a robotic hand. This section will briefly review previous works related to robotic hands based on their roles¹.

2.1.1 Humanoid robots and their robotic hands

There are lots of advanced humanoid robots in the world. Different humanoid robots are made based on a variety of applications. The Atlas robot from Boston Dynamics has been developed for outdoor search and rescue [3]. Several diverse, powerful non-humanoid robotic hands can be linked to its arm one at a time for use in various scenarios. The ASIMO from Honda Motor Co., Ltd is designed as an indoor helper. It has a couple of dexterous robotic hands that can open a cup's cover [4]. The i-Cub robot, which the RobotCub Consortium developed, has the learning ability to grasp objects [5].

The development of 3D printing technology promotes the design and fabrication of low-cost humanoid robots. Most parts of the Inmoov robot are 3D printable, and the total cost is below \$2000 [14]. These leading robots also have various kinds of powerful functions in motion control and perception. However, their robotic hands are unlike the human hand. They are shelled with plastic or metal, making them look like a robot more than a human. If people stand in front of them, they may be afraid of them. Some other humanoid robots are built with deformable silicone skin, similar to an actual human, to overcome this feeling.

The Nadine robot is a realistic female humanoid social robot designed by the Institute for Media Innovation of Nanyang Technological University and manufactured by the Kokoro Company in Japan. The robot has strong human-likeness with natural-looking skin and hair. The Kokoro company has already produced many well-known humanoid

¹ Some review of this chapter appears in my publication “Tian, L., Magnenat Thalmann, N., Thalmann, D., & Zheng, J. (2017). The making of a 3D-printed, cable-driven, single-model, lightweight humanoid robotic hand. *Frontiers in Robotics and AI*, 4, 65”.

robots as the “Actroid” serials [2]. Robot JiaJia, created by the University of Science and Technology of China, is also a good sample of realistic humanoid robots [6]. Hong Kong designer Ricky Ma successfully constructed a life-sized robot similar to Hollywood star Scarlett Johansson [7]. These realist robots look like human beings, but they cannot recognize objects and grasp them. Besides, their robotic hands are not articulated like human hands.

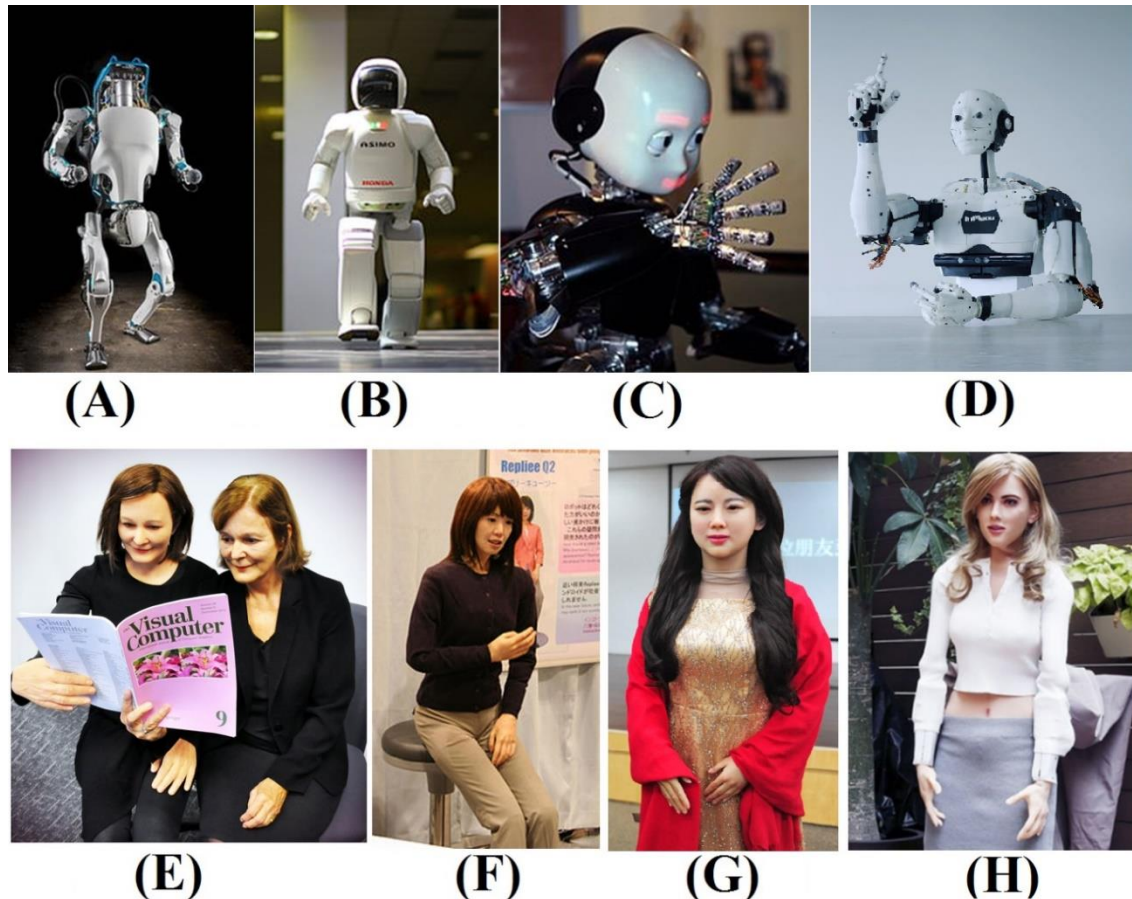


Figure 2-1 Humanoid robots (first row from left to right): Atlas robot [3], ASIMO robot [4], iCub robot [5], and InMoov Robot [14] (second row from left to right): Nadine social robot Actroid robot [2], JiaJia robot [6], Ricky Ma's robot [7]

2.1.2 Industrial robotic hands

At the early stage of robot history, humans expect robots to replace workers. An industrial robot² is a manipulator designed to move materials, parts, and tools and perform various programmed tasks in manufacturing and production settings. Most industrial robotic hands do not resemble a human hand as the human hand anatomy is too complex to simulate. There are simple and robust mechanical solutions that can perform better than a human hand. For example, a gripper or sucker could be considered

² Industrial robot: <https://www.robots.com/faq/show/what-is-an-industrial-robot>

a more stable solution than a human-shaped hand to grasp a standard sharp object. Most non-humanoid robotic hands or industrial robotic arms pursue higher accuracy, faster speed, heavier loads, and excellent stability in real-life applications.

The most common designs of gripper can be categorized into two-fingers, three-fingers or multi-fingers. The two-finger design is the most uncomplicated modeling of the robotic hand. The gripper, also a form of two-finger design, is often driven by a single motor or double motors to enhance the grip force. The gripper has only a single way to grasp an object. However, the most uncomplicated design gives the most reliability. This design reduces not only the complexity of control but also the manufacturing cost. Three-finger and four-finger designs with few DOFs also work similarly to a gripper. The other fingers can help to hold an object more securely. Figure 2-2 A and B depicts the two-finger and three-finger grippers from ROBOTIQ³. A 3D printed four-finger single actuator hand, which can be used for Unmanned Aerial Vehicle (UAV), is also shown in figure 2-2C [9]. Robotic hands with high DOFs can usually have more grasp gestures, such as UT/HDS hands from the University of Tokyo (Figure 2-2 D) [10].

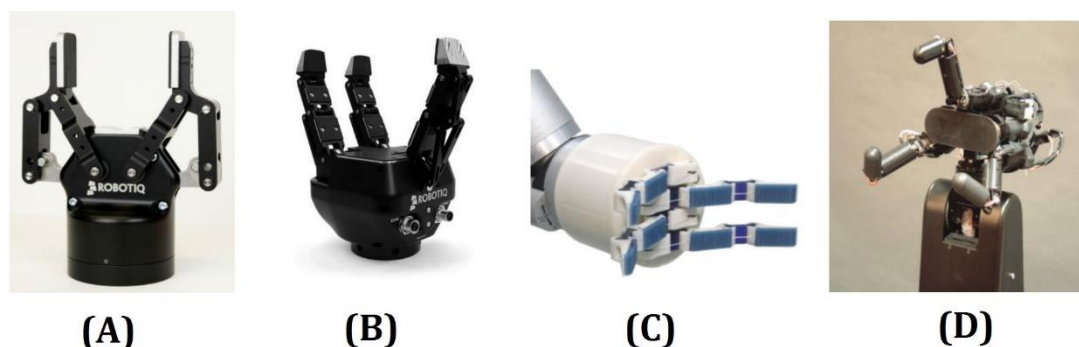


Figure 2-2(From left to right) Two-finger gripper and Three-finger gripper, Four-finger single actuator hand[9], and UT/HDS hand [10]

2.1.3 Prosthetic robotic hands

One statistic report has concluded that low-income countries have 30 million or more people with amputation, and most of them cannot afford prosthetic care [15]. A well-functioning prosthetic robotic hand will help them significantly improve their quality of life. For a commercial prosthetic hand designed to help people grip objects used in daily life, the ability to grasp is the first and most crucial function designers need to consider. Here, the “grasp” refers to a static posture with an object held securely with one hand [16]. There are many different kinds of objects used in daily lives. Cutkosky provided a

³ Robotiq gripper: <http://www.zacobria.com/robotiq-zacobria-universal-robot-grippers.html>

comprehensive and detailed organization of human grasps, including 15 different postures [17]. Unfortunately, due to the limitation of cost, weight and high grasping success rate, most commercial prosthetic hands are greatly simplified in design. As a result, commercial prosthetic hands can simulate only a limited number of gestures.

The typical commercial prosthetic hands, such as Bebionic hands, i-Limb hands, are made of laser-cut metal, motors, and screws. It usually comes in the shape of a human hand but is heavier than a human hand. The most common design consists of 11 joints, six DOFs (the thumb has one more DOF than the other fingers) and five or six actuators. The robotic hand's hardware, motion control system and power supply are integrated. The grasp is robust and built to last. Bebionic hand [18] and i-Limb hand [19] represent the latest commercial prosthetic hand. In recent years, several prosthetic hands also use 3D print technology to build the hand. The designer of the Tact hand claimed that although their robotic hand cost only US\$250, its performance meets or exceeds those of current commercial prosthetic hands [20]. Another 3D printed prosthetic hand is called the Dextrus hand [21], which uses the 16-joint design that comprises more joints in each finger, resulting in a more human-like grasp.

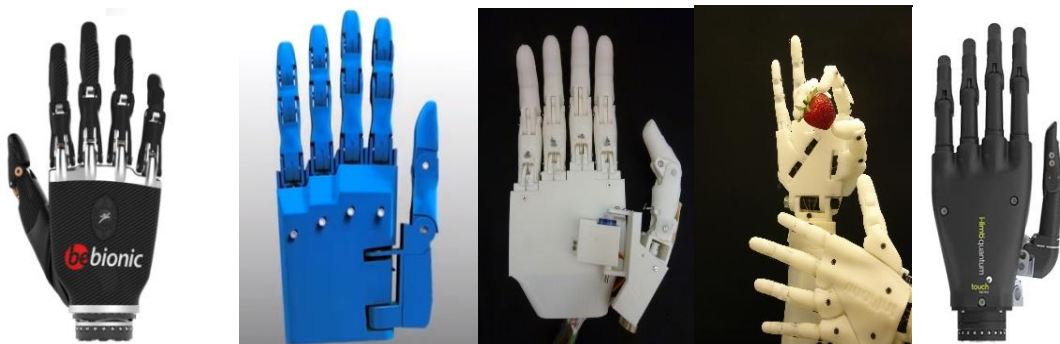


Figure 2-3 (From left to right) Bebionic, Dextrus, Tact, Inmoov and i-Limb hand [19, 20, 22]

2.1.4 Anthropomorphic robotic hands

Many researchers believe that the human hand is the perfectly engineered product of nature [23]. They envision building a robotic hand that could function as close as possible to a human hand. The anthropomorphic robotic hand does not emphasize the weight, cost, or linkage to a human arm, unlike the prosthetic robotic hand. The only aspect it focuses on is how to simulate the human hand motion. Most research work

related to robotic hands has been conducted before 2010 by H. D. Bos⁴.

Traditional anthropomorphic robotic hands focus on duplicating the kinematic features of a human hand. Many rigid body robotic hands have been designed over the last 30 years [12]. Most of them are pursuing to duplicate the functionality of a natural hand in terms of movement speed, force and degree of freedom. Unfortunately, the design concept for most existing anthropomorphic robotic hands follows that of industrial assembly robots [1, 24, 25]. The Shadow hand has 40 actuators and 20 DOFs, giving it a similar motion range to a natural hand, but its solid fingers and hinge joints distinguish it from a natural hand (Figure 2-4A) [26]. The UB hand IV [27] (Figure 2-4B) provides another simple design of a dexterous hand that is closest to the human hand regarding functionality. The ACT hand was designed in 2013 was the first trial for mimicking the natural hand on an anatomical level [28]. Following this way, Zhe Xu and his partners have made a low-cost modular, 20-DOF anthropomorphic robotic hand in 2013 [29] (Figure 2-4C). They also improved the ACT hand design in the joints, tissue and pulley system, creating a highly biomimetic hand in 2016 (Figure 2-4D) [30]. The “in-hand manipulation of a whiteboard eraser” demo closely mimics the real hand bones’ motion.

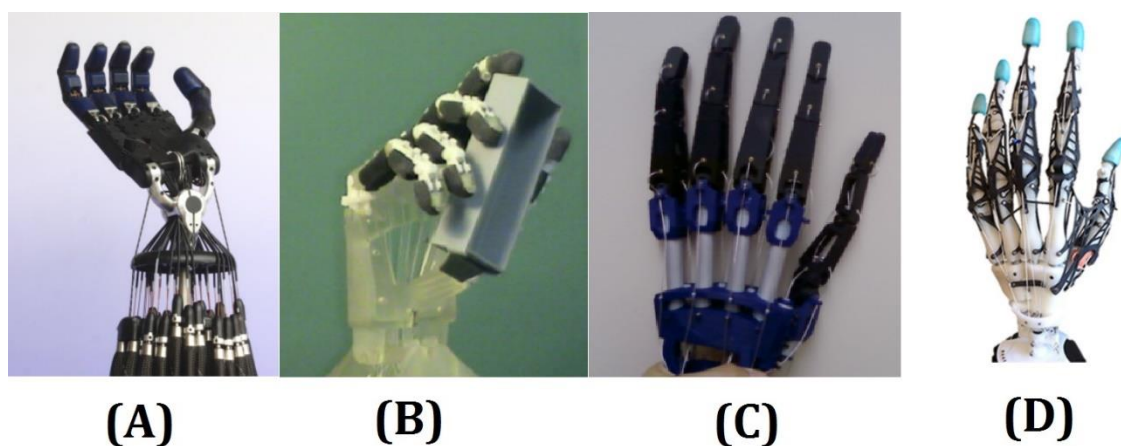


Figure 2-4 (From left to right) Shadow hand[26], UB hand IV [27], Xu Zhe's anthropomorphic robotic hand [29], and Xu Zhe's highly biomimetic robotic[30]

The concept of the “Anatomically Correct” robotic hand was raised in 2011 [28]. Unlike the traditional method, which focuses on duplicate human hand’s Degree of Freedom (DOF) and range of motion (ROM), the “Anatomically Correct” robotic hand typically has a hand-bones-shaped structure with human-like joint and tendon designs [30, 31].

⁴ Evolution of Robot Hands. Author: H.D.Bos Supervisor: ir. M. Wassink.:
<https://www.ram.ewi.utwente.nl/aigaion/attachments/single/363>

In 2018, A. Faudzi et al. showed “a Human-like Robotic hand,” which moved another big step towards total anatomical accuracy [31]. It uses McKibben actuators as intrinsic and extrinsic muscles of the index finger. In 2019, the Anatomically Correct Biomechatronic hand (ACB) was designed with 30 actuators. It aims to duplicate each vital tendon and muscle of the human hand [32]. Both [30] and [32] evaluated their robotic hand grasping ability by experiments following the hand grasp taxonomy [33]. “Anatomically Correct” robotic hands have a more biomimetic design compared to traditional design robotic hands. However, they are still required to be proven that they have better functionality in grasping and manipulation by solid experiment results. Furthermore, none of these designs deal with the soft tissue part, leading them to have a hand skeleton appearance and reduce their grasping ability.

2.1.5 Soft robotic hands

The soft robotic hand is another thread of robotic hand that developing fast in the last two decades [34]. With the use of soft materials, robotic systems will have much less chance of inadvertently harming humans. It has been proven in [35] by rigid robots with compliant joints. Thus, it will increase robots' safety fact when interacting with humans. A robotic hand made with compliant materials can create a stable and efficient grasping to different objects much easier than the hard surface robotic hand [36]. The motion way will also be changed and improved over the flexible substrates [37].

Unlike the robotic hand mentioned above, the body of a soft robotic hand is made of soft and deformable material. Nature rubber and silicon rubber are two commonly used soft materials in our daily life. Most soft body robotic chooses silicon rubber as it has better plasticity than other traditional materials. After the 3D printable soft material had been invented, more and more 3D printed artificial organs appeared for medical purposes in the last five years [38-41], as well as soft robotics [42]. The human hand tissue Young's modulus value is around 100 kPa which is soft [43]. When the human hand grasps an object, the finger contact surface will increase significantly when the finger force increases from 0.1N to 2N [1]. Recently, with the understanding of the benefit of soft design, more and more 3D printable soft robotic hands have emerged [34, 44]. A typical soft body robotic hand is usually actuated by gas/liquid pressure [36, 45, 46], driven cable or “new actuators” such as SMA (shape memory alloy) or artificial muscles [47-49]. In 2019, a soft robotic hand, BLC-26, did six in-hand manipulation variations: translations and rotations along the x-, y- and z-axes [50]. A recently invited four-finger soft body robotic hand showed it can unscrew the cap of a jar [51]. Compared

to rigid body robotic hands, soft body robotic hands deform when grasping or manipulating, which help to secure the target object [52-54]. However, most of them have a pure soft body structure design, making them move like invertebrates or resulting in a weak grip force [34, 47, 55, 56] (Refer to figure 2-5).

Another problem is that all existing actuators such as SMA, pneumatic actuators, and hydraulic actuators cannot fully duplicate the muscle function while taking up the same volume [57]. Two recently invented artificial muscle, “Thin McKibben muscle” and “artificial bubble muscles” has similar shape and flexibility as natural muscle. They also require air pressure as an input, and the efficiency is not as high as that with actual muscles [48, 49]. Due to these reasons, these soft robotic hands are not aimed to mimic human hand grasping gestures.

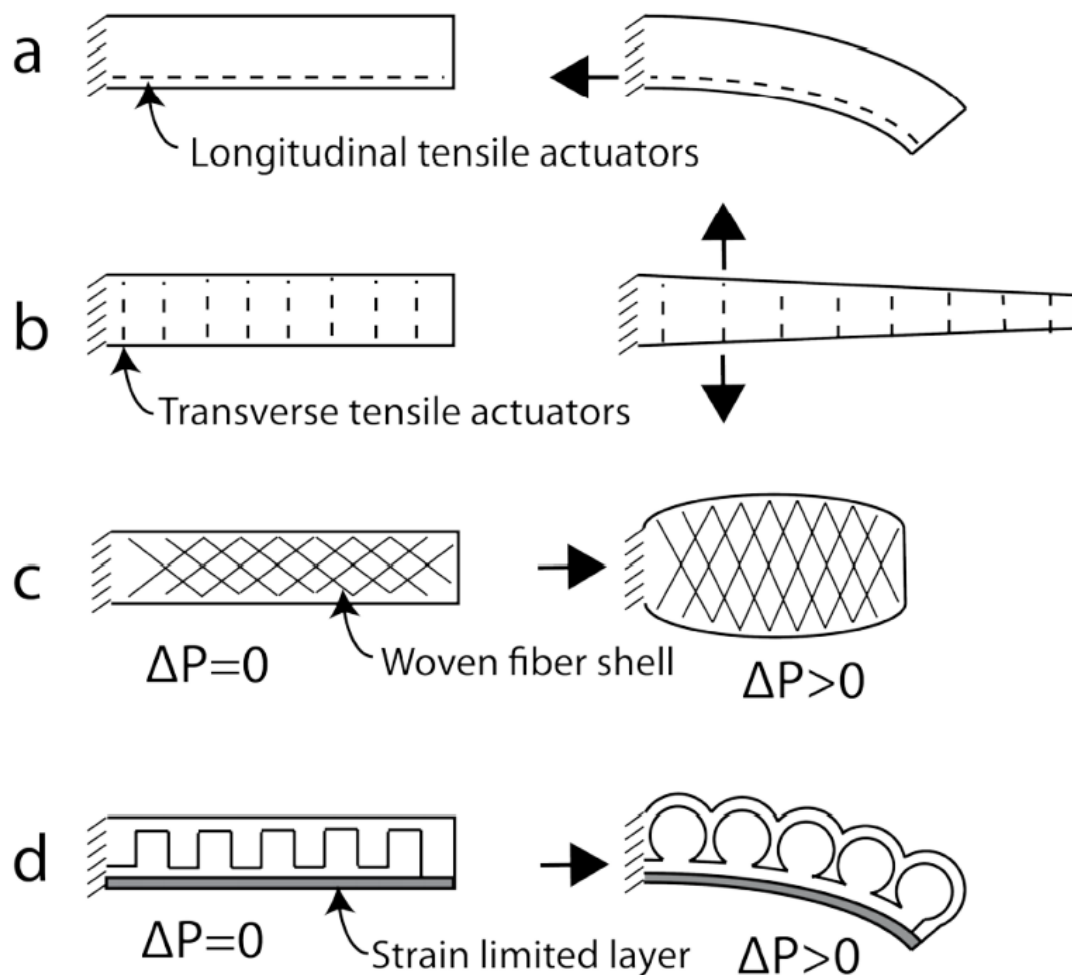


Figure 2-5 Common designs of soft robot bodies in resting (left) and actuated (right) states

[34]

2.2 3D modeling of hands

Most robotic hands have complex mechanical structures which manually 3D modeled by CAD software. The design progress is usually time-consuming and lacks design standards. In addition to manual modeling of a robotic hand, there are solutions to create the joints for the 3D model automatically. In [58], a method is proposed to convert 3D models into printable, functional, non-assembly models with internal friction. The approach takes an appropriately rigged 3D model, automatically fits novel 3D-printable and posable joints, and provides an interface for specifying rotational constraints. It can create an interlocked hand without manual assembly of joint components (Figure 2-6A).

Another approach [59] takes a skinned mesh as input and then estimates a single-material model that approximates the 3D kinematics of the corresponding virtual articulated character in a piecewise linear manner (Figure 2-6B).

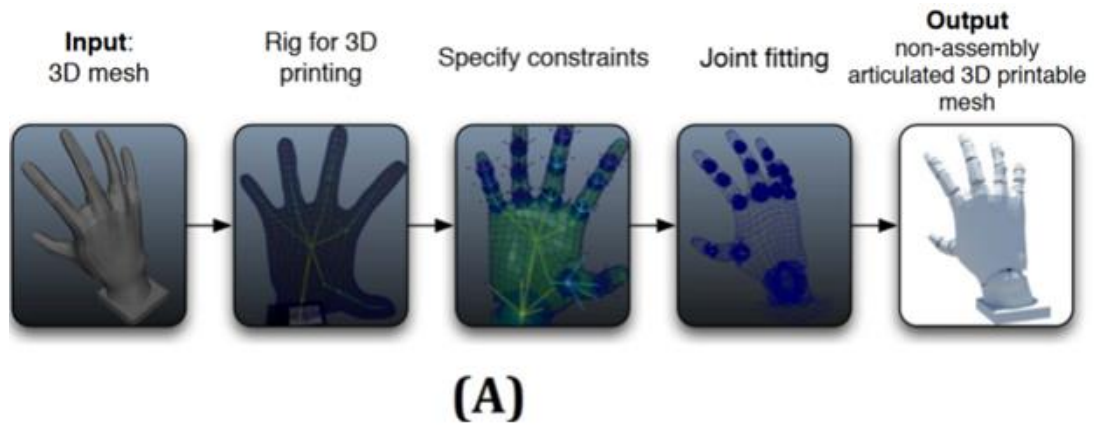


Figure 2-6 (A) 3D-Printing of Non-Assembly, Articulated Models[58] (B) Fabricating Articulated Characters from Skinned Meshes [59]

The two methods above provide automatic ways to creating robotic hands. However, the final models are both rigid and challenging to add actuators. Therefore, they are articulated hand models but not robotic hands. Compared to these methods, the methods proposed in chapters 3 and 4 provide new ways to create the joints of the hand and take care of the motion control, which makes the robotic hands compatible with cable-driven actuation systems. The proposed method to locate joints also differs from these two

previous works.

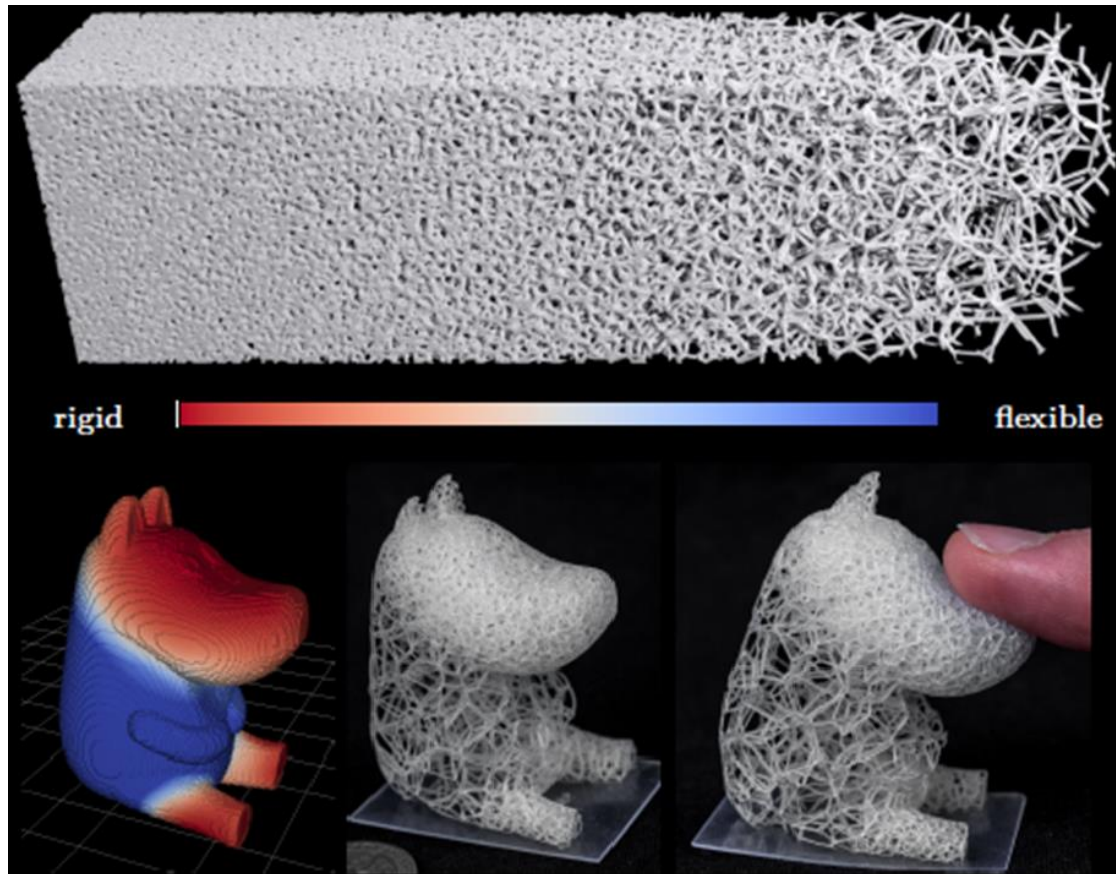


Figure 2-7 structures with graded material elasticities, which can be directly fabricated [60]

Besides automatic 3D modeling of the robotic hands, there are algorithms to edit the microstructures of objects. They change the physical properties of objects, making them lighter or more flexible [60]. These methods can be used to design the deformable body of robotic hands.

Various 3D modeling techniques that construct 3D mesh models from point clouds, images, sketches, etc. have been developed. Related work of 3D modeling can be found in [61-66]. To generate a nice 3D model, various digital geometry processes are usually performed. Examples of such processes are denoising, segmentation, completion, blending, and fairing. Similar techniques may also be found in image processing. More related work of geometric processing can be found in [67-77].

2.3 Actuation methods

The motion of a human hand is actuated by muscles located inside the hand and forearm. A robotic hand also has to have an actuation system to actuate each motion. This section reviews the popular existing actuation systems for both rigid robotic hands and soft

robotic hands. It also makes a comparison of the different actuation systems.

2.3.1 Actuation of rigid robotic hands

An actuation system is an indispensable part of the robotic hand as it provides kinetic energy to the mechanism. It usually consists of three parts: power source, force transmission system and mechanical frame. Each actuation system has a specific design purpose based on different requirements of the robotic hands.

Electric motors are the most used solution as the actuators of a rigid robotic hand. Without consider the limitation of the number of actuators used, researchers can simulate more than 20 DOFs in a single robotic hand [32] (Figure 2-8A). The accuracy of the motor improved drastically over the past decades. In contrast, the size and weight of the motor have not reduced significantly. Too many motors will yield a large and heavy robotic hand control system [26] (Figure 2-8B). Therefore, this hinders the use of motor from of a robotic hand for most daily applications. “Underactuation” is a widely used concept in robotics [78] (Figure 2-8C). It means having fewer actuators than DOFs. Several previous robotic hands can have only one actuator. Researchers have used the hardware lock way [79], adaptive synergy [80] to adjust the control of the robotic hand’s fingers. This kind of design usually has a more complex mechanical structure to alter the control of fingers. Besides the electric motor, pneumatic is another way to actuate robotic hands. However, it requires a big and heavy pneumatic control unit which blocks it from daily applications [29] (Figure 2-8D).

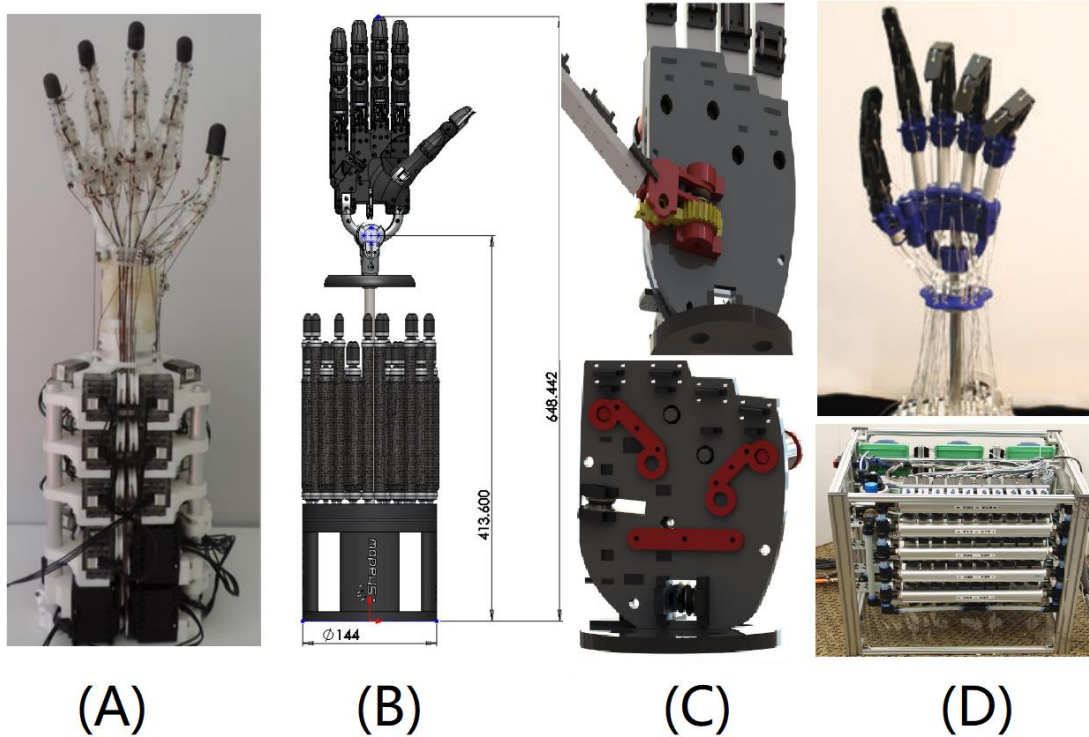


Figure 2-8 (From left to right) Biomechatronic Hand's actuation system [32], Shadow hand's actuation system[26], Selectively Lockable mechanism [78], Xu Zhe's anthropomorphic robotic hand's actuation system [29]

For a typical underactuation cable-driven robotic hand, each finger is usually controlled by two cables and one motor. The motor uses a round or a two-arm horn to pull the two cables. The turning of the motor actuates the flexion/extension motion of the corresponding finger. This actuation system has limitations in motion. For example, their DIP and PIP work synchronously as an underactuation system [81]. As a result, the hand is difficult to bend the DIP alone. According to hand grasp taxonomy, most grasping actions require flexing the finger's DIP, PIP and MCP joints to work independently [33, 82]. The majority of existing robotic hand designs use underactuation systems to control the fingers, leading to the number of the actuator being less than the DOF of the fingers. For instance, the InMoov hand [14], Xu et al.'s hand [30], and some other previous works [83-85] use one actuator to control the flexion of all three joints of one finger. The underactuation design reduces the number of required actuators and the total control complexity. It also substantially reduces the ROM of the finger. However, fingers should be fully actuated with the actual DOFs and ROMs to mimic all the possible gestures made by human hands.

2.3.2 Actuation of soft robotic hands

In order to actuate the soft body made by silicon rubber, variable-length tendons are widely used. In [56], a silicone arm with tension cables embedded replicates the functionality of the muscles of the octopus' arm (Figure 2-9A). The arm is capable of pushing-based locomotion and object grasping.

Shape memory alloy (SMA) is another solution to drive soft body robotics. Laschi et al. created a prototype that presented the biological model's morphology and the broad arrangement of longitudinal and transverse muscles. Actuation is obtained with cables for longitudinally-move-muscles and SMA springs for transversally-move-muscles [47] (Figure 2-9B).

Pneumatic actuation is a commonly used approach to inflate the soft material to get the motion. Pneumatic artificial muscles (PAMs) and Fluidic elastomer actuators (FEAs) are two soft actuators, which have been used recently. "RBO Hand 2" uses a highly compliant, pneumatic continuum actuator design, called "PneuFlex," which was invented by Deimel and Brock [36] (Figure 2-9C). FEAs also can work with hydraulic pressure [45] (Figure 2-9D).

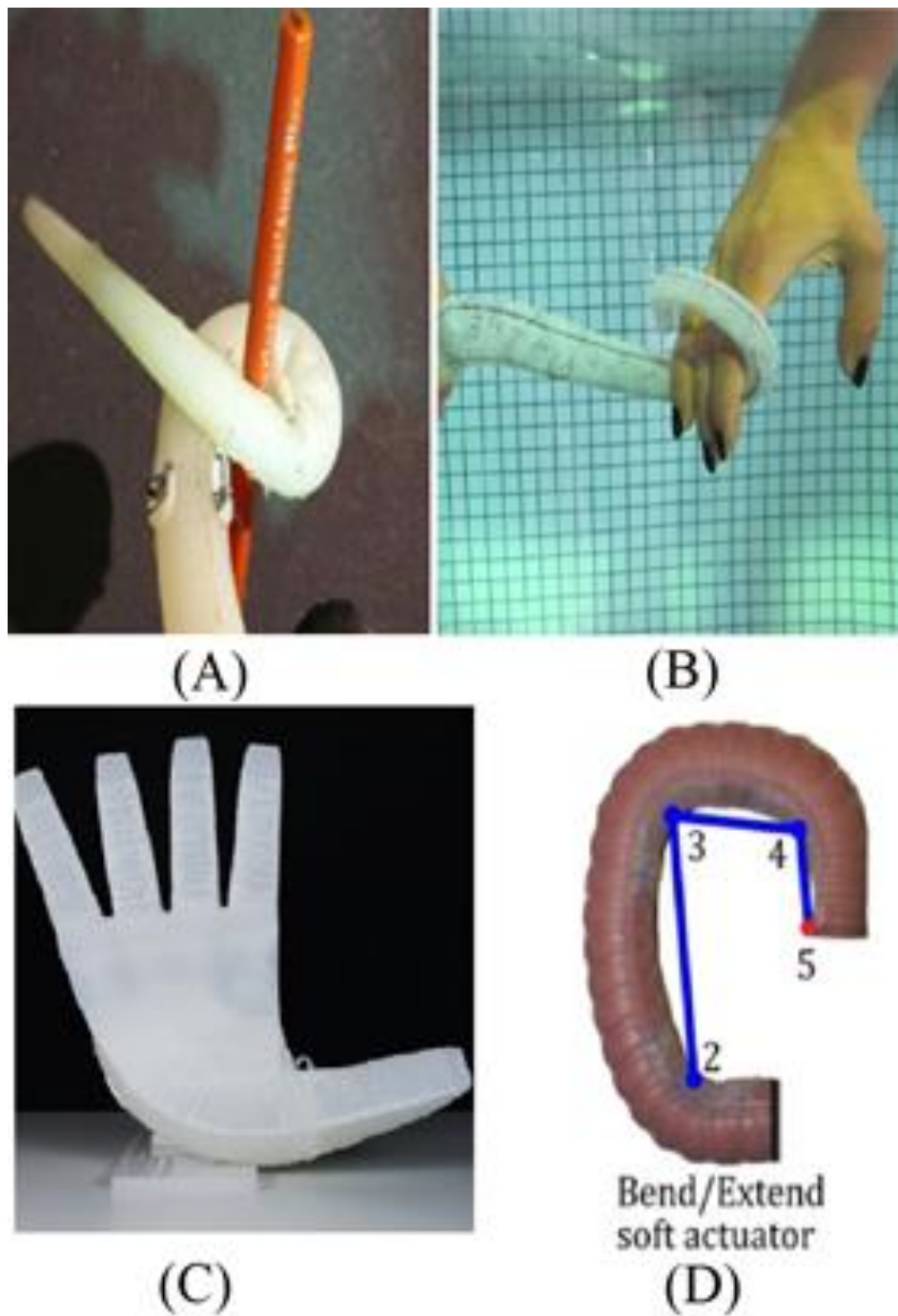


Figure 2-9 Four types of soft body robotics

For all designs mentioned above, the actuators are built outside the robot. Tendons transmit the force from actuators to the robotic hand for the variable-length tendons method. For the SMA method, electric wires are used to supply voltages. For the pneumatic method, pipes are used to provide pressure. Figure 2-10 shows the current famous designs of soft robotic hands with their force transmit tools.

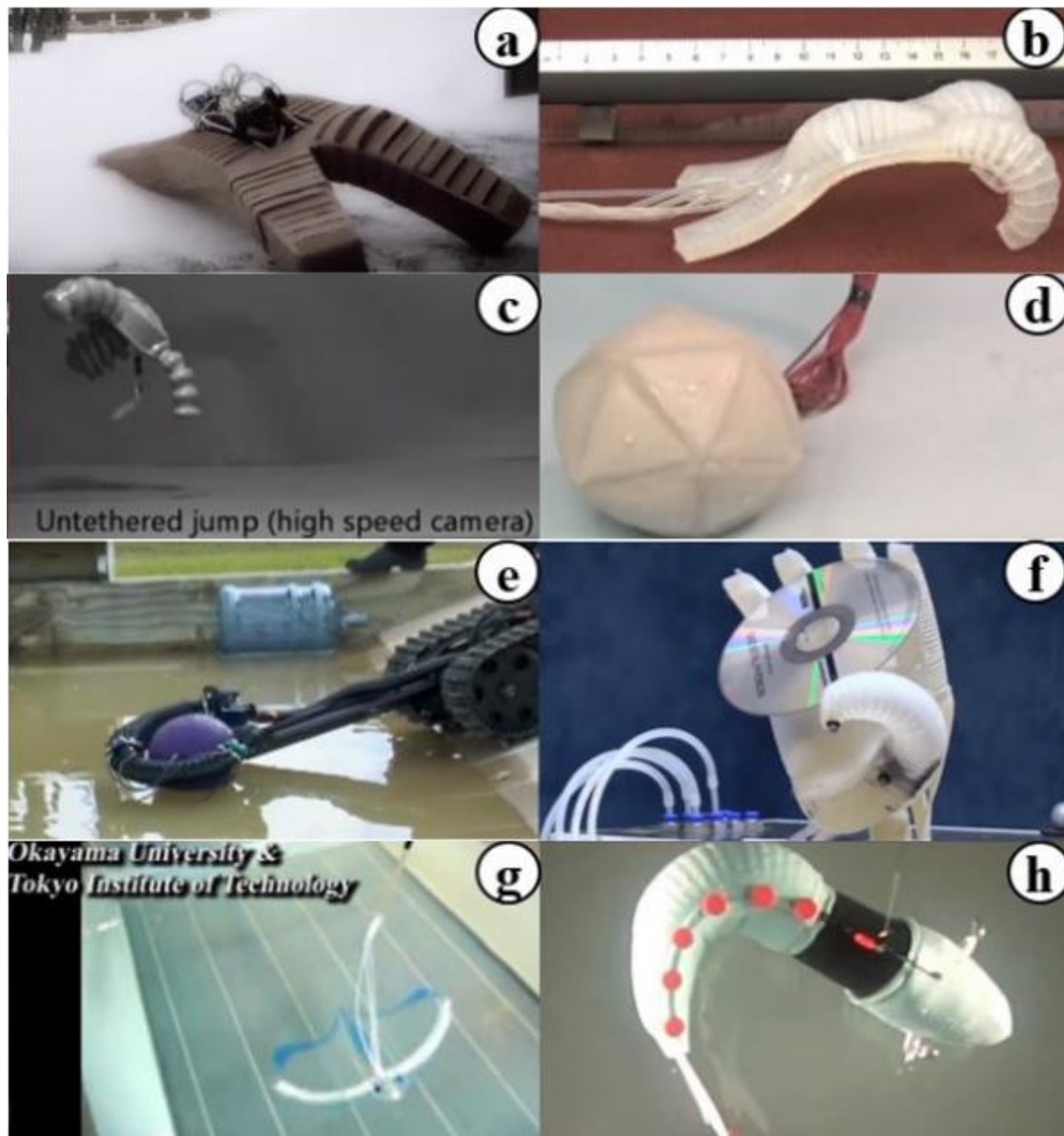


Figure 2-10 (a) A resilient untethered robot (b) Multigait soft robot (c) Untethered jumping robot (d) Jamming skin enabled locomotion (JSEL) (e) OctArm (f) Compliant and underactuated robotic hand (g) Manta swimming robot (h) Hydraulic autonomous soft robotic fish [86]

2.4 Object detection and grasping

2.4.1 Object detection

For robot perception, category-specific object detection (COD) is one of the most fundamental yet challenging problems in the computer vision community [87]. Object detection is the progress of finding predefined objects among a large number of images. One existing solution (Figure 2-11) uses regions with convolutional neural network features (R-CNN) and fast versions [88, 89]. In this solution, they solve the object localization question in two parts: 1. Generate object proposal from an image and find where it is. 2. Classify each proposal into different categories and thus recognize the

object. This progress brings a tremendous amount of repeated computing, and its speed is slow regarding real-time automatic grasping.

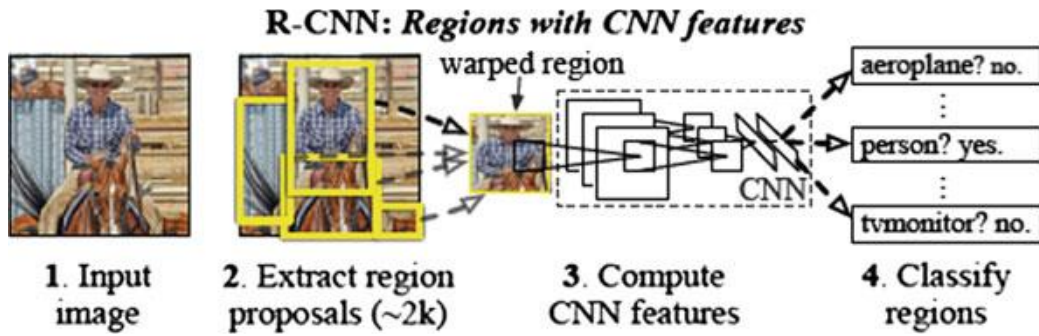


Figure 2-11 Fast CNN workflow [88]

In [90] and [13], the authors compared YOLO and YOLOv2 with other existing detection frameworks and showed that their methods are faster and more accurate. Regarding the perception of the robot, the speed is fulfilled for real-time grasping. (Table 2-1)

Table 2-1 Comparison of the performance and speed [13, 90]

Real-Time Detectors	Train	mAP	FPS
100Hz DPM	2007	16.0	100
30Hz DPM	2007	26.1	30
Fast YOLO	2007+2012	52.7	155
YOLO	2007+2012	63.4	45
SSD300	2007+2012	74.3	46
YOLOv2 288×288	2007+2012	69.0	91
YOLOv2 352×352	2007+2012	73.7	81
YOLOv2 416×416	2007+2012	76.8	67
YOLOv2 480×480	2007+2012	77.8	59
YOLOv2 544×544	2007+2012	78.6	40
Less Than Real-Time			
Fastest DPM	2007	30.4	15
R-CNN Minus R	2007	53.5	6
Fast R-CNN	2007+2012	70.0	0.5
Faster R-CNN VGG-16	2007+2012	73.2	7
Faster R-CNN Z	2007+2012	62.1	18
YOLO VGG-16	2007+2012	66.4	21

2.4.2 Grasping of a humanoid robot

There are two commonly used methods that deal with uncertain shape objects when a manipulator is grasping. One is to rely on sensors, such as the tactile sensor, the force sensor, the laser sensor, to feedback more information about the object, to compensate for the shape error caused by the vision sensor (camera), and finally to control the multi-degree-of-freedom machine [91]. The other is to apply machine learning to the manipulator grasping [5, 87]. A large amount of data obtained through enough grasping experiments can train feasible grasping configurations for manipulators. A grasping model obtained from empirical data can be obtained. In [5] (Figure 2-12), they create a complete framework for the iCub robot to let it learn how to roll affordances of the object and explore handheld tools and learn how to use them and finally put the learned skill in actual actions.

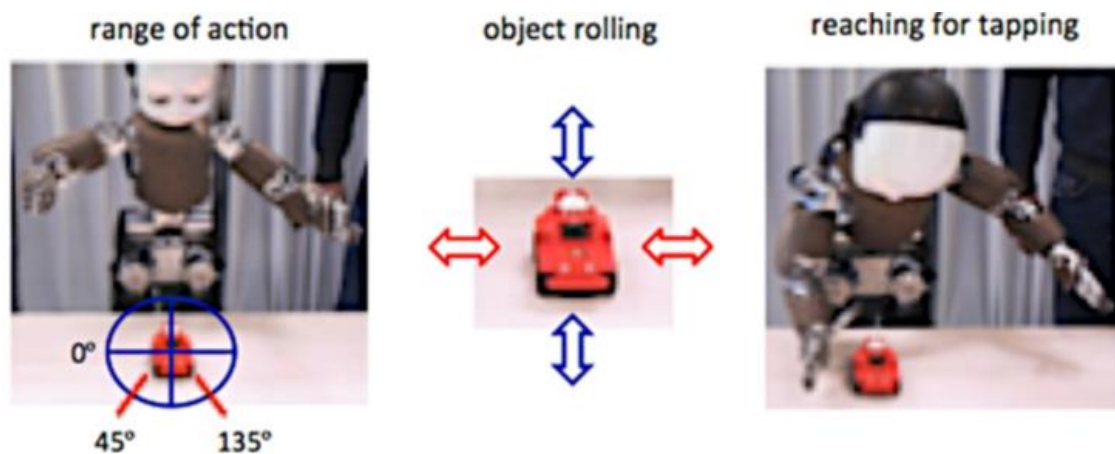


Figure 2-12 Autonomous grasping by iCub [5]

2.5 Discussion

Due to developments in mechanical structure design and increasingly efficient actuators over the last few decades, the performance of industrial robotic arms/hands has significantly improved. Robotic arms/hands can beat the human hand in specific movement speed, force, and accuracy. For example, the Meca500 robotic arm has a repeatability of 0.005 mm, much superior to the human hand [92]. The KUKA robot was recorded winning a game against famous table tennis player Timo Boll [93]. However, how to apply these cutting-edge technologies to general-purpose robotic hands is still unsolved.

The most demand for human-like robotic hands comes from the prosthetic hand [15]. Due to the robust and mass production requirement, most traditional prosthetic hands

use gears or linkage bars to actuate the fingers [19]. The anthropomorphic robotic hand is research-oriented, which has less design restriction compared to the prosthetic robotic hand. They have a relatively more minor limitation on the weight, size and control method. Therefore, they can focus on simulating certain aspects of human hands and make them closed to nature. Cable-driven (or tendon-driven) is a widely used actuated robotic hand as it is similar to the human muscle-tendon-bones drive system [94]. The soft body robotic hands are deformable like human hand. However, as their internal design consists of soft segments, the motion trajectories of these robotic finger are unlike human finger. Both rigid and soft of robotic hands have their own advantages: rigid-body hands are reliable, sturdy, and better reflect the movement kinematics and dynamics of the human hand, while soft robotic hands are deformable and inherently safer.

It is improper to adopt non-humanoid robotic hands for a humanoid robot such as the Nadine robot, as it needs a couple of humanoid robotic hands to match its physical appearance. However, the precise motion control of the industrial robotic hand is an excellent example for designing the motion control of other robotic hands. Prosthetic robotic hands have a human-like model and robust performance. However, they are too big and heavy for a robot. Even though the anthropomorphic robotic hands have superior grasping abilities, their actuation control systems are too large and complex to integrate into a humanoid robot. A small and compact actuation control system, which could plug-and-play, is required.

Most realistic humanoid robots do not have articulated robotic hands. Only a few of the latest Actroid robots have movable fingers that are limited to displaying gestures. Initially, the Nadine robot does not have articulated hands. So, this research aims to create a robotic hand for humanoid robots such as Nadine, which gives them the ability to grasp objects like a human being does. Thus improve the overall performance of the humanoid robot. Table 2-2 shows the comparison of robots and their robotic hand.

Table 2-2 Comparison of robots and their robotic hand

Robot name	Type	Robotic Hand Appearance	Robotic Hand Function
Atlas robot[3]	Humanoid	Gripper	Strong for grasp
ASIMO robot [95]	Humanoid	Human-like	Dexterity for grasp
i-Cub robot [96]	Humanoid	Human-like	Dexterity for grasp
InMoov Robot [14]	Humanoid	Human-like	Dexterity for grasp
Actroid robot[2]	Realistic	Realistic	Displaying gestures
JiaJia robot[6]	Realistic	Realistic	Not articulated
Ricky Ma's robot[7]	Realistic	Realistic	Displaying gestures
The Nadine robot with an original robotic hand	Realistic	Realistic	Not articulated
The Nadine robot with the new robotic hand	Realistic	Realistic	Dexterity for grasp

Regarding the actuators of robotic hands, the electrical motor is the most widely used solution as it is compact, low-cost and high efficiency in force conversion from electricity. One limitation of the electrical motor is that the finger-size motor is not strong enough to actuate the finger, while the standard-size motor is too big to build into a finger-size structure. So, in a typical motor-based actuation system, motor(s) are always placed apart from the robotic hand mechanism. A force transmission system is required to transmit the force from the motor's shaft or gears to the applied force structure. Driven cable, gears and linkage bar are three commonly used force transmission methods in robotic hand applications. From the efficiency point of view, the driven cable method is not as good as gears and linkage bar. However, the flexible soft cable gives designers higher design freedom to design the robotic hand mechanical structure.

PAMs and FEAs both actuate the structure by inflation or pressure. They can easily result in a neat robotic hand design as the actuator can be far from the robotic hand linked by slim pipes. However, they have high-cost and big-size actuators, which is not suitable for removable robotic hand design. SMA requires no force transmission system. However, its force and efficiency are too low for the grasping of a robotic hand. Table 2-3 shows the comparison of different actuation methods.

Table 2-3 Comparison of different actuation methods

Actuator	Force transmission	Cost	size	efficiency	Design freedom
Motor	Driven cable	Low	Small	Middle	High
Motor	Gears	Low	Small	High	Middle
Motor	Linkage bar	Low	Small	High	Low
SMA[56]	Not Required	Middle	Small	Low	High
PAMs[36]	inflation	High	Large	Middle	High
FEAs[45]	inflation	High	Large	Middle	High

Chapter 3 Methods for the Design of Customized Low-cost Robotic Hands

3.1 Introduction

Researchers are constantly faced with two main issues when building robotic hands: making robotic hands look human-like and making robotic hands function like real hands. Most existing solutions solve these issues by manually modeling the robotic hand. However, the design processes take a long time, and it is difficult to duplicate the geometric shape of a human hand. In order to solve these two issues, this chapter presents a simple and effective method that combines 3D printing and digitization techniques to create a 3D printable cable-driven robotic hand from scanning a physical hand. The method involves segmenting the 3D scanned hand model, adding joints, and converting it into a 3D printable model. Compared to other robotic hand solutions, the proposed solution retains more than 90% geometry information of a human hand⁵, attained from 3D scanning. The modeling progress takes around 15 minutes, including 10 minutes of 3D scanning and 5 minutes for modeling the scanned model to an articulated model by running a specially designed algorithm. Compared to other articulated modeling solutions, this proposed method is compatible with an actuation system that provides this customized robotic hand with the ability to mimic different gestures. This chapter also includes developing a way of representing hand skeletons based on the hand anthropometric.

This chapter considers creating customized robotic hands, which should function as a human hand and have a similar shape, size, and appearance as the target hand. Creating such hands is beneficial in making hands for disabled people and robotics (primarily social robots). The problem is challenging since it involves 3D modeling, manufacturing, and mechanics. Moreover, the complexity of hand structures and functions makes the problem even more demanding.

⁵ Measured by hand's surface area

The human body has 244 Degrees of Freedoms (DOFs), controlled by 630 muscles [97]. DOFs are most concentrated in human hands, which contribute a total of 54 DOFs [94]. Besides high dexterity, human hands are also quite solid and good at grasping. A male adult's grip strength is generally up to 50 kg [98]. Human hands are complex and have inspired many different designs of robotic hands [99]. However, when evaluating the hand's DOFs, range of motion of each joint, accuracy, speed, grasping trajectory, grasping force, weight, and appearance. So far, no robotic hand could fully match the human hand [19]. The main challenge comes from three aspects: 1) The human hand is covered with skin, elastic, and freeform shape [94]. 2) The human hand has a complex mechanism combined with different parts such as bones, muscles, tendons, ligaments. The modelings of robotic hands usually do not include soft tissues such as muscles and ligaments. It is thus complicated to simulate all mechanical properties to a robotic hand model [19, 94]. 3). Concerning the actuators, the current artificial muscle solutions are still not as efficient as the human muscles, which require more space to provide the same amount of force [100].

Inspired by the advance of 3D scanning and 3D printing technologies, this chapter proposes a new solution to creating a customized humanoid robotic hand [101]. The proposed design consists of digitization by 3D scanning, 3D modeling, and mechanical control design. Specifically, it first uses a 3D scanner to scan a physical hand, which produces a 3D mesh model with high accuracy as the base model of the robotic hand. Then design an algorithm to convert the scanned 3D mesh model into an interlocked articulated 3D model that a 3D printer can print out. Two product designs, rigid surface and soft surface robotic hands, are 3D printed out to verify the proposed idea. Finally, for the actuation, the proposed method uses six high-torque (3.7 kg/cm) but tiny (20x18x30mm) and light (12.7 grams) servo motors. These actuators work with a specially designed servo-bed as the control solution of the customized robotic hand to simulate the motion of the human hand.

3.2 Human hand anatomy

3.2.1 Human hand mechanical structure

The human hand is the golden example of our robotic hand. Figure 3-1 displays the skeleton of a natural human hand, made of 27 pieces of bones [102]. The five fingers are constituted by eight small wrist bones, five metacarpal bones (in palm) and 14 finger bones. The bones are connected by five distal-interphalangeal (DIP) joints, four

proximal-interphalangeal (PIP) joints and five metacarpophalangeal (MCP) joints in hand. The thumb is a particular case with no DIP or PIP but an Interphalangeal (IP) joint, a trapezio-metacarpal (TM) joint and an MCP joint. Thus, the natural human hand has 15 movable joints, and each finger has three⁶.

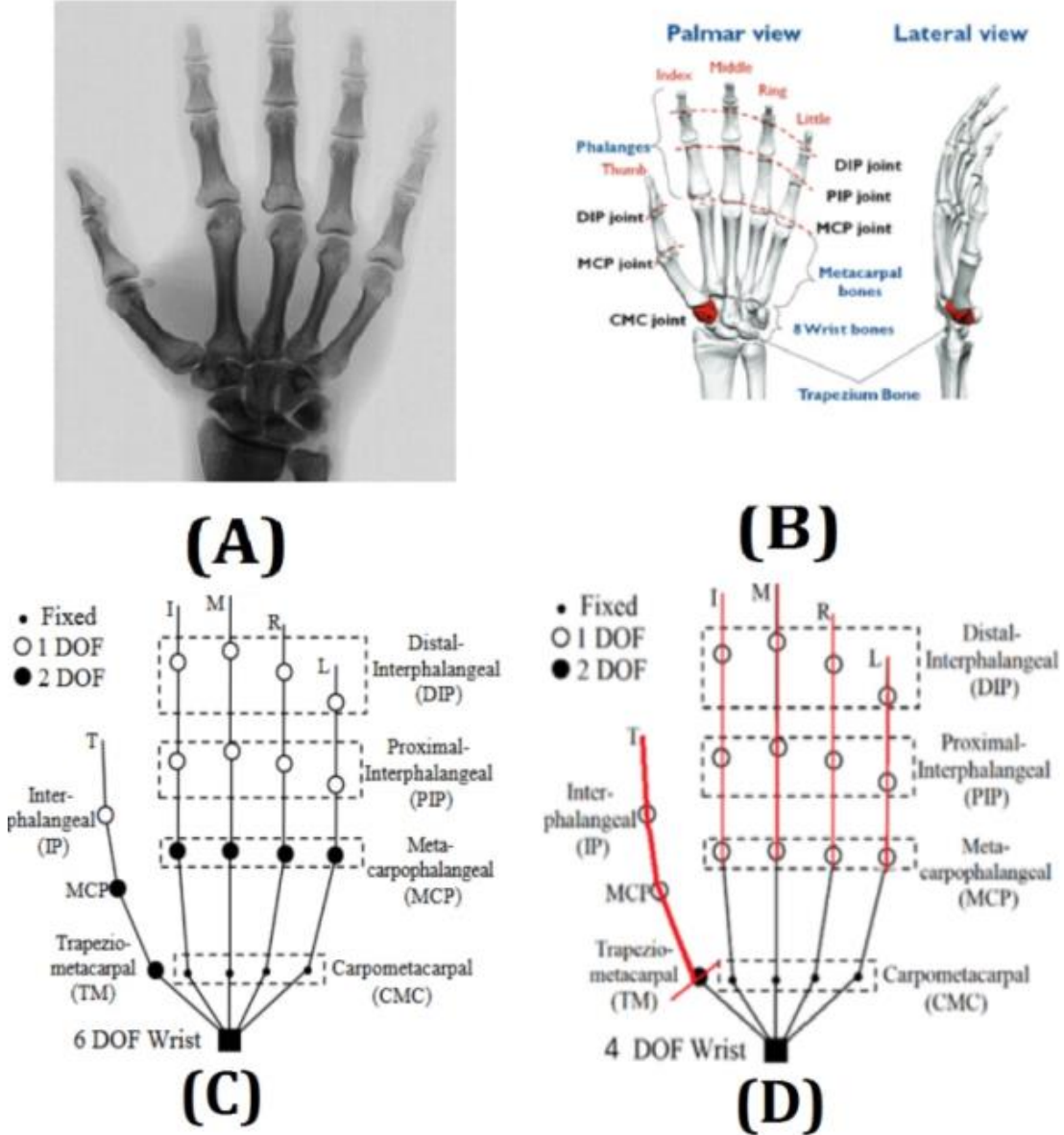


Figure 3-1 Bones in human hand (A, B) [94], hand's 27 DOFs (C) and mechanical model of the proposed robotic hand (6 DOAs) (D) [103]

A human hand has 27 DOF in total. There are five DOFs in the thumb, four DOFs in each other finger, and six in the wrist [24]. The six DOF in the wrist have the property of “global motion,” which means that all the palm and fingers will move simultaneously,

⁶ Part of the work is published in “N. M. Thalmann, L. Tian, and F. Yao, “Nadine: a social robot that can localize objects and grasp them in a human way,” in *Frontiers in Electronic Technologies*: Springer, 2017, pp. 1-23.”

while the other 21 DOF in hand has the property of “local motion.” In most prior studies of the motion or the design of robotic hands, only the “local motion” of the hand is considered.

3.2.2 Human finger structure

Figure 3-2 shows how the tendons and muscles drive the finger bones with the help of ligament and hood. The flexion of fingers is controlled by two tendons called Flexor Digitorum Superficialis (FDS) Tendon and Flexor Digitorum Profundus (FDP) Tendon. In contrast, the finger’s long extensor tendon controls the extension of the fingers. The muscles pull the bones through the tendons. The ligaments wrap the joints and tendons to regulate the motion when the bones rotate based on the corresponding joints. The cable-driven actuation mimics this natural system closely compared to other actuation methods such as gears or linkage bars.

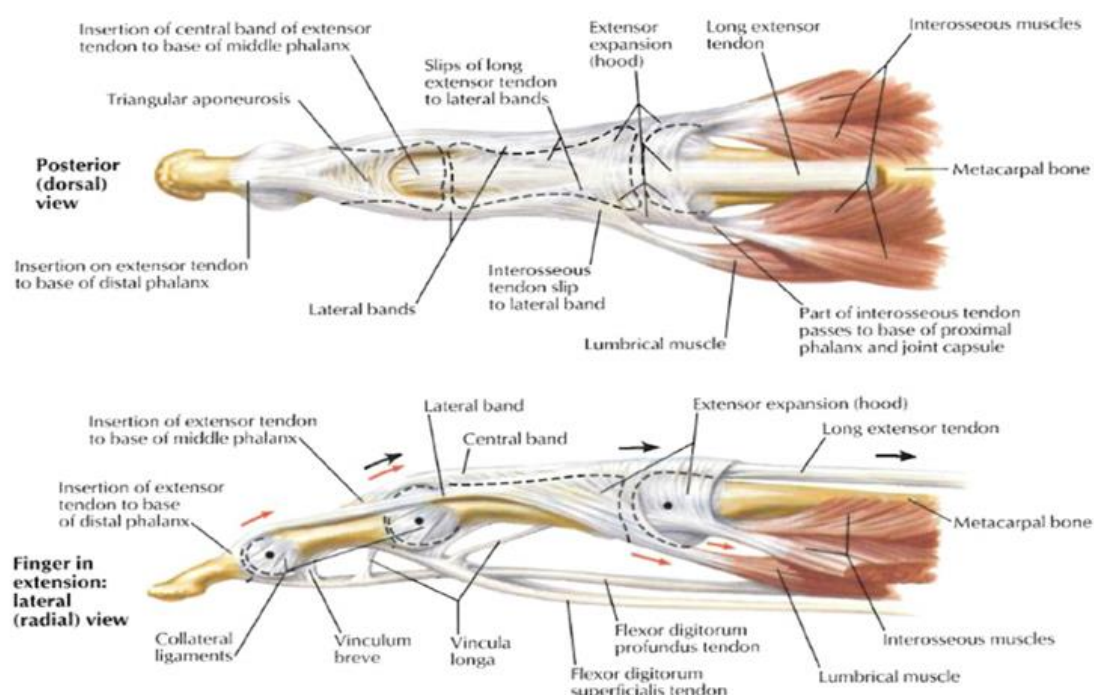


Figure 3-2 Structure of a middle finger [104]

3.2.3 Human hand constraints

From our daily life experience, the human hand and fingers have the following constraints:

- Fingers cannot bend backward without external force.
- The movement of the pinky finger will affect the ring finger or even the middle finger. Also, all the other four fingers are affected if the middle finger is bent.

- The DIP joint of each finger cannot be moved alone.

A formal representation of the constraints of human hands is proposed by Lin et al. [81], in which the constraints are divided into three types:

Type I has static constraints that limit the finger motion as a result of the hand anatomy. For example, the DIP joints cannot be moved more than 90 degrees.

Type II has dynamic constraints that limit the joints in motion. For instance, when bending a DIP joint, the corresponding PIP joint must be bent too.

Type III has the constraints that exist in certain human hand gestures. Sometimes they are not hard constraints, but most human beings follow them. For example, most people bend all the fingers together to make a fist instead of bending fingers one by one.

3.3 Proposed Methods

3.3.1 Modeling of the hand surface by 3D scanning

Compared to manual 3D modeling, 3D scanning is a quick and accurate way of getting a 3D hand model. The scanned target can be a natural human hand or even an artificial silicon hand skin. The proposed method scanned a natural human hand using a handheld 3D scanner, “Artec Space Spider.” The 3D scanned model can be represented in different formats. Here, the proposed method uses triangle mesh in stereolithography (STL) format⁷.

The first step that needs to take is to make the hand hollow. The thickness will significantly affect the strength and the weight of the final robotic hand. The proposed method uses software “MeshMixer” to separate the hand model from the wrist and set the thickness to 1.5mm. After comparing 2mm and 1.5mm, it concludes that 1.5mm is sufficient for print with Acrylonitrile Butadiene Styrene (ABS). This 3D model of the 3D scanning and shelled model are shown in Figure 3-3.

⁷ Part of the work in Chapters 3.3.1 and 3.3.2 is published in “Tian, L., Magnenat-Thalmann, N., Thalmann, D., & Zheng, J. (2018). A methodology to model and simulate customized realistic anthropomorphic robotic hands. In *Proceedings of Computer Graphics International 2018* (pp. 153-162).”.

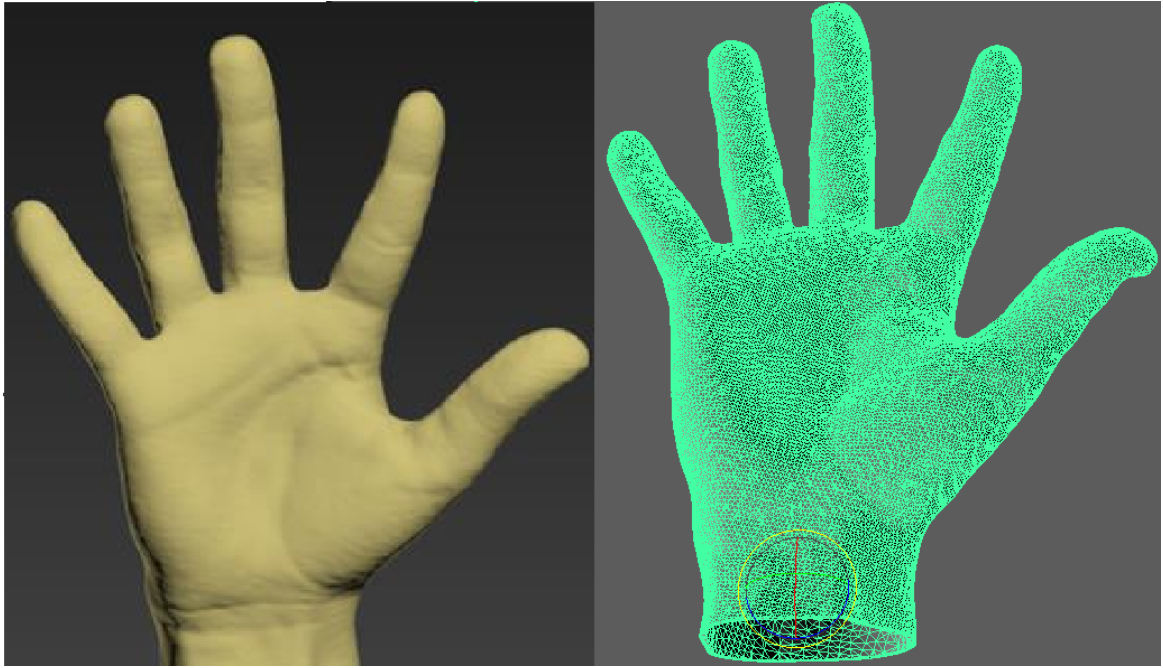


Figure 3-3 (A) 3D scanned hand model, (B) Shelled (1.5mm), 3D hand model

3.3.2 Modeling of the hand with a rigid, articulated structure

3.3.2.1 Reduction of the hand DOF

Due to the natural mechanism of the human hand, all 21 DOFs have a different range of motion. Past research has shown that the five MCP's adduction and abduction motions are limited within the range of 0 – 30 degrees [81]. According to hand grasp taxonomy, they are relatively unimportant in the grasping action [33, 82] and be neglected when designing the customized robotic hand. In the proposed design, except for the thumb, the other four fingers' DIP and PIP are controlled by the same tendon named “flexor digitorum profundus tendon” [94].

In this section, the proposed method proposes several heuristics to reduce the DOF of the hand model. Firstly, reduce 5 DOF of the human hand by ignoring the subtle abduction/adduction motion of the fingers' MCP joints. So, the DOF of the hand's local motion is reduced to 16. Most gestures are required to move each finger's three joints together [33]. The thumb plays the most crucial role in grasping [33]. It has been simplified to two DOFs. At the same time, the other four fingers are simplified to one DOF.

Moreover, only the thumb's TM joint has 2 DOF. It is challenging to simulate 2 DOF on one joint due to mechanical limitations. In the proposed design, a new joint is added

to represent the TM joint of the thumb and simulate the abduction/adduction moving of the thumb. The final DOF is 16 and is shown in Figure 3-4. Each DOF controls the three-finger joints together. The horizontal red line (Figure 3-1D at the TM joint) represents one additional DOF that controls the thumb's abduction and adduction move.

Regarding the wrist part, with the help of the Nadine robot's arm motion, Nadine can move the hand up/down, side to side, forward/backward, which contributes 3 DOF. However, as the design limitation of the Nadine robot, it has only one actuator to simulate flexion/extension between the carpals and radius. So, the abduction/adduction and supination/pronation motion from the wrist bone is omitted, and there are 4 DOF to represent the global motion of the hand. This omission will not affect the global hand motion much as the arm will assist the hand in making the global motion. Together with the local motion, there are 20 DOF for Nadine's hand (Figure 3-4).

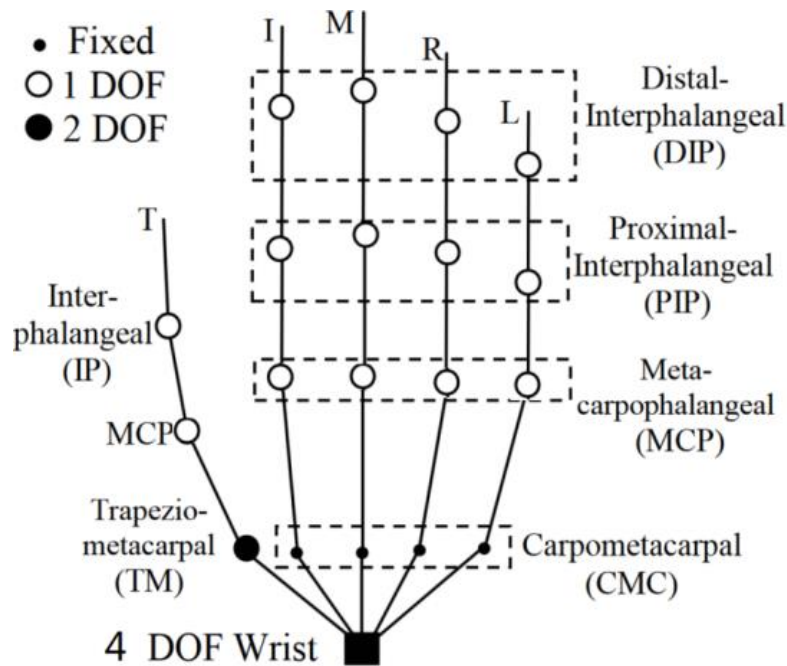


Figure 3-4 Mechanical DOF of the proposed robotic hand

3.3.2.2 Segmentation of the hand model

Based on the placement of hand bones, the proposed method segments the hand into several linked sections [105]. Prior research shows that these segments are relatively proportionate with minor deviations [105, 106]. Therefore, it can either estimate the dimension of each segment by the proportions or measure them.

Similar to other mechanisms, a hand needs the joint structure for centripetal movement. The joints in human hands have a complex biological structure, whereas ligaments link the bones. Between them, there are articular cartilage, synovial cavity and synovial membrane. All of these are hidden beneath the skin and are difficult to mimic. The proposed method will provide a general solution to transform from a 3D hand model to an actuated model.

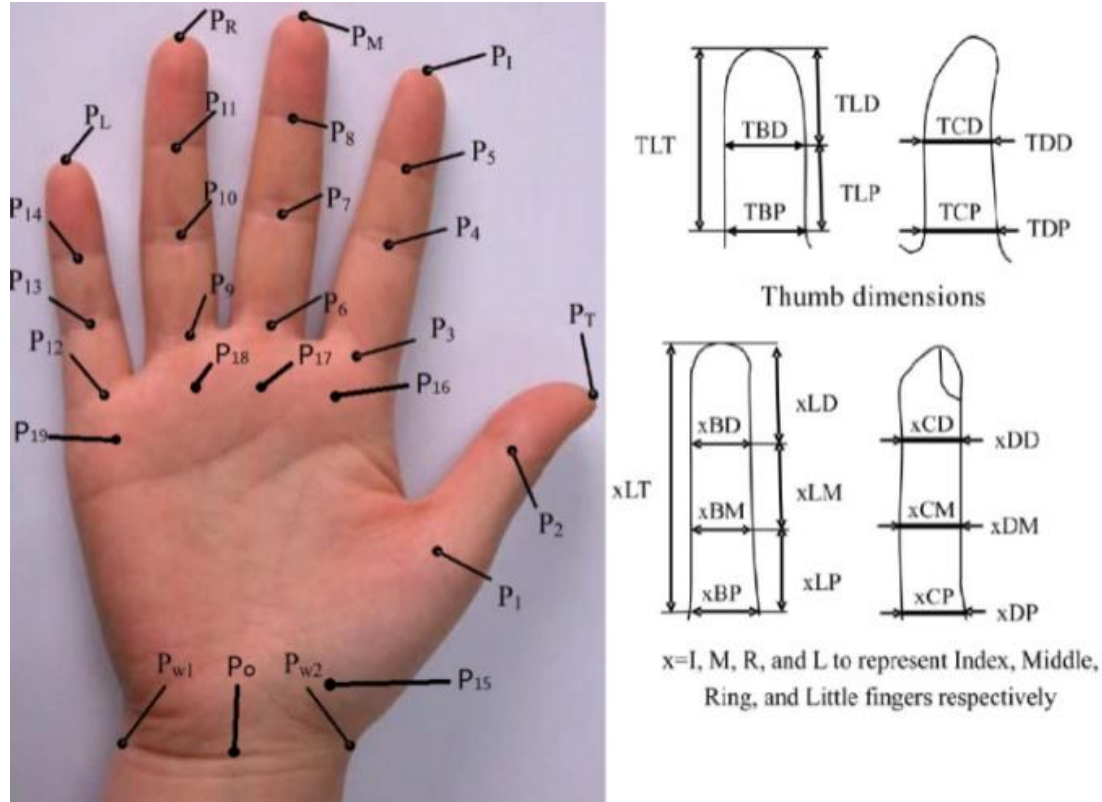


Figure 3-5 (left) Landmarks of the hand and (right) dimensions of fingers (amend from [106])

The proposed method first identifies 21 landmarks in the human hand (Figure 3-5) based on previous research [106]. After which, it then added six more landmarks. Five of these are P15 to P19, representing the thumb's TM joint and MCP joints of the other four fingers. The details of these notations can be found in the appendix. The landmark "Po" is the original point of the hand, which is located at the bottom end of the capitate bone. It is at the middle point of Pw1 and Pw2.

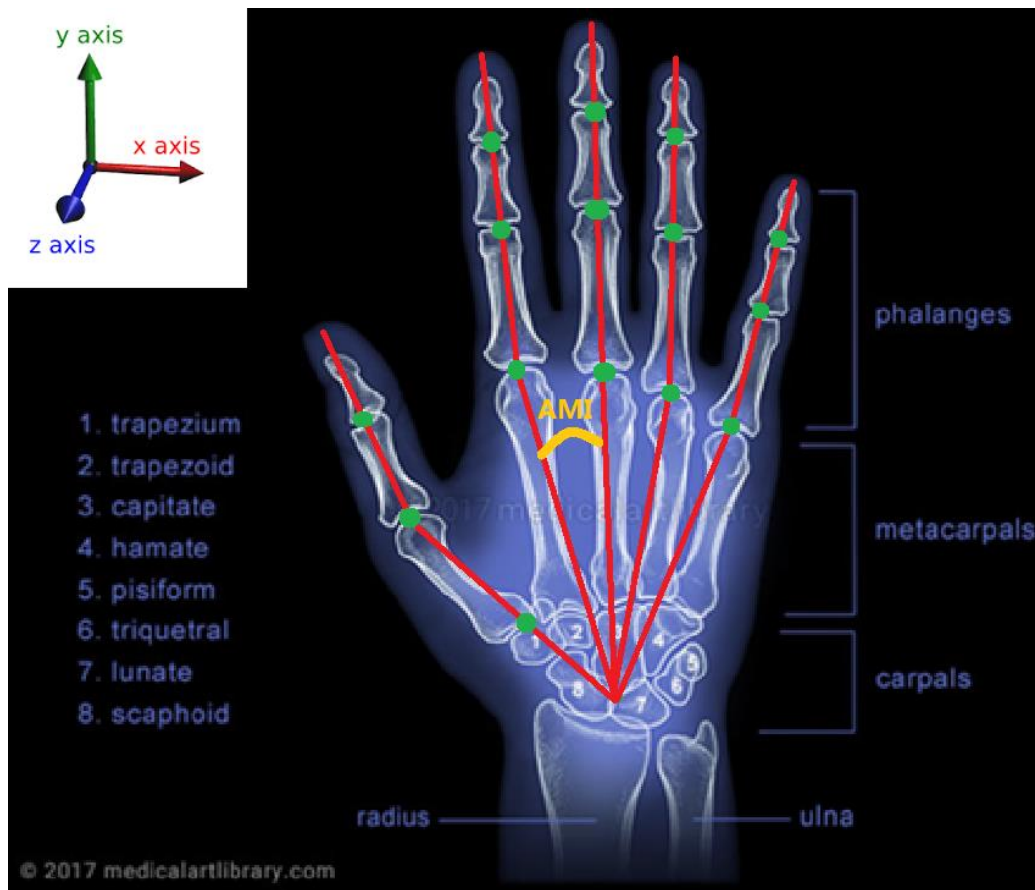


Figure 3-6 Movable joints of the human hand (in green dot)

The 3D hand articulation needs to divide the hand into segments and apply joints to link these segments. As the hand has 15 movable joints, precise positions are required to implement the joints. Here the proposed method provides a simple way to calculate them. Figure 3-6, based on a hand X-ray photo, the method marked the 15 movable joints of the human hand in the green dot, which are similar to corresponding hand landmarks. Draw lines from the tips to the point “Po” for each finger, with four straight segments passing through three movable joints. Finally, get a total of 20 segments in four layers.

The proposed method can get the length of the hand from the line (P_M , P_O) either from a natural hand or a 3D hand model. It also can calculate the length of each finger bone, metacarpals and the length of Capitate. The ratio and the calculation results of a 180-millimeter hand are shown in Appendix Table A-1 at the end. Here the proposed method chooses 180 millimeters (mm) as a previous study (<http://www.theaveragebody.com>) found that hand sizes for males range from 159 mm to 206 mm, and rounded up the average to 180 mm.

$$xLy = HLT \times Rxy \quad (3-1)$$

$$CVL = HTL - HTL \times (RMM + RMP + RMI + RMD) \quad (3-2)$$

The proposed method sets the segment (P₁₇, P₀) as the central line of the hand and makes it vertical to the “xz plane” (Figure 3-6). Human’s Metacarpals are not precisely straight. However, the offset is not significant [94]. So, assume all five root joints and P₀ are in the same plane with zero z coordinate. As the wrist’s breadth and wrist circumference decide the palm size and the position of the root joints, then assume the four angles made from (P₁₇, P₀) and the other four segments from the palm can be calculated from the HTL. (One of angle “AMI” is marked in yellow in Figure 3-6) So the proposed method can use the below formula to calculate the 3D coordinate of root joints’ landmark.

For P₁₆ - P₁₉:

$$\begin{aligned} P_a X &= xLM \times \sin \frac{AMx \times \pi}{180} \\ P_a Y &= xLM \times \cos \frac{AMx \times \pi}{180} \\ P_a Z &= 0 \end{aligned} \quad (3-3)$$

a= 16, 17, 18 or 19. X, Y, Z are the 3D coordinates from P₀

For thumb’s P₁₅, the segment (P₁₅, P₀) is slightly larger than CVL, and the proposed method sets an offset to correct the value. Currently, the proposed method sets it to 2 millimeters under the condition of HLT = 180 millimeters. The ratio is yet to be proven.

$$\begin{aligned} P_{15} X &= \left(CVL + \frac{HLT \times 2}{180} \right) \times \sin \frac{ATO \times \pi}{180} \\ P_{15} Y &= \left(CVL + \frac{HLT \times 2}{180} \right) \times \cos \frac{ATO \times \pi}{180} \\ P_{15} Z &= 0 \end{aligned} \quad (3-4)$$

For an ideal 3D scanning position, the two requirements are 1. All 15 movable joints’ landmarks are on the same plane with zero z coordinate. 2. All landmarks in each finger lay on a straight line. The proposed method can calculate the rest of the landmark positions using the same way as root joint, and all of this calculation is based on one input, HTL. Here, the way to calculate the position of the remaining landmarks based on the five root joints was also provided. For example, to calculate the P₃, P₄, P₅ and P₁,

from the human hand limitation, can get

$$0^0 \leq AFP_3, AFP_5 \leq 90^0$$

$$0^0 \leq AFP_4 \leq 110^0$$

$$-15^0 \leq AAP_3 \leq 15^0$$

$$AAP_4, AAP_5 = 0^0 \quad (3-5)$$

Hence, it needs the value of AFP_3 , AFP_4 , AFP_5 and AAP_3 for further calculation based on the equation of a sphere.

$$\begin{aligned} P_4X &= P_{16}X + ILP \times \sin \frac{AFP_{16} \times \pi}{180} \times \sin \frac{AAP_{16} \times \pi}{180} \\ P_4Y &= P_{16}Y + ILP \times \sin \frac{AFP_{16} \times \pi}{180} \times \cos \frac{AAP_{16} \times \pi}{180} \\ P_4Z &= P_{16}Z + ILP \times \cos \frac{AFP_{16} \times \pi}{180} \end{aligned} \quad (3-6)$$

The coordinate of the other landmarks can be calculated by the same method.

3.3.2.3 Creation of the internal mechanical structure

In order to validate the proposed method, this chapter implemented the algorithm in Maya with Python script. The steps are 1) Placed the hollowed hand model with the “ P_O ” point overlapping the original point with coordinates (0,0,0) in Maya. 2) Set the segment (P_{17} , P_O) vertical to the “xz plane.” 3) Run the Python script to edit the 3D hand model. The code has input length parameters and necessary angles if the hand model is not in the ideal case. 4) Calculate the position of the movable joints and the dimension of the hand. 5) Cut the finger into 15 pieces based on points $P_1 - P_{15}$. 6) Use these 15 landmarks as reference points to place 15 blocks to each knuckle’s position. The blocks are slightly shorter than knuckles to make a gap between the neighbors’ knuckles. So different knuckles will be 3D printed in different parts. 7) Create 15 joints structures for the 15 hand’s movable joints. The thumb’s TM joint uses a ball joint to meet the two DOFs requirement, while the other 14 joints use the hinged design for one DOF. Each hinge joint is made out of five standard objects. The upper connector is a cylinder linked to the upper knuckle (red lines, as shown in Figures 3-7). It is also linked to two other

cylinders called the middle connector and lower connector. The two pipes are linked with the lower knuckle. They are precisely placed, surrounding the lower connector with a 1-millimeter gap. This design allows the upper knuckle to rotate using the lower connector as a rotating shaft. The sizes of these parts depend on the dimensions that were calculated above.

Most existing robotic hands mimic the MCP joint motion with the axis of rotation at the endpoint of four fingers (except for the thumb). For example, in Figure 3-5, the MCP joints of the four fingers are placed at the landmark P_3 , P_6 , P_9 and P_{12} . However, according to the human hand anatomy, the MCP joints are inside the palm with landmark P_{16} , P_{17} , P_{18} and P_{19} . The proposed method uses these points as references to add the rotating shafts.

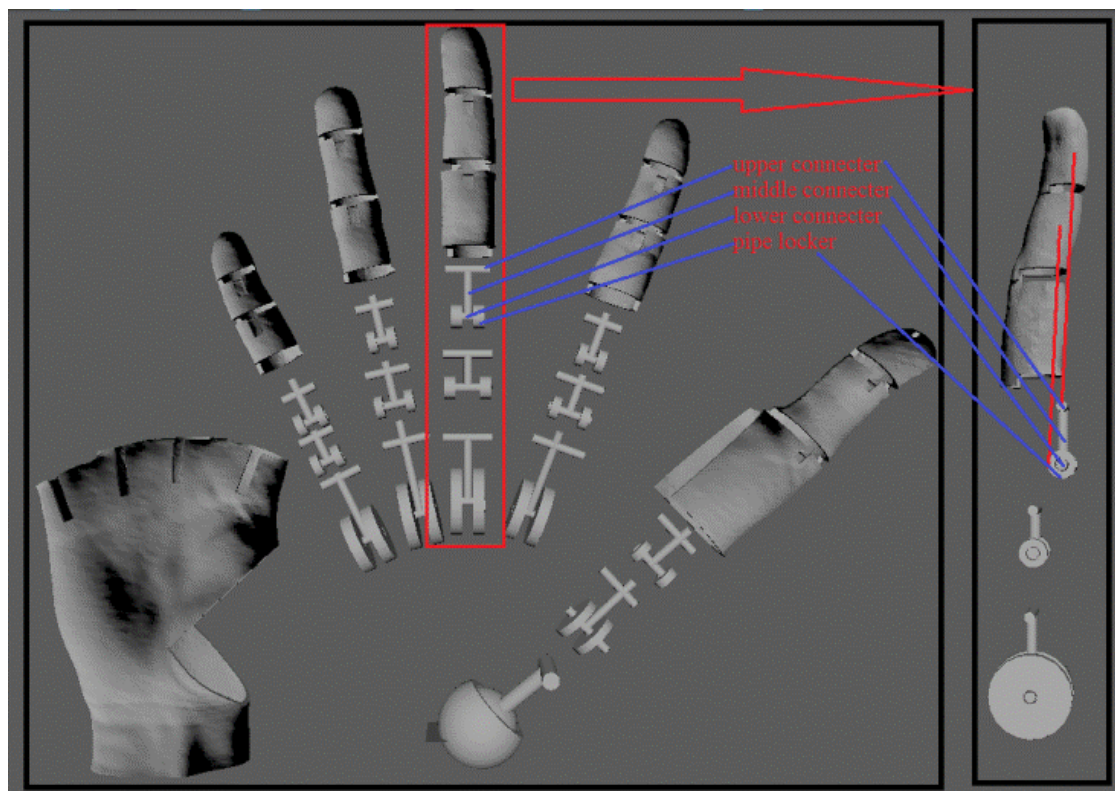


Figure 3-7 (left) Front view of the inside structure of our robotic hand (right) Side view of the middle finger

The thumb's TM joint has two DOFs, and both of them are important for grasping. The ball joint is a typical design in our daily life and is already applied to robotic hands [107]. Here is the proposed method of using script code to create a ball joint in Maya in Figure 3-8.

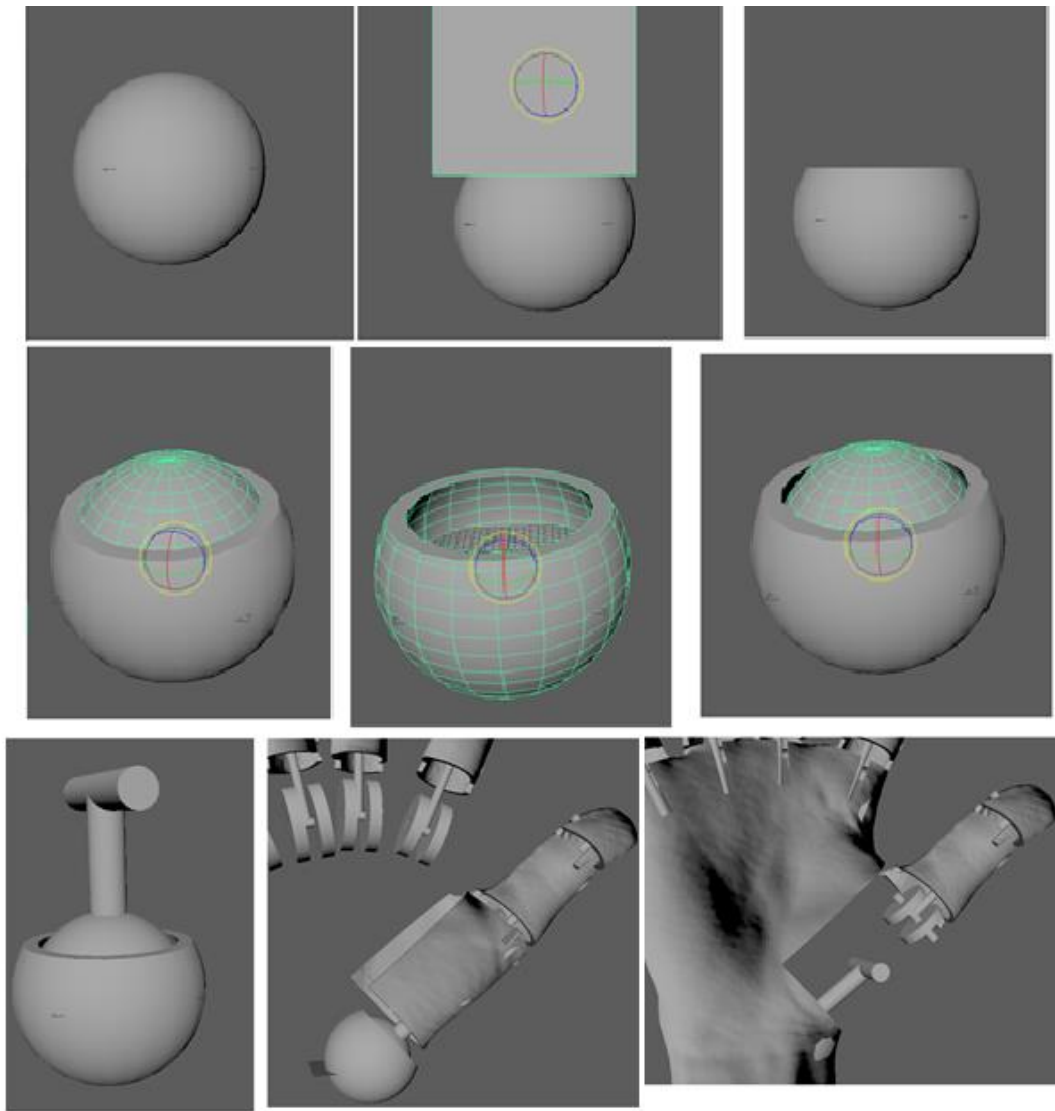


Figure 3-8 Steps to creating the ball joint for TM joint

This proposed method uses Maya to simulate the collision caused by the finger motion. As the hinge joint target range of motion is 0 to 90 degrees, the method simulates the motion of fingers with the same range of motion to identify overlapping of the adjacent parts. Then remove the colliding parts which could obstruct the motion. Finally, add holes to all five fingertips for the control cables, and get the interlocked robotic hand model ready for 3D printing. (Video link: <https://youtu.be/eICcC19o0vo>)

3.3.2.4 Result of 3D printing



Figure 3-9 (Top) 3D-printed scanned hand and natural hand (Bottom) our robotic hand and its 3D model

Figure 3-9 shows the complete pipeline of the proposed method. 1. 3D scanning the natural human hand to get a 3D hand model. 2. Segment the model and create an internal mechanical structure. 3. 3D printed the model out. This chapter also compares the weight of the customized robotic hands with other robotic hands in Table 3-1.

Table 3-1 Mass comparison of the robotic hands

Robotic Hand Name	Developer	Mass (g)
Customized robotic hand (2018)	This research	175
Soft-surface robotic hand (2019)	This research	225
InMoov Hand (2015) [14]	Gael Langevin	400
Tact (2015) [20]	University of Illinois	350
Dextrus (2013) [21]	Open Hand Project	428
Bebionic (2014) [18]	RSL steeper	550
i-Limb (2010) [19]	Touch Bionic	460-465
Xu et al.'s hand (2016) [30]	Xu et. al.	942

3.3.3 Modeling of the hand with a flexible surface structure

3.3.3.1 The benefit of flexible surfaces

Traditionally, researchers have used firm materials to design and make predictable robotic systems mechanisms, including robotic hands. However, most natural systems have deformable bodies superior to rigid robotic systems in many comparable areas. In recent years, 3D printers capable of more different materials, including flexible resin materials⁸. This chapter also designs a flexible surface 3D printable robotic hand based on previous research, aims the deformation of a robotic hand [84, 85, 103]⁹.

Human hands have inspired various designs of robotic hands [99]. However, the conventional robotic hand failed to duplicate the natural human hand's deformation when choosing the rigid materials to represent the hand. These materials' physical properties are far from human hand skin. Recently, engineers have begun to explore the design and control of soft-bodied robots composed of soft or flexible material. Young's modulus is defined as prismatic, homogeneous bars subject to axial loading and small deformations. It is also a useful measure of the robotic systems' material in hardness[108]. Figure 3-10 below shows that the traditional robotic hand is usually made from high-order moduli (10^9 - 10^{12} Pa), including metals and 3D printable hard plastic. The materials composed of the human hand (skin, tissue and muscle) have low

⁸ <https://formlabs.com/3d-printers/form-2/>

⁹ Part of the work in Chapters 3.3.3 and 3.6.3 is published in "L. Tian, J. Liu, N. M. Thalmann, D. Thalmann, and J. Zheng, "Design of a Flexible Articulated Robotic Hand for a Humanoid Robot," in 2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids), 2019: IEEE, pp. 572-577."

moduli on the order of 10^4 - 10^9 Pa. Previous research defined soft robots as the systems capable of autonomous behavior primarily composed of materials with moduli in the range of the moduli of soft biological materials [34].

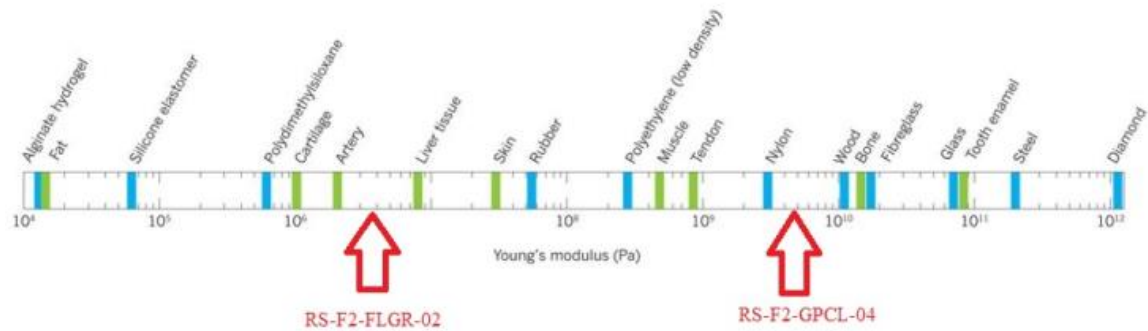


Figure 3-10 Young's modulus for various materials and the two 3D printing materials the proposed robotic hand used (Red arrow)Adapted from [34]

3.3.3.2 Result of 3D printing

Figure 3-11 shows the proposed soft-surface robotic hand. This design prints the palm bones and the surface part using firm and flexible material (RS-F2-GPCL04 and RS-F2-FLGR-02) with a “Form2” 3D printer. The actuation uses six high-torque servomotors to simulate the 15 joints motion of the human hand. This approach provides a more straightforward and effective way to create a soft surface robotic hand than existing work. The experiment shows that the soft surface robotic hand could have a similar trajectory as the rigid robotic hand.

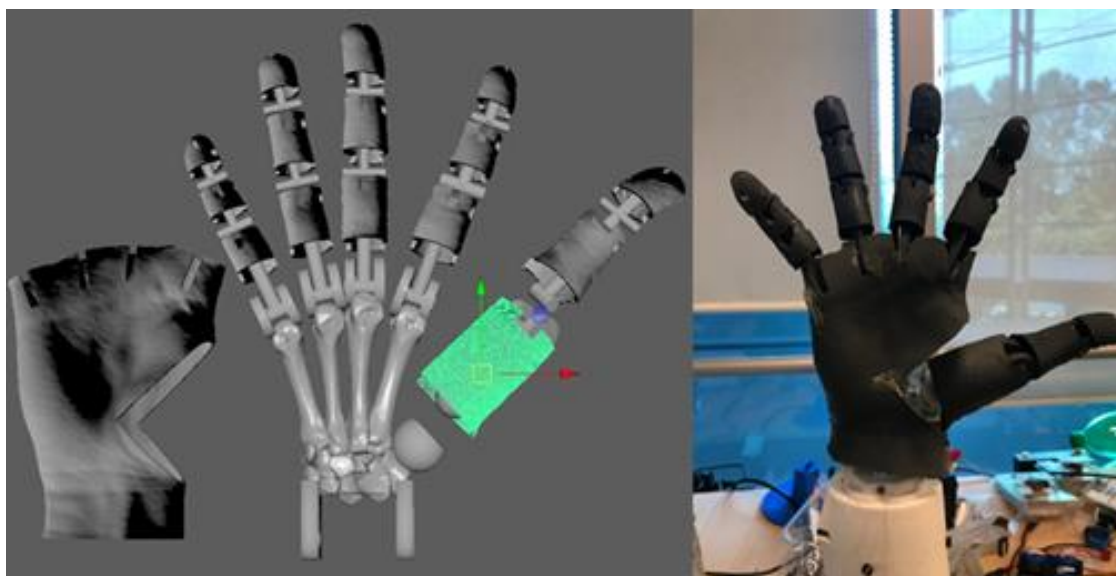


Figure 3-11 Soft-surface robotic hand's 3D model and the final product

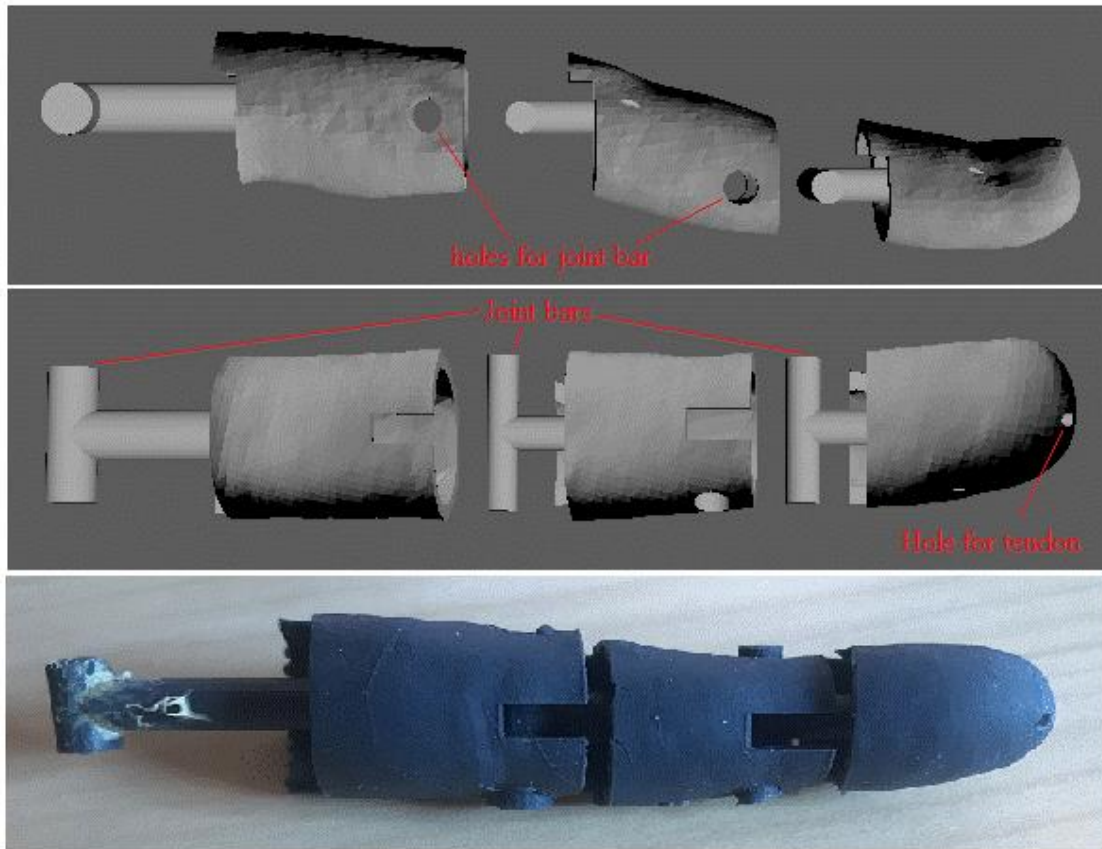


Figure 3-12 3D scanned hand model, hand landmarks and segmented hand

The proposed method uses the python script to add the pin joints to each finger except the thumb. The holes in the finger are made by the “Boolean-difference function” in Maya. It also removes the possible collision part to control the angel’s motion range. The three-finger parts are printed by a “Form2” 3D printer using flexible Resin (RS-F2-FLGR-02). They can be snapped together quickly by hand. Flexible Resin is an elastomer that allows bendable/compressible parts to be printed on a 3D printer. It is ideal for adding soft overmolds to multi-material assemblies.

As the human hand has very soft skin and tissues in the fingers and palm, an obvious hand deformation will happen during grasping. This deformation will increase the contact area to the grasping object, thus increasing the grasping quality. Prior research about grasping deformation can be found in [109-111].

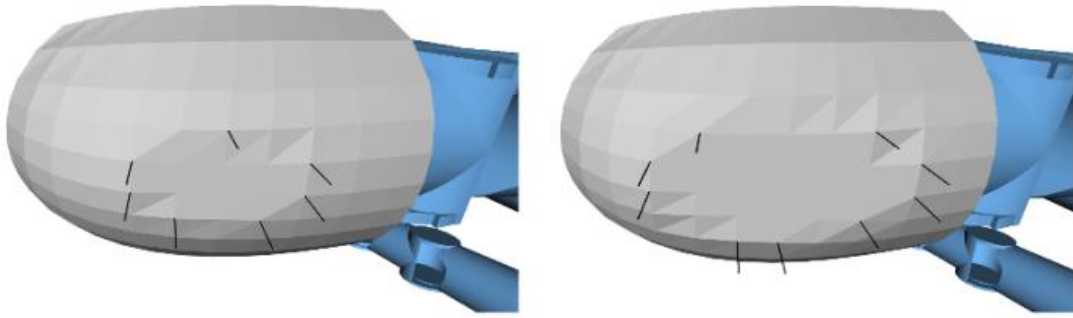


Figure 3-13 The contact areas for a 5 N normal force (left) and a 25 N normal force (right) within a transparent cube. The vertices of the convex boundary of the contact area are marked with the thin cylinders [109]



Figure 3-14 3D scanned hand model, hand landmarks and segmented hand

The palm has two separate parts in the proposed design. The inside part is 3D printed with a rigid material (RS-F2-GPCL04). It combined four palm bones and eight wrist bones. Besides the bones, it has one ball joint holder for the thumb and four pin-joint holders for the other four fingers. It also has a connector, which allows linking to the forearms part of the robot. The palm skin and thumb are 3D printed with flexible material, like other robotic fingers (Figure 3-14). All parts can be manually linked, and the final product is shown in Figures 3-11.

3.4 Actuation system design

3.4.1 Cable-driven system and servo bed

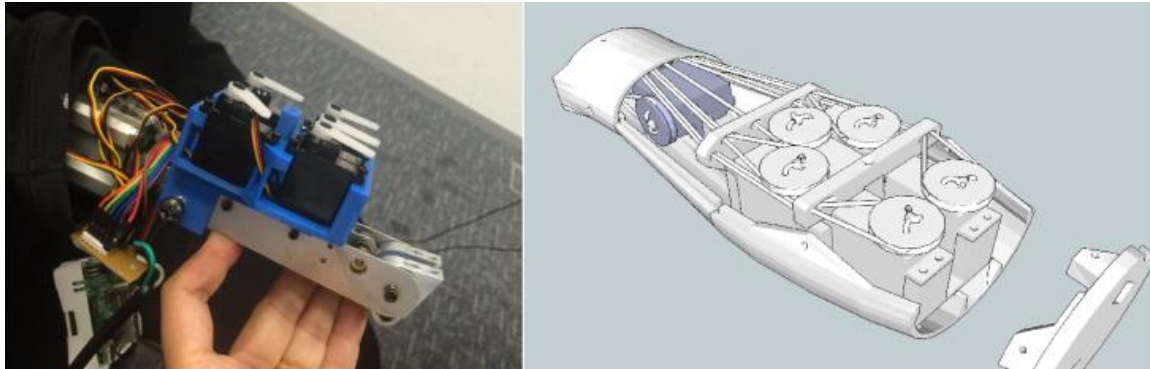


Figure 3-15 (A) Servo bed for the Nadine robot (B) Servo bed from the Inmoov robot [22]

The proposed customized low-cost robotic hand uses the cable-driven method for actuation. It is compatible with different cable-driven actuation systems. It supports both two-cable and one-cable designs. The one-cable design uses one cable to control each finger, which only actuates the flexion motion of the finger. The customized robotic hand's size is adjustable to be inserted into a normal-sized silicon artificial skin. The elasticity of the artificial skin will return the fingers to an extended position once the cables are relaxed. The one-cable design only requires a one-arm motor horn, which is smaller than a two-arm horn. Figure 3-15A shows the servo bed (3D printed in blue) specially designed for the Nadine robot. The servo motor, HITEC HS-5070MH, is tiny and light (12.7g). The two-cable design uses two cables to control each finger, which is for flexion and extension. The customized robotic hand also works fine with the Inmoov robot's hand actuation system, a two-cable design (Figure 3-15B).

Moreover, the proposed one-cable design allows positioning the servo motors' bed in various steps, simultaneously preventing any collision between servo motors. In contrast, the two-cable design takes up more space but enables the hand to function without artificial skin. The proposed one-cable actuation system uses a Raspberry Pi II™ as the motor controller, sending pulse-width modulation (PWM) signals to control the motion of each motor.

Electric and pneumatic motors are two widely used actuators for robotic hands, while linkages, camshafts, gears and cables are standard tools for transmitting the force from the actuator to fingers [19]. Although there are several artificial muscles such as [112],

the customized robotic hand still chooses electric servo motor and cable-driven method for actuation solution because of their high efficiency and low cost [113].

The driven cable uses a 0.5mm diameter Nylon as a hand tendon. One side of the cable is tied outside the fingertips (Figure 3-16A). The knot is covered with reusable putty-like adhesive to increase the friction between the fingertips and the target objects. The cable goes through the inside of the fingers and the palm. The other side of the cable is tied to the horn of the motor. When the motor's horn turns, the finger will move from the DIP joint, which has minor resistance. PIP and MCP joints will be actuated in sequence. Figure 3-16 shows how the motors actuate the middle finger and the thumb. The range of motion is controlled by control software which results in human-like hand motion.

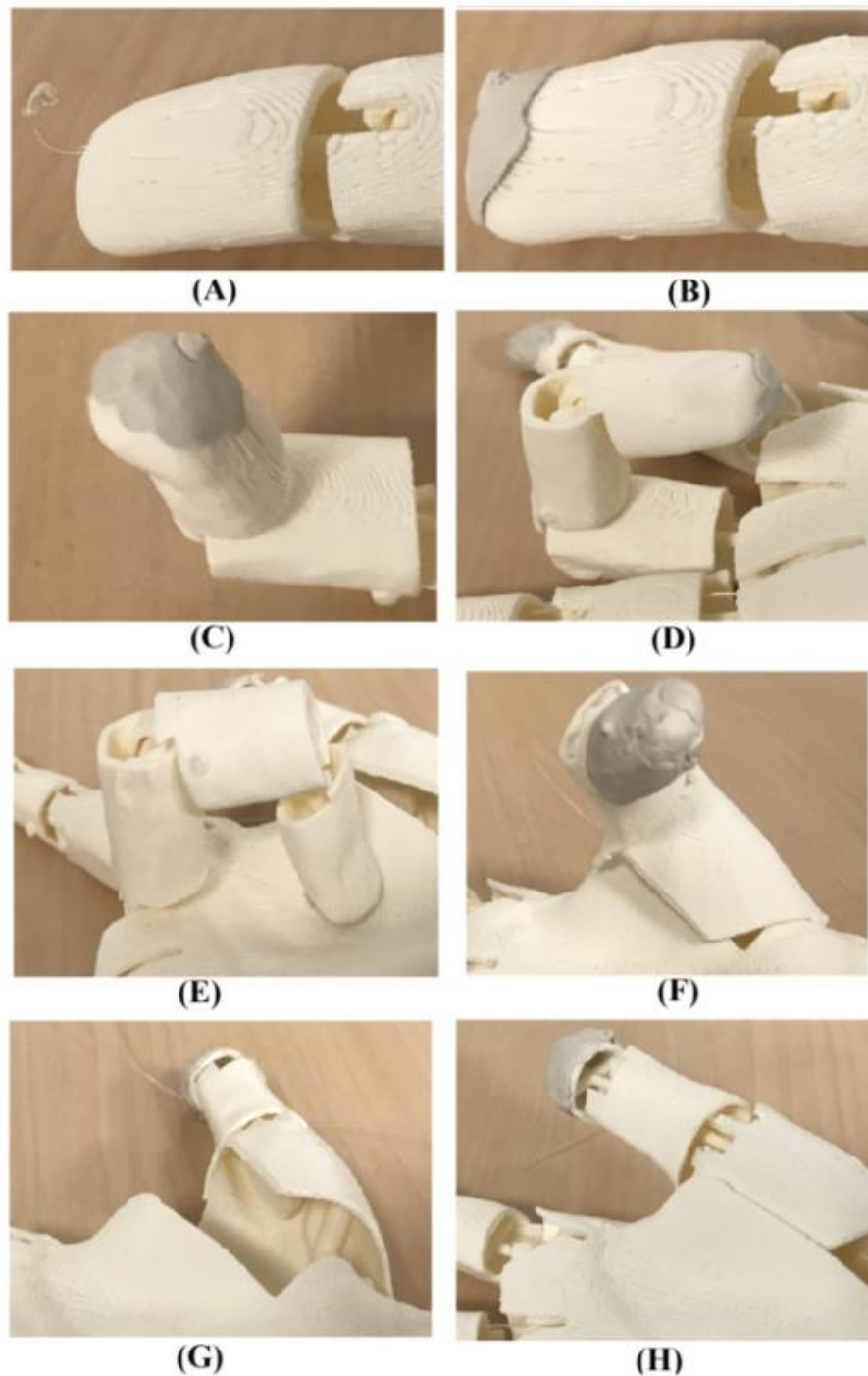


Figure 3-16 Cable-driven finger

3.4.2 Weight control

Lightweight is one of the design priorities of the proposed method. Lightweight is substantial, especially when the robotic hand has been integrated with the humanoid robot. According to the previous test result, the Nadine robot's forearm motion would be affected when the mass of the linked robotic hand is heavier than 500 grams. According to Table 3-1, the customized robotic hand is the lightest because the proposed method uses a hollow design with a thin shell (1.5mm). The robotic hand is printed with

ABS high-density material using a “uPrint SE Plus” 3D Printer. It weighs only 72 grams. The actuator server motor, HITEC HS-5070MH, is also tiny and light (12.7g). The total weight of the robotic hand is 175 grams, including servos, servo bed and 3D hand model, and the artificial skin weight is 127g.

3.4.3 Range of motion

This section compares the range of motion of the proposed design with other robotic hands and a natural human hand. The results are given in Table 3-2. While the artificial skin reduces the range of motion of each joint, it dramatically improves the appearance and increases the friction of the grasp.

Table 3-2 Hand joint moving angle

Robotic hand name	MCP	PIP	DIP	TM flexion	TM circumduction
Customized robotic hand (With artificial skin)	0-90 (0-70)	0-90 (0-70)	0-90 (0-70)	0-90 (0-70)	0-60 (0-30)
Customized robotic hand [84]	0-90	0-110	0-90	0-90	0-90
Tact hand[20]	0-90	23-90	20	0-90	0-105
Dextrus hand[21]	0-90	0-90	0-90	0-90	0-120
i-Limb hand[19]	0-90	0-90	20	0-60	0-95
Bebionic hand[18]	0-90	0-90	20	-	0-68
Human hand[114]	90	100	90	70	70

3.5 Path planning and control of a cable-driven robotic hand

3.5.1 Overview

The human hand has 21 Degree of freedom (DOF) for five fingers. Due to the cost and complexity, almost all existing robotic hands [19, 82] are under-actuated [61] robotic hands with less than 21 actuators. The cable-driven underactuated robotic hand usually has a limited motion range, which is different from the natural hand. Human grasping is the perfect combination of speed, accuracy and strength. The development of robotics and virtual reality has promoted the research of human hand movement. Since the first appearance of Virtual Humans in the early 1980s, many types of research related to grasping plans have been conducted in a virtual environment [115, 116]. As the hand is the most flexible part of the human body [94], the unique structural features and cognitive factors of the brain determine the complexity of its movement. At present, the research on human hand grasping is particularly prominent in the humanoid robot field [17, 117, 118]. The researchers found that the joints of the human joints were in motion with certain movement rules and could be used to control the grasping of multiple fingers. In the virtual hand research, Rezzonico et al. first defined this motion rule as automatic grasping and grabbed it into two categories: automatic grasping and interactive grasping. They also propose a general framework to enhance grasping interactions[119]. Further research about individual robotic hand kinematics can be found in [30, 120, 121]¹⁰.

The trajectory of each finger is a fundamental property of the robotic hand. In[122] and [30], researchers also provide the trajectory of their robotic hand. They captured the motion of the fingertips by the motion capture system. Pitarch draws the workspace of thumb in 3D space[123]. Yang et al. propose a method to visualize and analyze the intersection workspaces of multi-finger hands[124]. All of them construct the motion in a virtual environment. From Figure 3-17 below, it can be concluded that the fingers' trajectories from a cable-driven robotic hand are continuous irregular curves. The irregularly curved working surface is generated if the finger has more than one DOF. Compared to these methods, the proposed method is easy and practical. This section

¹⁰ Part of this work is published in Tian, L., Thalmann, N. M., Thalmann, D., & Zheng, J. (2019). "Nature grasping by a cable-driven under-actuated anthropomorphic robotic hand." TELKOMNIKA, 17(1), 1-7.

also provides the approximate linear equations to represent the trajectories.

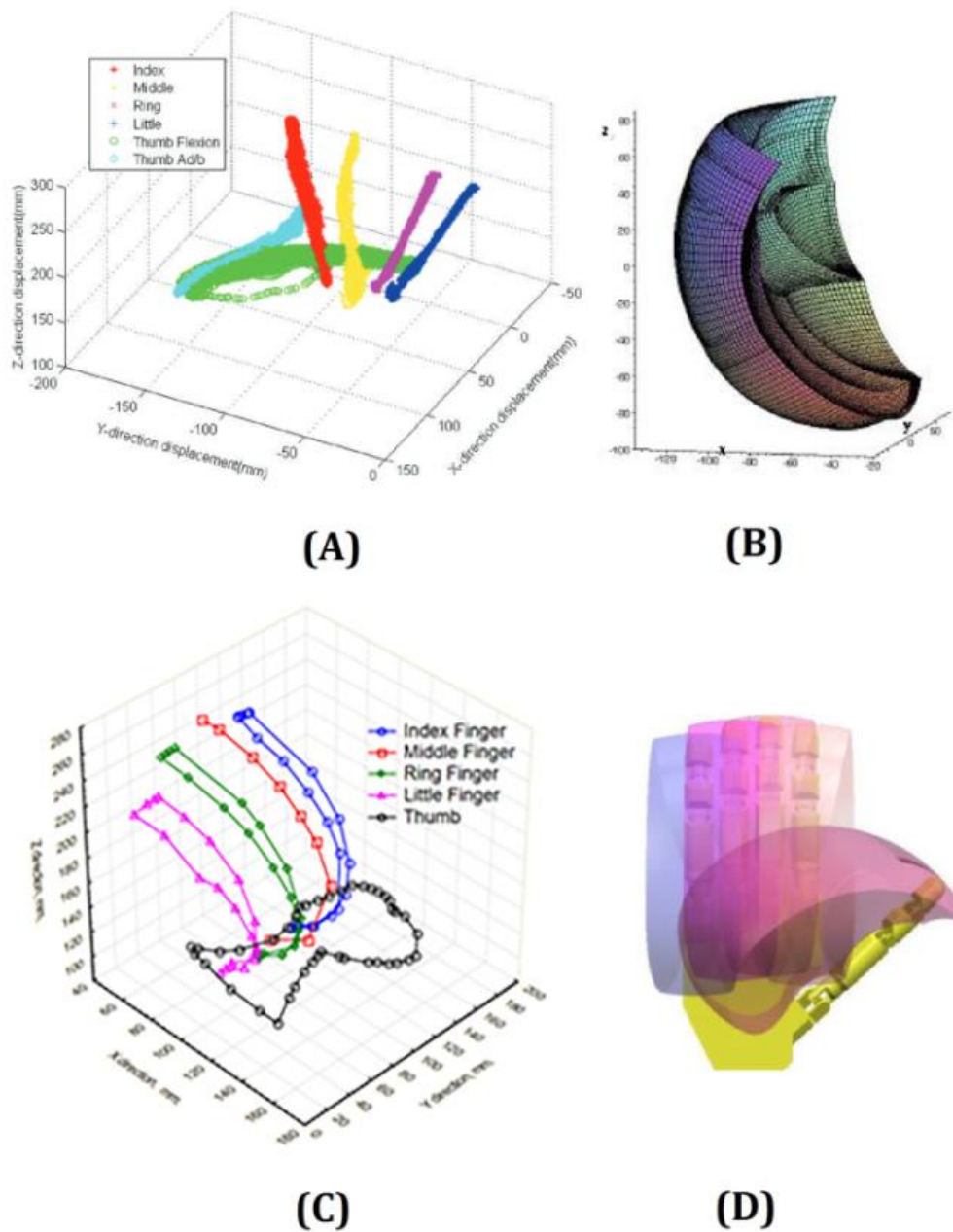


Figure 3-17 Trajectories of the fingers (A)The trajectory of fingertips of Xu highly biomimetic robotic [30] (B) Thumb workspace [123] (C) trajectory of a prosthetic hand [122] and (D)Whole workspace of ZSTU Hand[124]

3.5.2 Calculation of end effect

To make the robotic hand articulate, it needs to divide the hand into segments and apply joints to link these segments. Based on the placement of hand bones, the proposed method segment the hand into several sections [105]. [105, 106] shows that the finger bones have stable proportionate. Therefore, it can either estimate the dimension of each segment by the proportions. Additionally, with the angle of each joint, it can calculate

the coordinates of each joint and tips just by transformation and rotation in a 3D space. For example, Figure 3-18 can calculate the end effect of the index finger, T_{pl} , by equation (3-7). With these parameters, the proposed method implements a Python script that can generate joint structure to correct position in the scanned hand model asthmatically.

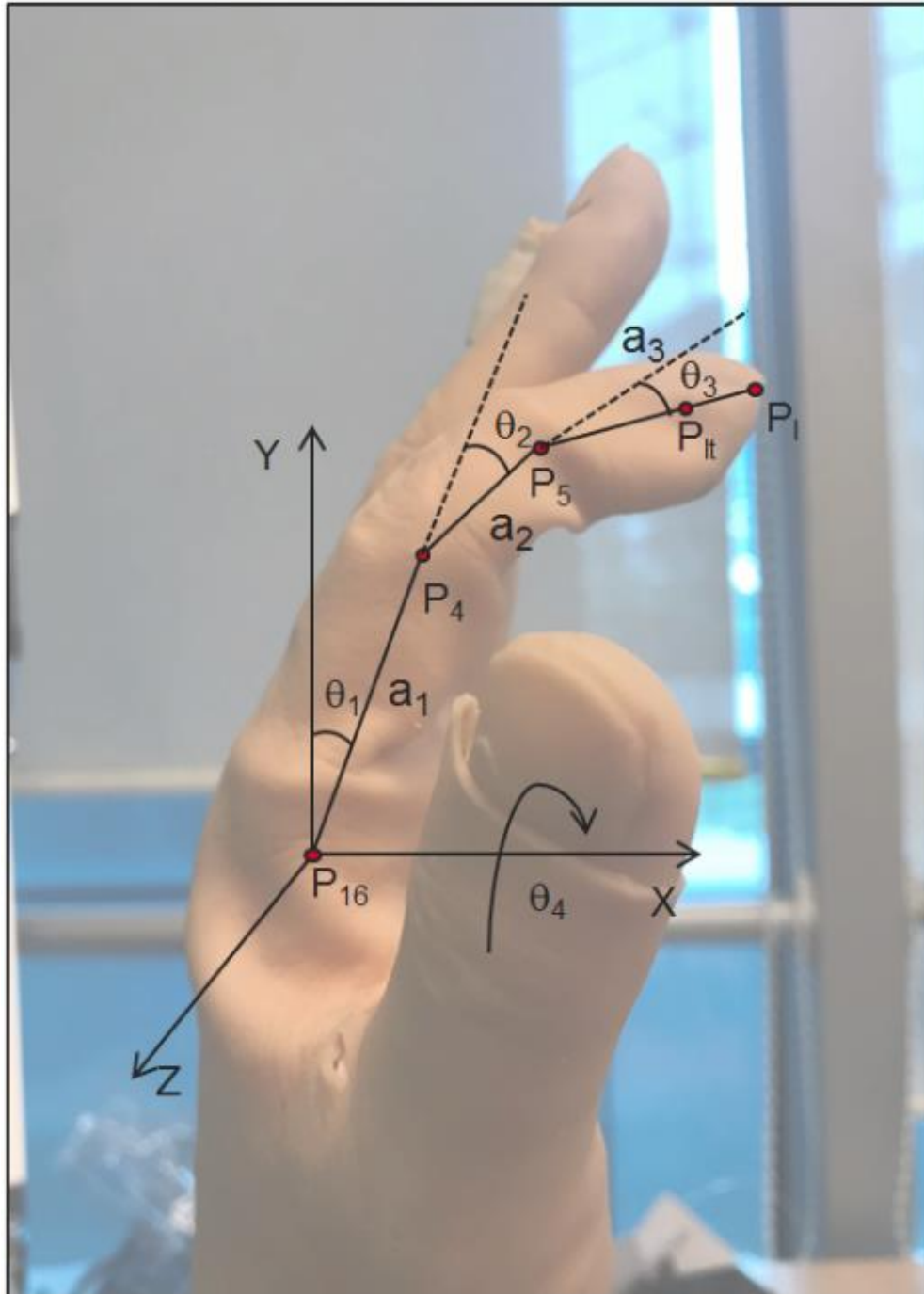


Figure 3-18 3D system of the index finger

$$T_{pl}=R(\theta_1)T(a_1)R(\theta_2)T(a_2)R(\theta_3)T(a_3) \quad (3-7)$$

Where function $R()$ stand for rotation and function $T()$ stand for transmission

3.5.3 Data fit of finger trajectory and grasp plan

The trajectories of the cable-driven robotic hand are uncertain within the diverse condition of mechanical design and artificial skin. This section chooses two common grasp gestures as an example to design a grasping plan for the local motion. It also studies the detail of Tripod and Wraps grasp samples and the end effector of each landmark of hand. Then, it provides a general way to get the trajectory of each finger by data fitting. Furthermore, calculate the PWM pulse for each motor for the grasping action.

A Tripod grasp is a precision grasp widely used daily for small-sized objects smaller than 70 mm. While Wrap grasp is a common power grasp for objects with the shape of slim cylinders. Much prior research about human grasping has defined the Tripod grasp [17, 33, 125-127]. The common parts of these definitions are that the tripod grasp is formed only by three fingers, and the fingers surround the target object to hold the object firmly. However, the touchpoints are different in these works. Here this section chooses the latest research result from the human grasping database as the target grasping gesture. From below Figure 3-19A, the touchpoints of the thumb and index finger are near the fingertips. The touchpoint of the middle finger is near the PIP joint. (Refer to figure 3-19A red points 2, 3 and 1). The Wrap grasp has five touch points from five fingers. As previous research on trajectories of fingers is regard to the fingertips, this section introduces a new way to get the trajectory of any point on the fingers.



Figure 3-19 (A) Tripod with touchpoints (B) Wrap grasp with touchpoints

3.5.4 Sampling of points

Servo motors are commonly used as actuators in cable-driven systems. The proposed method chooses HS-5070 MH servo motors with active pulse width modulation (PWM) range 0.75 ~ 2.25 milliseconds. It samples the motion from 0.70 to 2.20 milliseconds with a 0.1-millisecond interval. The finger poses and angle changes are recorded during the test. Table 3-3 below shows the result of the middle finger. The data under the column “touch-point.x” and “touch-point.y” shows the coordinate changes when the motor moves from one limit value to another.

Table 3-3 Kinematic analyses of middle finger

PW M	posi tion	dip.de g	pip.de g	mcp. deg	mcp.x	mcp.y	pip.x	pip.y	dip.x	dip.y	touch- point.x	touch-point.y
8	27	0	5	25	16.90	36.25	29.40	57.90	43.40	82.15	38.40	73.49
9	38	0	5	25	16.90	36.25	29.40	57.90	43.40	82.15	38.40	73.49
10	49	5	7	27	18.16	35.64	32.14	56.37	49.76	78.13	43.47	70.35
11	59	8	11	30	20.00	34.64	36.40	53.51	57.53	71.88	49.99	65.32
12	72	15	22	38	24.63	31.52	46.28	44.02	73.32	51.27	63.66	48.68
13	84	20	25	40	25.71	30.64	48.37	41.21	76.26	43.65	66.30	42.78
14	96	31	33	49	30.19	26.24	54.95	29.72	80.72	18.78	71.51	22.69
15	106	33	38	52	31.52	24.63	56.52	24.63	80.00	9.38	71.62	14.82
16	116	36	41	55	32.77	22.94	57.63	20.33	78.44	1.59	71.01	8.29
17	125	40	43	60	34.64	20.00	59.00	14.38	75.85	-7.99	69.83	0.00
18	133	43	48	65	36.25	16.90	59.26	7.14	70.65	-18.44	66.59	-9.31
19	140	46	50	70	37.59	13.68	59.24	1.18	66.01	-25.99	63.59	-16.28
20	151	62	60	75	38.64	10.35	56.31	-7.32	48.13	-34.10	51.05	-24.54
21	162	62	63	78	39.13	8.32	54.86	-11.11	43.92	-36.89	47.83	-27.68
22	173	62	63	80	39.39	6.95	54.44	-13.02	42.60	-38.40	46.83	-29.33

Use the same method, and it can get the trajectory of the index finger and thumb. The proposed method samples the trajectory in three conditions for the index finger when

the abduction angle is 0, 20 or 40 degrees. For the thumb, it samples the trajectory in two conditions: maximum abduction and maximum adduction.

3.5.5 Working space of three fingers

This section draws the six sets of sample data of trajectories from the above section in lines. It shows them in a 3D space with the help of Matlab™ “plot3 function” to virtually simulate the customized robotic hand grasping. It also estimates the motion area of the index and thumb by constructing a surface based on their trajectories (Figure 3-20).

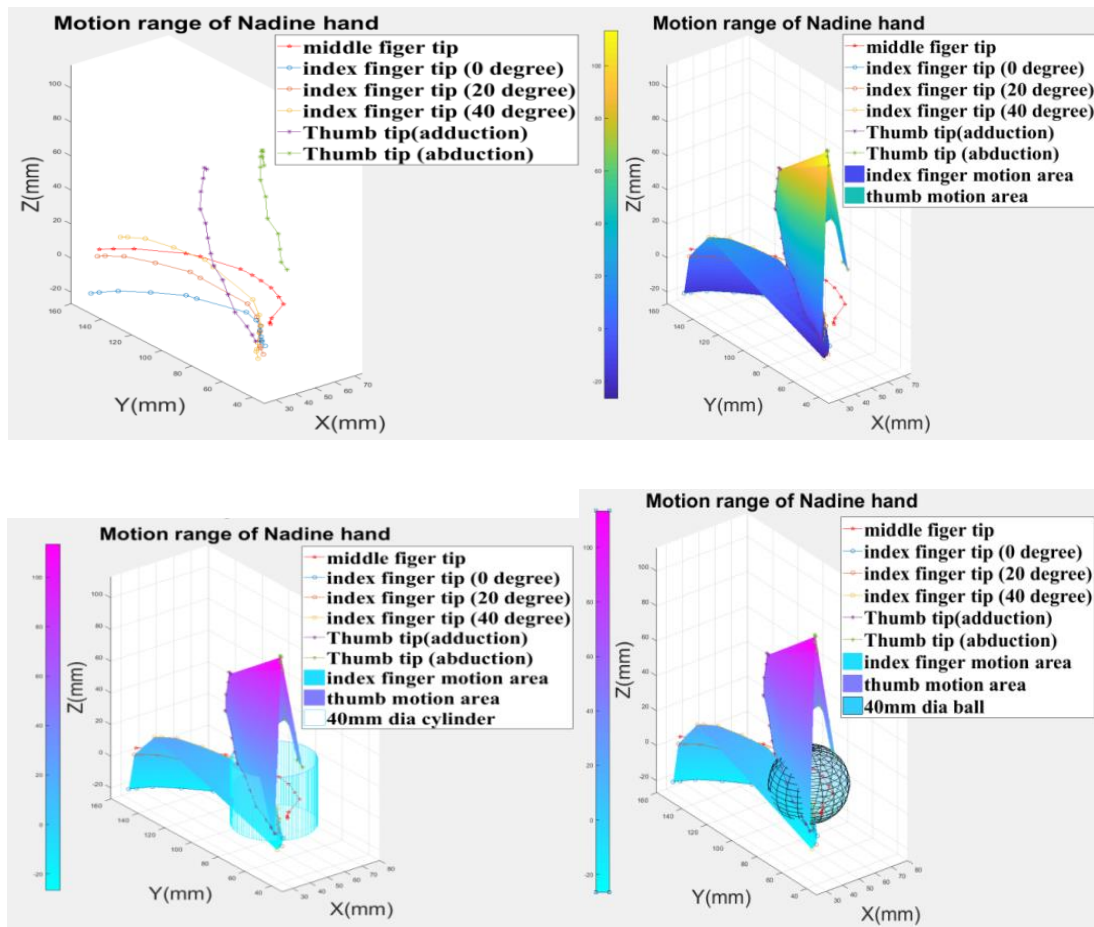


Figure 3-20 3D Trajectories and estimated working space

3.5.6 Dimension-reduction and data fitting

From the above 3D drawing, a 40 mm dimension object can be placed in a suitable position that touches all trajectories of these three fingers simultaneously. However, it is complex to calculate the precise position of the target and how the three fingers need to move to form the Tripod gestures. The test data of grasping objects within 10-60mm cross-section dimension concludes that the difference of three fingers in the X-axis is smaller than 13mm. The proposed method reduces the X-dimension with the condition of

objects' height of more than 20mm. Figure 3-21 shows that all trajectories are linear or close to polynomial. With the help of the curve fitting function in MatLab™, a degree-3 polynomial curve is generated to represent the trajectory of the Index finger. From the below Figure 3-21, the root-mean-square error (RMSE) is 0.4697mm. The “curve's fitting function” is in equation (3-8). The other trajectories also can use the same method to generate the functions.

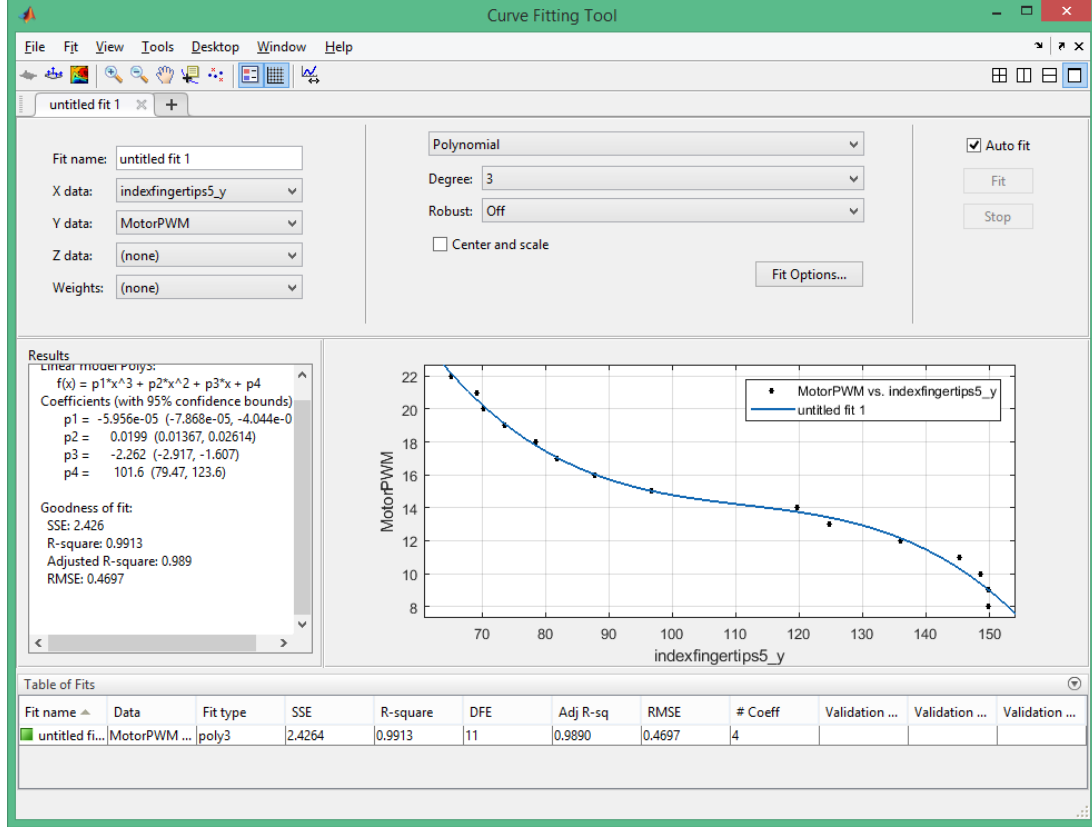


Figure 3-21 Data fitting result of the index finger

$$y = p1 \times x^3 + p2 \times x^2 + p3 \times x + p4$$

$$p1 = -5.956e-05; p2 = 0.0199; p3 = -2.262; p4 = 101.6; \quad (3-8)$$

3.5.7 Grasping plan for tripod gesture

For grasping an object using the Tripod grasp gesture, the proposed method assumes the hand or the target can move to the ideal position for grasp. In the case of a 40mm diameter ball, the ideal position is 106mm high (Y-axis) from the original point of the robotic hand. This value is got from the result of natural human hand grasping. As the width of the middle finger's distal is 14mm, the touchpoint of the middle finger is (7,106). Then calculated the other two expected touchpoints based on Tripod grasp's definition, which is located at (47,106) and (27,126). The touchpoint of the index finger

is landed within the working space of the index finger. So the trajectory of the index finger can be estimated (refer to figure 3-22).

Furthermore, the PWM values are calculated based on equation (5-2). The touchpoint of the thumb is out of the working space of the thumb. So the proposed method uses the closest trajectory and calculates the PWM value.

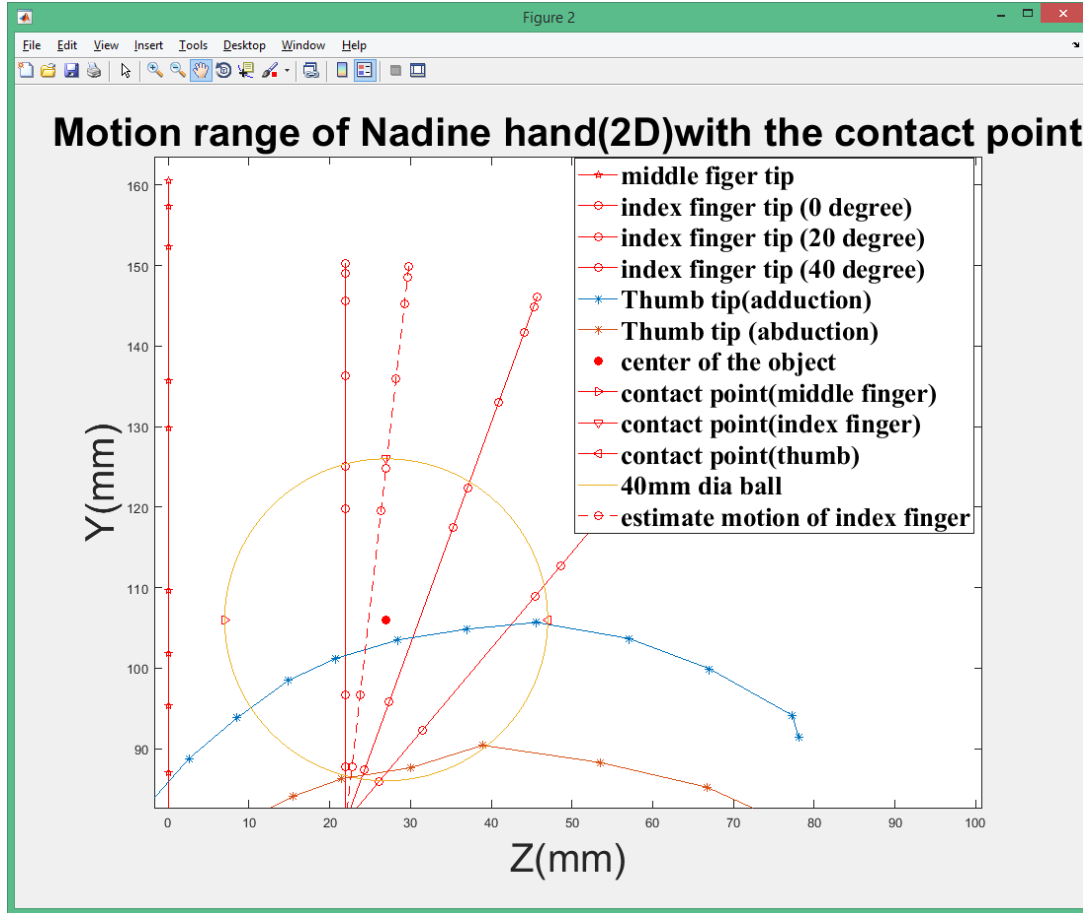


Figure 3-22 Touch point and estimation trajectory

3.6 Experiments

3.6.1 Grasping test of a customized robotic hand

With the calculated PWM values, this section tests the customized robotic hand and demonstrates that it works well with artificial skin in Figure 3-23. The customized artificial hand skin uses silicon of 0-degree hardness in 1-2mm thickness. The result shows that the proposed robotic hand and grasp plan algorithm works fine. For the Tripod grasp, the Target objects include a cylinder which 10-60 mm dimension, 40 mm cube, cone and triangular prism.

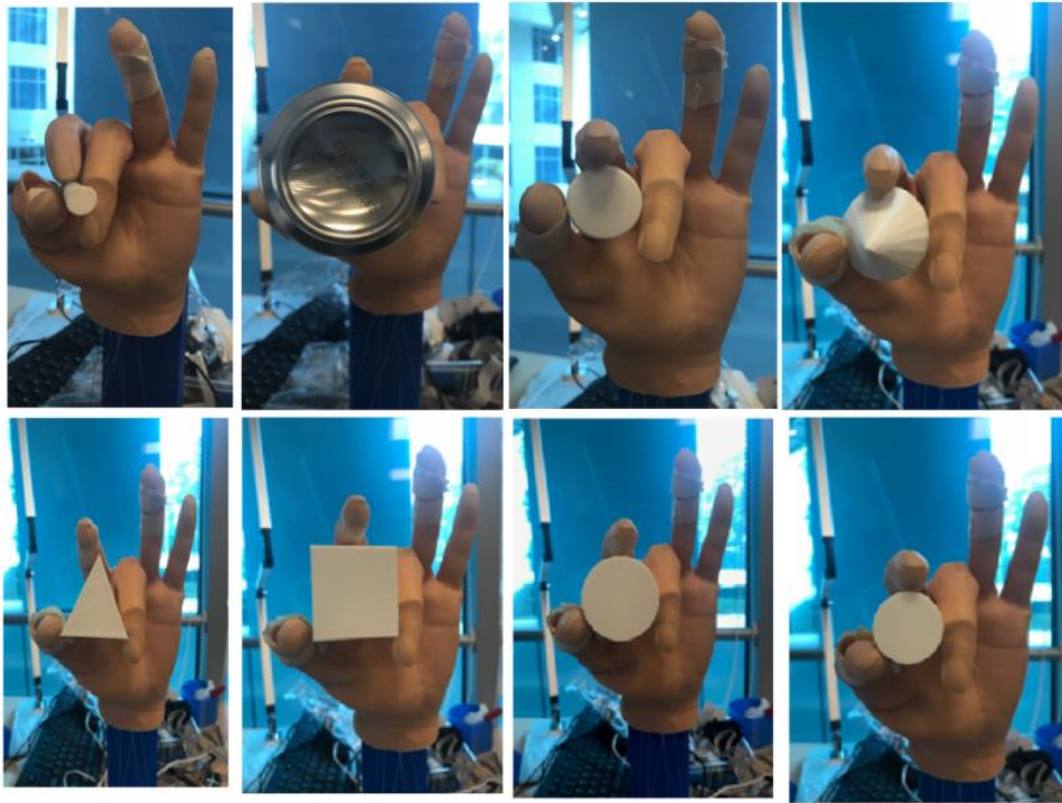


Figure 3-23 Tripod Grasp test

In Cutkosky's human hand taxonomy[17], 16 grasping types have different gestures. He divided the grasp into two significant categories, power and precision. These two categories have several sub-categories based on the geometry of the target. The “power grasp” emphasizes security and stability, whereas the “precision grasp” emphasizes dexterity and sensitivity. For all grasping tests, the tester places the target objects at a fixed position in front of the proposed robotic hand and then sends a command to control each finger to approach the target object. A few gestures were generated only after multiple trials.



Figure 3-24 Grasping test

3.6.2 Grasping test of a customized robotic hand with artificial skin

The artificial silicon skins can improve the appearance of robotic hands. With the proposed method, a robotic hand that fits the artificial skin can be quickly fabricated. It either 3D scans the artificial skin to get the primary 3D model or 3D scans the natural hand (then the output 3D model is used to make the artificial skin). In both cases, 3D printed customized robotic hand works fine with the artificial skin as they use the same base model.

This chapter tests the customized robotic hand with artificial silicon skin and demonstrates that it works well in Figure 3-25. The customized artificial hand skin uses silicon of 0-degree hardness in 1-2 mm thickness. (Video link: <https://youtu.be/7r29Z69nbiY>)

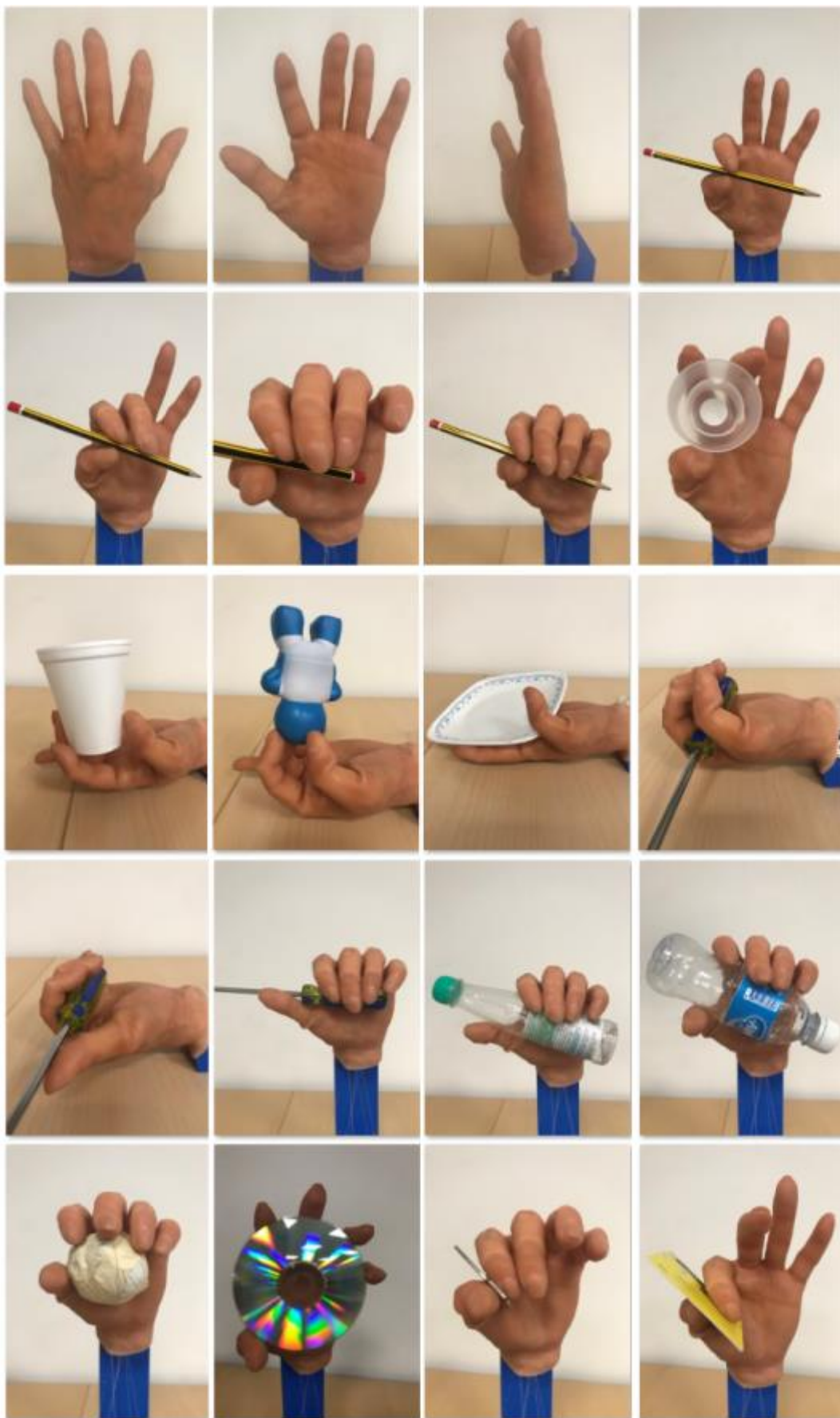


Figure 3-25 Grasping test with artificial skin

3.6.3 Grasping test of a flexible-surface robotic hand

The proposed one-cable actuation system also works fine with the flexible surface robotic hand. For all grasping tests, the tester places the target objects in front of the robotic hand at a fixed position. The control system drives the actuators and controls each finger to approach the target objects according to the 15 different postures. A few gestures are generated after multiple trials. Figure 3-26 shows that the flexible surface robotic hand capable of all 15 different postures.

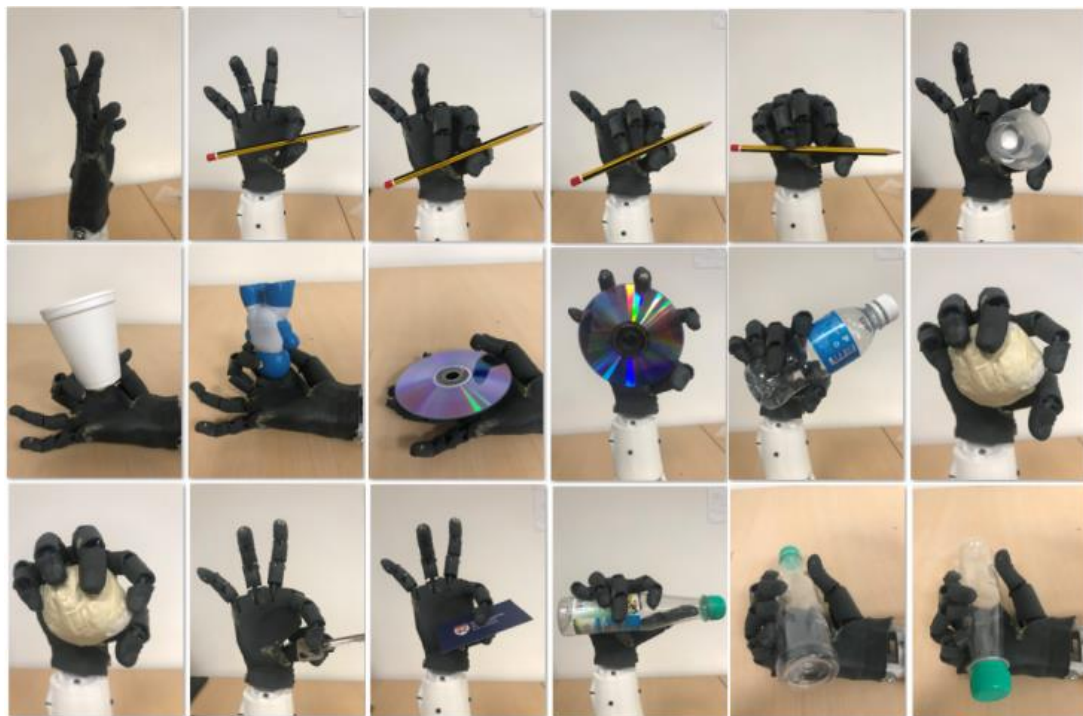


Figure 3-26 Grasping test of Soft-surface robotic hand

3.7 Summary

This chapter has described a new method to create personalized robotic hands. A hard-surface customized robotic hand and a soft-surface robotic hand are designed and fabricated to verify the method. This chapter starts with studying how the human hand functions. A method is proposed to replicate the essential features of the 3D hand model using the algorithm. The algorithm transforms a 3D scanned hand model to an articulated hand model with a similar range of motion as a human hand. The hard surface customized robotic hand has 15 joints with only a single inter-locked model, so this part of the hand is free of assembly. In the case of 3D print the hand with 1.5mm thickness, the created hand weighs only 72 grams. While soft-surface robotic hands can be 3D

printed in 16 parts and easily for assemblies. The hard-surface robotic hand and soft-surface robotic hand have six DOFs powered by six small-size actuators. The wrist joint can be customized for different robots. The experiments show that the customized hard-surface robotic hand and soft-surface robotic hand can express major grasping configurations. Compared to other robotic hands and actuated modeling methods, this chapter has provided a comprehensive procedure for automatically creating a personalized robotic hand. Refer to Figure 3-27 for the flow chart of the methodology of the proposed method.

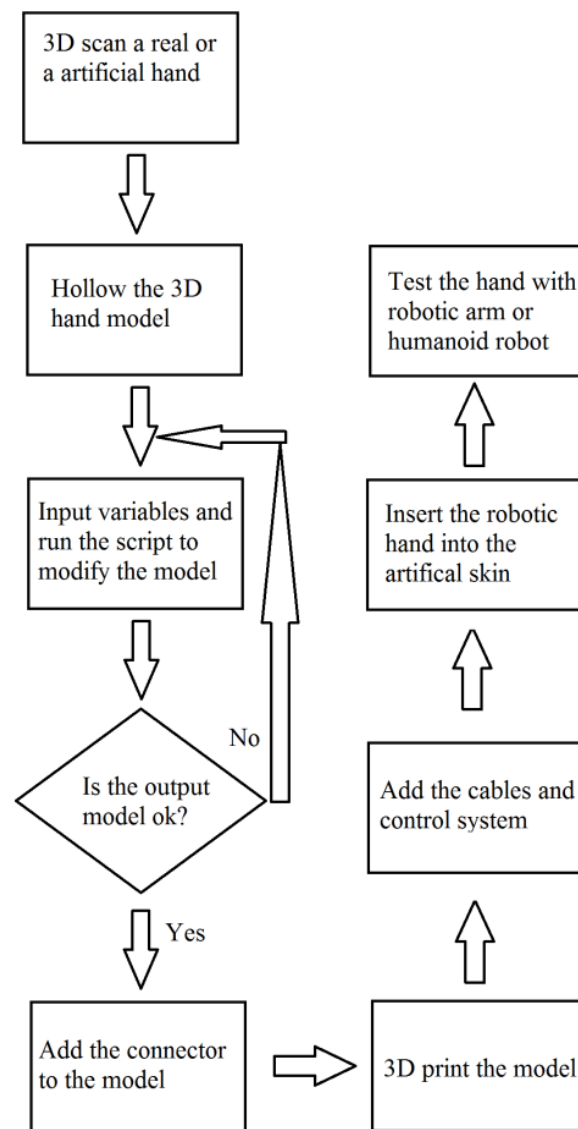


Figure 3-27 Flow chart of the Methodology

In the future, the proposed method can be improved in several ways:

- 1). Increasing the grasping force and the range of motion of the fingers.
- 2). Integrating visual recognition to its control system to achieve autonomous grasping

of objects based on visual information.

3). Improving the grasping manner to make it more natural and human-like.

Chapter 4 A Method for Design of Multi-Layer Deformable Robotic Hand

4.1 Introduction

Current research of anthropomorphic robotic hands focuses on improving their functionality by devising new mechanical structures and actuation systems. However, most of them rely on a single structure/system (e.g., bone-only or tissue-only) and ignore that the human hand is composed of multiple functional structures (e.g., skin, bones, muscles, and tendons). A single structure/system design may lower the robustness and flexibility of the hand. Besides, other factors like customization, the time and cost for production, and size and space limitation are often ignored. In order to tackle these problems, this chapter proposes a 3D printable multi-layer design that models the hand with the layers of skin, tissues, and bones. The proposed design first obtains the 3D surface model of a target hand via 3D scanning and then generates the 3D bone models from the surface model based on a fast template matching method. The tissue layer is introduced and represented by a concentric tube-based structure to overcome the disadvantage of the rigid bone layer in deformation. A parameter can explicitly control deformability. The three layers are produced by 3D printing with different materials, respectively. After that, a low-cost yet effective underactuated system is adopted to drive the fabricated hand. The proposed actuation system has 15 degrees of freedom and 6 degrees of actuation and adopts nylon cables and rubber bands to simulate tendons and ligaments. The proposed design is tested with 33 widely used object grasping types and unique objects like fragile silken tofu and tiny objects and outperforms previous designs remarkably. The multi-layer anthropomorphic robotic hand can be produced quickly with low cost and deformability with the proposed design¹¹.

¹¹ Part of the work is published in “L. Tian, J. Liu, N. M. Thalmann, D. Thalmann, and J. Zheng, "Design of a Flexible Articulated Robotic Hand for a Humanoid Robot," in 2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids), 2019: IEEE, pp. 572-577.”

Designing anthropomorphic robotic hands that mimic the general aspects of the human hand is one of the most challenging problems in robotics due to the sophisticated structure and functionality of the human hand [128]. Most current robotic hands can be roughly divided into two groups: (i) Rigid-body robotic hands (e.g., bone-based) consisting of rigid, individual structures replicating phalanges and joints as Shadow Dexterous Hand and ACB hand. (ii) Soft, tissue-like hands built using soft materials and actuators, RBO hand is the typical example [36]. In recent years, replacing rigid mechanical structures with soft materials and simplifying hand designs have been emerging research trends.

Despite the recent notable process in soft actuators and materials, object grasping and manipulations, such as the dexterous movement of objects within the hand, remain challenging [129]. The lack of actuators equivalent to human hands is an issue for applications like social and service robotics. Besides, the customization of existing robotic hands is not easy, which means many of them are built with predefined shapes and sizes instead of a target given on the fly.

In order to tackle the above issues, this chapter proposes to combine the advantages of both rigid and soft robotic hands, especially the human-like mechanism of rigid hands and the deformability of soft hands. It considers the human hand the template because its kinematics and dynamics are well studied, while the deformability provides more reliable contacts for object grasping and manipulation. Most existing methods assume that a single structure can realize the functionalities of the human hand. Such an assumption increases the complexity of the design process and limits the candidate materials for fabrication, as various mechanical structures and actuators need to be compatible and integrated. Therefore, instead of relying on a single structure, this chapter proposes a novel multi-layer design, which highly replicates the anatomy of the human hand. The proposed design is composed of three layers, namely, bone, tissue and skin, and each of them is devised for a particular purpose: the bone layer serves as the rigid, supportive structure and is attached to actuators to enable object grasping; the tissue layer is made of soft materials to guarantee the deformability of the hand; the skin layer provides the human-like appearance.

In order to ensure the proposed design can be fabricated efficiently, the proposed design exploits the advantages of 3D scanning and 3D printing in rapid and adaptable fabrication [34, 42, 55]. A fast template matching approach is proposed to obtain the 3D models of bones and a concentric tube-based structure as the 3D model of tissues.

Moreover, an underactuated system, which simplifies previous complex motion control systems [31, 130], is introduced. In section 4.4, a fully-actuation system is also proposed and tested.

Table 4-1 Comparison of human-like robotic hands

Type	Representative product	Appearance	Actuated method	Joint	Motion	Comments
Traditional Rigid	Shadow hand [26]	Mechanical Rigid	Electric Motor	Pin-joint	Turn	Rigid structure, robust
Highly biometric Rigid	Xu Zhe's robotic hand [30]	Bones based	Electric Motor	Bone-joint	Turn	Dexterity motion, No tissue, hand skin
Soft material	RBO hand [36]	Streamlined cylinder	Pneumatic/Fluidic motor	No	Curl	Soft body, Big actuation system
Soft material + Soft actuator	Yu She's robotic hand [131]	Streamlined cylinder	Soft actuator (Shape memory alloy)	No	Curl	Soft body, Small grip force
flexible surface + rigid palm bones	Nadine hand V4 [132]	hand shape	Electric Motor	Flexible pin-joint	Turn	Soft body, weak in joint structure
elastic tissue + hand bones	The proposed design	hand shape (capable with silicone skin)	Electric Motor	Bone-joint	Turn	Soft body, rigid bones

This chapter proposes the first customizable multi-layer design for anthropomorphic robotic hands to the best of the author's knowledge. The proposed design takes advantage of soft robotic hands in deformation fully. This chapter conducts extensive experiments, including the standard Feix object grasping test and the trajectory test, to demonstrate that the proposed design can effectively simulate the functionality of the human hand [116]. Due to the deformability of the proposed design, unique objects, including extremely fragile silken tofu, smooth marbles, and tiny screw caps, can be grasped by the fabricated hand. Table 4-1 summarizes the differences between the proposed design and other robotic hands.

In summary, the contributions of this chapter are threefold: 1) It proposes a multi-layer anthropomorphic robotic hand design. This design combines the stability of rigid hands (via the bone layer) and the deformability of soft hands (via the tissue layer). 2) It introduces a fast template matching method to generate customizable 3D models of bones and tissues, which reduces the cost and complexity of robotic hand fabrication. A simplified underactuated system of 15 DOFs and 6 DOAs is proposed as well. 3) The proposed tissue layer provides our robotic hand with notable deformability, validated via our robotic hand's contact models and extensive experiments.

4.2 The layer structure of a human hand

Under the skin, the human hand has a multipart structure that is combined with different human tissues. The essential elements of the structure are bones, joints, ligaments, tendons, muscles, nerves and blood vessels [94] (Figure 4-1), among which the first five play dominant roles in the dynamics of the hand. The joint serves as the linkage of the bones. It has a complex structure containing ligaments and other fine tissues. Each finger has three joints. For the middle finger, starting from the fingertips to the palm, there are Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints. The PIP and DIP joints work as two simple 1-DOF hinge joints for the extension and flexion motion. The MCP joint is similar to a 2-DOFs saddle joint giving both flexion-extension and abduction-adduction motion. Other joints have insignificant motion (less than 5 degrees) and are neglected in most hand studies [133]. The muscles are attached to and actuate bones through the tendons. From the engineering point of view, bones and joints work as a complete mechanical construction. It enables the middle finger to have 4 DOFs. The muscles and the tendons build the actuation systems, which give each joint an individual ROM. The nerves are perceptive and deliver the control signals, while the blood vessels supply the energy. For a highly biomimetic hand, the basic problem is how to mimic the hand's mechanical structure and actuation systems.

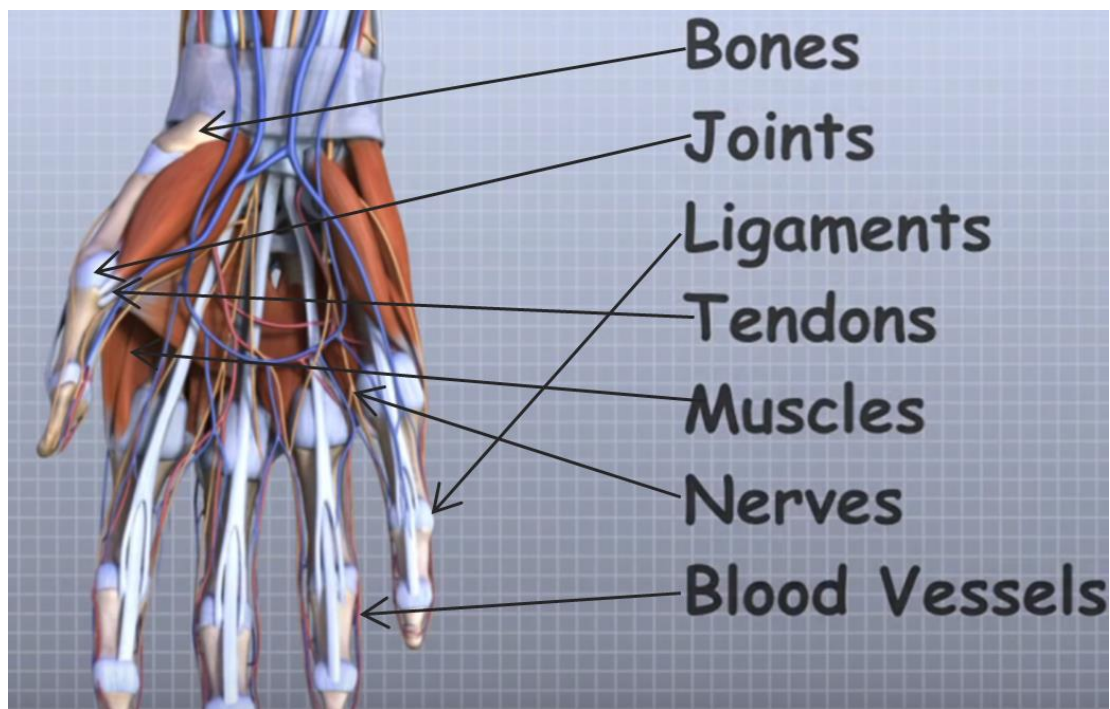


Figure 4-1 Human hand anatomy [94]

Various muscles and tendons work together to give the middle finger's three joint ranges of motion. The muscles shown in Figure 4-1 are called intrinsic muscles, while the extrinsic muscles are located at the forearm. Table 4-2 lists their names, associated joints, and the joints' ROM for the middle finger. The values of ROM are numerical values with five degrees as a step, which are obtained from previous research on the hand ROM.

Table 4-2 Joints and muscles of a middle finger

Joints	ROM (Deg.)[133, 134]	Muscles, tendons[135]
MCP	Extension 0	Extensor Digitorum Communis (EDC)
	Flexion 90	Medial Band (MB)
	Ulnar deviation 25	Dorsal Interossei (DI)
	Radial deviation 15	Palmar Interossei (PI)
		Lumbrical (LUM)
PIP	Extension 0	Central Slip (CS)
	Flexion 110	Lateral Band (LB)
		Flexor Digitorum Superficialis (FDS)
DIP	Extension 0	Terminal Extensor (TE)
	Flexion 70	Flexor Digitorum Profundus (FDP)

The top part of Figure 4-2 shows that the tendons are possibly connected to more than one bone through multiple vinculum. As a result, MCP and PIP can move independently. The motion of DIP is affected by PIP, but it is still an independent joint.

From the posterior view of Figure 4-2, the extensor expansion (hood) covers the bones like a big net. From the lateral view, the FDP and FDS tendons are connected to bones just like cables. They are tightly held in a pulley system and are combined with tendon sheaths (Refer to Figure 4-2's bottom part). The tendon sheaths play an essential role in regulating the finger's motion while holding the tendon's position.

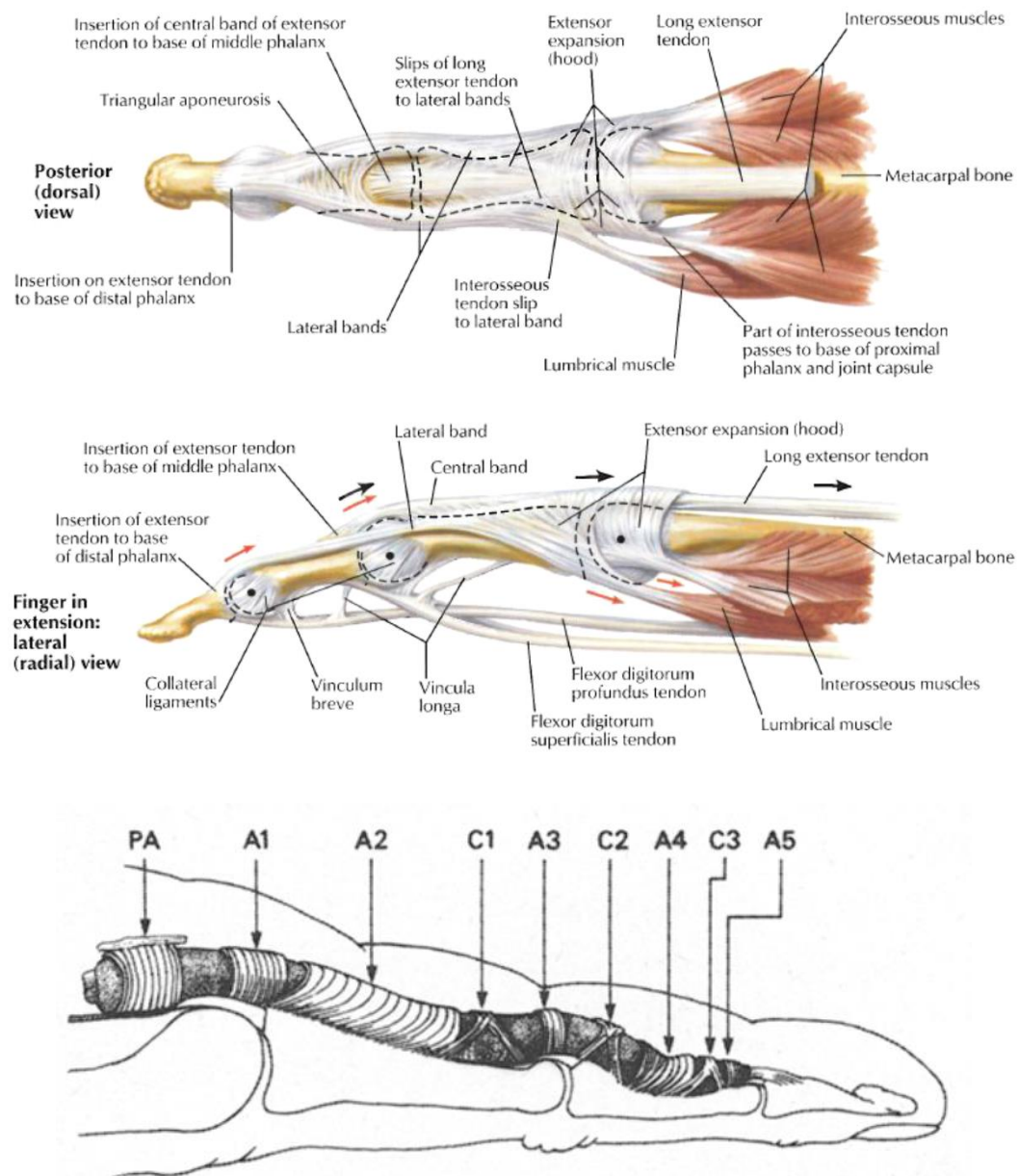


Figure 4-2 Top and middle: Finger anatomy without pulley system [104] and Bottom: the pulley systems for flexor tendon [136]

4.3 Proposed Method

4.3.1 A multi-layer deformable design

The design goals of the proposed anthropomorphic robotic hand can be specified into

two aspects: first, the modeling process of the robotic hands should be fast and customizable so that it can fabricate hands of various shapes and sizes quickly; second, the proposed robotic hands should have the similar functionality of the human hand, especially in completing different grasping gestures. To this end, this chapter proposes a multi-layer deformable design of anthropomorphic robotic hands, which mainly consists of (i) a layer of silicone skin, (ii) a layer of 3D printed tissues and (iii) a layer of 3D printed bones.

Specifically, given a natural human hand as the target, the proposed method obtains its surface model via a 3D scanner. The skin layer could be de-molded directly from the target hand to mimic the appearance of the target hand. The method also proposes a fast template matching method to obtain the corresponding 3D bone models based on the surface model. After that, an effective concentric tube structure is adopted to construct the tissue layer. The tissue layer serves as the intermediate layer between the skin and bones and is made of elastic materials to allow the high deformability of our robotic hands. In section 4.5, the proposed design adopts a low-cost cable-driven system to provide the robotic hands with mobility and stability. Compared with conventional single-layer/structure robotic hands, the proposed multilayer design is more similar to human hands from biomimetics. More importantly, as demonstrated in the experiment section, such a deformable design is versatile for grasping objects of different shapes, textures and materials.

4.3.2 Materials

For easy customization and fabrication, all materials used in this method are low-cost and widely accessible. Based on Young's modulus, [34] this method considers two 3D printing materials with the desirable tensile strength and compatible with the Form-2 3D printer. The bone models use rs-f2-gpcl-04, which is a rigid material and has 2.8 GPa tensile strength. The tissue layer uses an elastic 3D printable material, rs-f2-elcl-01, with 50A shore hardness and 3.23 MPa tensile strength. The skin layer is silicone rubber, and it chooses PlatSil Gel 10 with 10A shore hardness.

As to the actuation system, it uses rubber bands as ligaments to connect bones. Nylon cables of 0.3 mm diameter and 44.5 N average breaking force are used as tendons. Figure 4-3 demonstrates a fabricated robotic hand's significant materials and components based on the proposed design.



Figure 4-3 The proposed robotic hand consists of 4 materials: 3D printed bones, 3D printed elastic tissues, nylon cable and rubber band.

4.3.3 3D modeling of bones

Modeling bones is the necessary procedure of customizing a highly biomimetic robotic hand because it provides the basic structure of the hand and the perfect guide for hand motions. However, the direct modeling of bones is intricate, as they are hidden beneath the skin. Radiology methods, such as computed tomography and magnetic resonance imaging, are costly for customized fabrication. Therefore, the method proposes to first obtain the surface model of the target hand via 3D scanning and then generate the 3D mesh models of bones based on the fast template matching method.

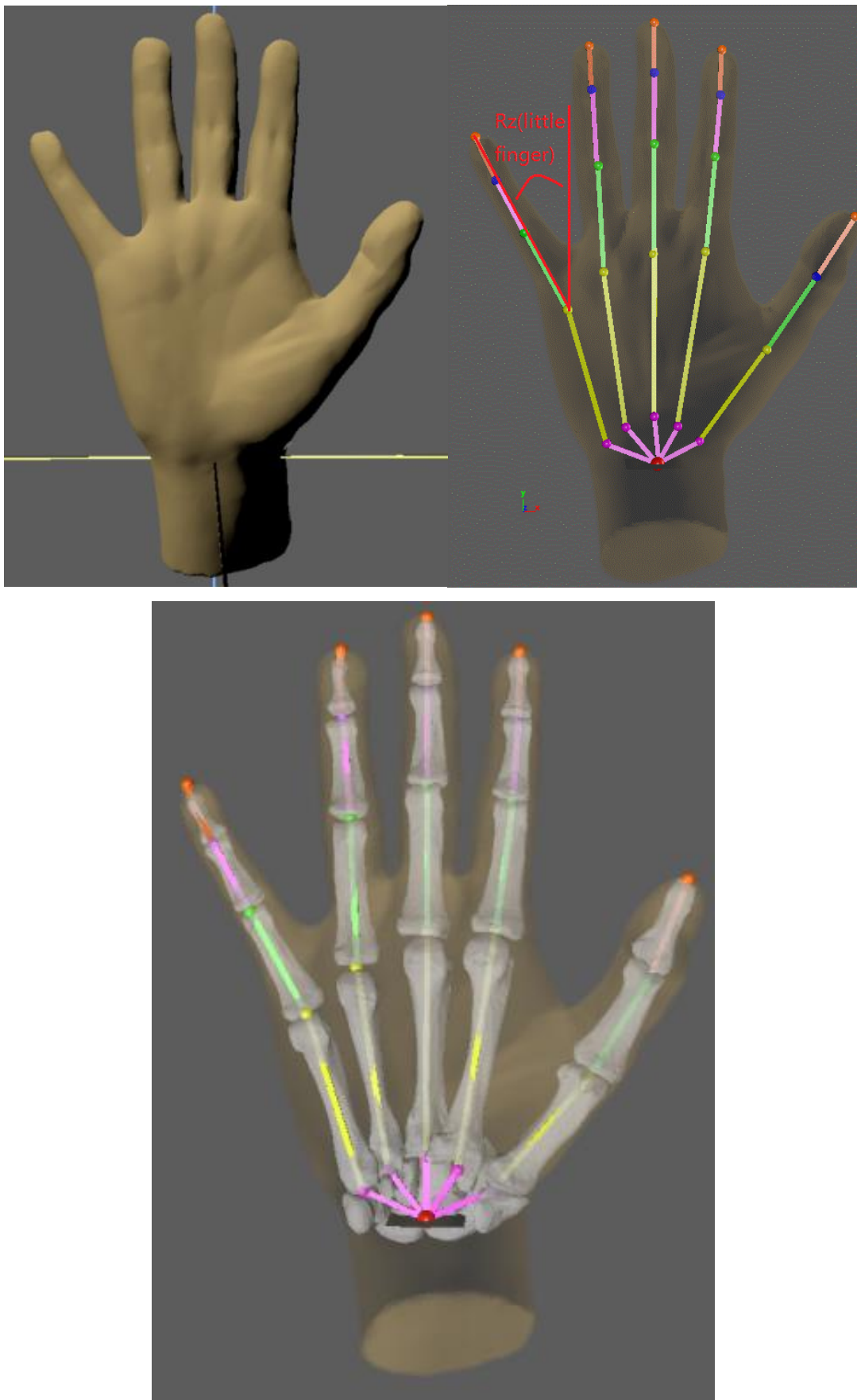


Figure 4-4(Up left) hand 3D model acquired through 3D scanning (Up right) 25 landmarks and 24 segments (Bottom) Bones 3D model

3D scanning provides faster and more accurate modeling than traditional modeling techniques [101]. The first robotic hand design in chapter 3 also demonstrates that it is possible to maintain more than 90% of the geometric information of a human hand via 3D scanning. Thus, given a target hand, the method scans it with the “Go! Scan 50” 3D scanner to obtain the corresponding triangle mesh-based 3D model. As shown in Figures 4-4, the scanned 3D model is a vivid and precise representation of the surface of the target. (Red dot: Original point, Purple dot: carpometacarpal (CMC) joint, Yellow dot: metacarpophalangeal joints (MCP), Green dot: proximal interphalangeal joints (PIP), Blue dot: distal interphalangeal joints, Orange dot: fingertip)

Next, this chapter proposes to estimate a series of geometric transformations to match a template of 3D bone models to the surface model. It places landmarks on the surface model to determine the positions, orientations and sizes of bones. As the bones have relatively fixed proportions and connections [105, 106], this method adjusts the surface model to make it be symmetric w.r.t. the xy-plane (Figure 4-4). So that the z coordinates can be ignored, and this method can use 2D landmarks to reduce the complexity of labeling and computation. Based on the anatomy of the human hand, 25 landmarks are used in total, as shown in Figures 4-4. In this way, each bone is uniquely determined by two landmarks, and this method can construct a local 2D coordinate system for each bone, in which one of the landmarks is considered the origin. At the same time, the other one is used as a reference to estimate the transformations. That is, let P denote the point set of one of the template bone models, and $p = [p_x, p_y]^T \in P$ be an arbitrary point, the corresponding coordinates of p in the local coordinate system of the customized bone model, p' , is calculated as follows:

$$p' = R(\theta)S(\lambda)p, \quad (4-1)$$

where $R(\theta)$ is the rotation matrix parametrized by θ , the counterclockwise angle of rotation w.r.t. the x-axis:

$$R(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \quad (4-2)$$

Furthermore, $S(\lambda)$ is the uniform scaling matrix with the scaling factor λ :

$$S(\lambda) = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \quad (4-3)$$

The reference landmark can determine θ and λ . Let r' and r denote the reference

landmark in the customized and the template local coordinate system, respectively. For θ , this method estimates it via the inverse trigonometric functions like arcsine, while for λ , the method considers $\lambda = \frac{\|r'\|^2}{\|r\|^2}$, where $\|\cdot\|_2$ is the 2-norm.

Before 3D printing the bones, this method also put holes at their ends to easily connect the bones with rubber bands (as ligaments). Unlike the previous method requiring specific transformations for different landmarks, the above matching process can be applied to all 3D bone models of the template to generate the customized models. This matching process significantly improves the efficiency of producing customized robotic hands, as the only manual operation is to locate the 2D landmarks, which can be completed within a few minutes.

4.3.4 3D modeling of tissue

The tissue layer is critical to the anthropomorphic hands, as it helps overcome the disadvantages of rigid, bone-only hands in object grasping. From the anatomical perspective, the soft tissues surrounding the fingers are of complex types and structures, such as subcutaneous fat and muscles. Hence, the core of modeling the tissue layer is to design a unified representational structure, which is 3D printable and deformable.

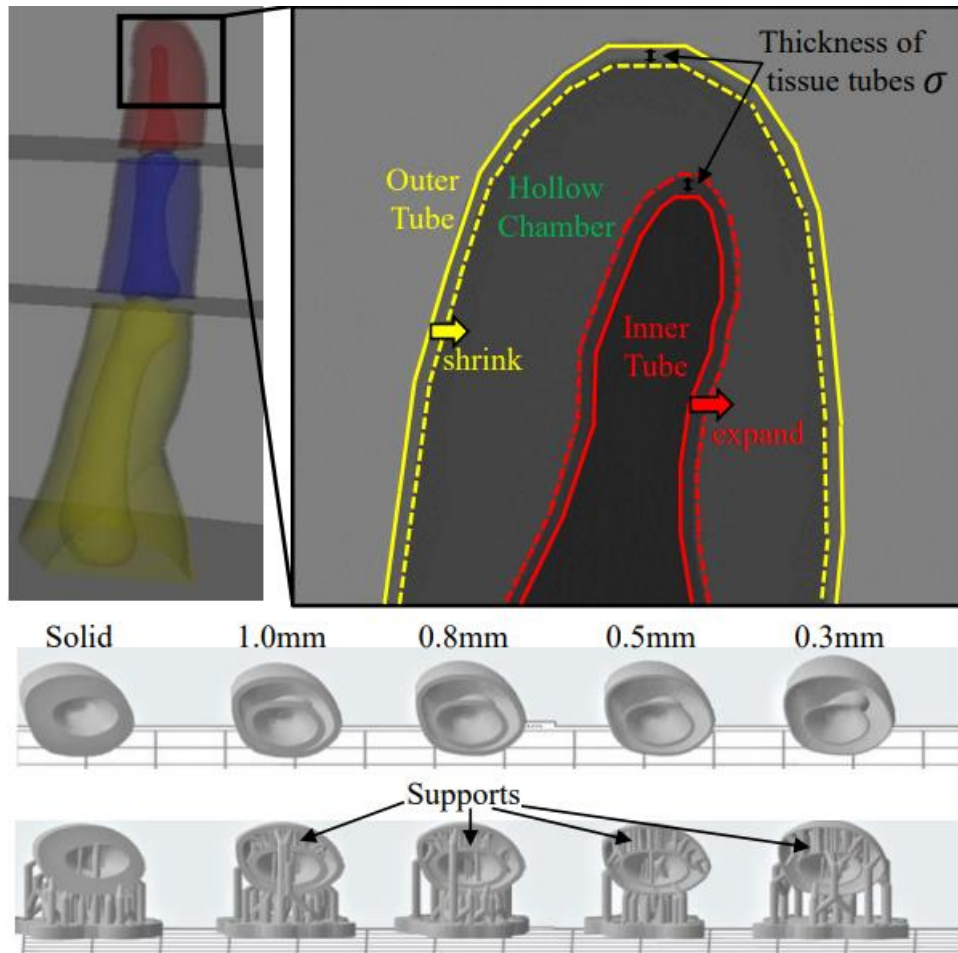


Figure 4-5 Top: Modeling the tissue layer as a concentric tube structure. Middle: Demonstration of tissue tubes with different thicknesses. Bottom: Supports for stabilizing the structure.

The proposed method for the tissue modeling problem is a novel concentric tube structure, which is constructed via the following three steps: (i) Hull generation. As the tissue layer cannot be scanned and modeled directly, it proposes to generate a 3D hull to determine the surfaces of the tissue layer. Note that the method already obtains the 3D mesh models of the surface and bones via the fast template matching method. Therefore, it considers the surface model as the outer hull, while the bone model as the inner hull, as demonstrated in figure 4-5. The proposed method shrinks the surface model (marked with the yellow solid curve) while expanding the bone layer (marked with the solid red curve) to obtain the two tubes of the tissue layer. These steps allow the method to have a basic structure to model and 3D print the tissue layer. (ii) Structure hollowing. This step aims at providing the basic structure with deformability. Although the material used for the tissue layer (RS-F2-ELCL-01) is a common choice for soft structures, it is much more complex than the finger tissues. Therefore, instead of using a solid structure, this method hollows the tissue layer model and adds supports to obtain

a more elastic tube-shaped structure. Any support structure could be used, and the proposed method uses the default one provided by the Form-2 3D printer. The choice also brings a side benefit that can reduce the cost of 3D printing materials, e.g., the solid design of the tissue surrounding the distal phalanx of the index finger requires about 2.9 ml material. In contrast, the hollow one only requires about 1.4 ml. (iii) Deformation curve fitting. This method further introduces an extra parameter σ , i.e., the thickness of the tissue tube, to control the deformation modulus of the tissue layer. The step is feasible as the larger σ is, the harder it is to deform the tissue layer. Moreover, the 3D tissue model with the thickness of σ can be generated easily by shrinking the outer hull by σ while expanding the inner hull by σ as well. In this way, the tissue layer is modeled by two concentric tubes, as demonstrated in Figures 4-5. In order to determine the optimal value of σ , this method records the curves of regular forces and contact surfaces with different values of σ . It sets σ as the one with the curve being closest to that of the human finger.

4.3.5 Deformation and contact model

Due to the deformability of the tissue layer, objects of various sizes can be grasped with different gestures. In this case, it is insufficient to describe the contact-mechanics model of the proposed hand merely based on a single model. In order to tackle this problem, the proposed method proposes to categorize the contacts with objects into two types based on the sizes of objects. Specifically, for grasping an object with a standard size, multiple contact surfaces may be generated. Each of them can be described with a nonlinear elastic model; While for a tiny object, because the finger can enclose the object, a cage-based model is more suitable.

The nonlinear elastic surface model is proposed by Xydas et al. [137, 138], which extends the Hertzian model for describing the contact surface of a soft finger as follows:

$$a = cF^{n/(2n+1)} \quad (4-4)$$

where c is a constant determined by the properties of the fingertip, such as the material and shape. F is the normal force pressing on the fingertip, n is the strain hardening exponent of the material, and a is the radius of the contact surface, which is assumed to be circular. However, observe from experiments that, most contact surfaces of the proposed design are more like ellipses than standard circles. Therefore, the proposed method approximates the contact surface with an unrotated ellipse and applies Eq. (4-4)

along its horizontal and vertical axis. That is, let x and y denote the horizontal axis and the vertical axis of the ellipse, and b be the abbreviation of n , the proposed method records a_x and a_y with respect to various F , where $a_x = 1/2\|x\|_2$ and $a_y = 1/2\|y\|_2$, to estimate c_x , b_x and c_y and b_y . The experimental results validate that this nonlinear elastic model depicts the contact model of the robotic hand well: for $F = [0, 4]$ and $\sigma = 0.4$, the estimated $a_x = 4.2960$, $b_x = 0.3497$, $a_y = 5.776$, and $b_y = 0.2203$, with the coefficient of determination (R^2) > 0.94 .

As to tiny objects, such as an M1 screw cap with a head diameter of 2 mm, they are far smaller than the contact surfaces generated with normal-sized objects. Object grasping, in this case, can be considered as forming an inescapable cage surrounding the target object, and current two-finger/multi-finger caging theories [139], [140] can be adopted for analysis. Remarkably, the proposed robotic hand forms a squeezing cage [141] that the object is grasped and remains caged when the fingers move closer towards the object. Furthermore, there is an exciting activity that can be completed by the robotic hand and yet has not been studied in previous caging methods: the proposed robotic hand can “press and pick up” a tiny object with the tip of a single finger. This result is due to the tissue layer's weak adhesive 3D printing material and the friction provided by the contact cage generated by the deformation of the fingertip.

4.3.6 Algorithm for automatic 3D modeling of the robotic hand

The above progress from 3D scanned hand model to generate 3D printable parts is done by Python script with CAD software (Maya™) without manual work [85, 132]. The proposed script code saves a lot of manually 3D modeling time and proves a precise and duplicable solution for any size of input hand 3D model.

Algorithm 4-1: Generate the 3D model for hand bones and tissues

Input: 3D hand model, primitive 3D hand bones, artificial layer thickness

Output: 3D hand bones model, 3D artificial layer

While next layer exist

While next joint exist

 Estimate the joint position (If necessary, manually adjust joint)

 Scale and move the bone

End

End

Extrude the 3D hand model inwards by input thickness

Foreach finger

 Extrude finger bones outwards by input thickness

 Cut the finger into 3 segments

 Add joint and pulley structure to bones

End

This chapter compares the script code running time and the manually 3D modeling time obtained from five junior researchers' average values. (Refer to table 4-3)

Table 4-3 Comparison of 3D modeling time

Action	Placing bones	3D modeling the joints	Modeling tissues
Manually	3 hours	2 hours	5 hours
By Script	15 seconds	20 second	20 seconds

4.4 Experiments with a fully actuated actuation system

Overview

In order to fabricate a humanoid robotic hand that can achieve the motions of a natural human hand, one solution is to simulate all DOFs of the human hand with an anthropomorphic robotic hand. This section presents an actuation system for a fully actuated robotic finger. It takes the middle finger as an example (Figure 4-6). This section proposes to use a simple and highly biomimetic design method to realize the essential motion functions of the hand. This design aims to replicate dynamic characters of the human finger in terms of the DOFs, the ranges of motion (ROM) and the movement speed. The method focuses on bones, joints and actuation systems, which play an essential role in the dynamics of fingers. The main contributions of the section lie in the template-based modeling for generating personalized finger bone models. Furthermore, this section proposed a “3 layer cascade cable-driven system” for the pulley systems, which achieves the full actuation¹².

¹² Part of this work is published in “L. Tian, N. M. Thalmann, J. Zheng, and D. Thalmann, "Design of a Highly Biomimetic and Fully-Actuated Robotic Finger," in 2019 IEEE Symposium Series on Computational Intelligence (SSCI), 2019: IEEE, pp. 2382-2387.”.



Figure 4-6 Fully actuated robotic hand's middle finger

4.4.1 Mechanism of the fully-actuation system

It can be seen from figure 4-7 that the finger joint is made of bones, ligaments, bursa, synovial cavity, joint capsule and synovial lining. Previous work did a unique and complex design to simulate the bones structure using crochet and gimbal [136]. Recently, [6] presented a robotic finger that uses a few pieces of silicon to represent the ligaments of the joints.

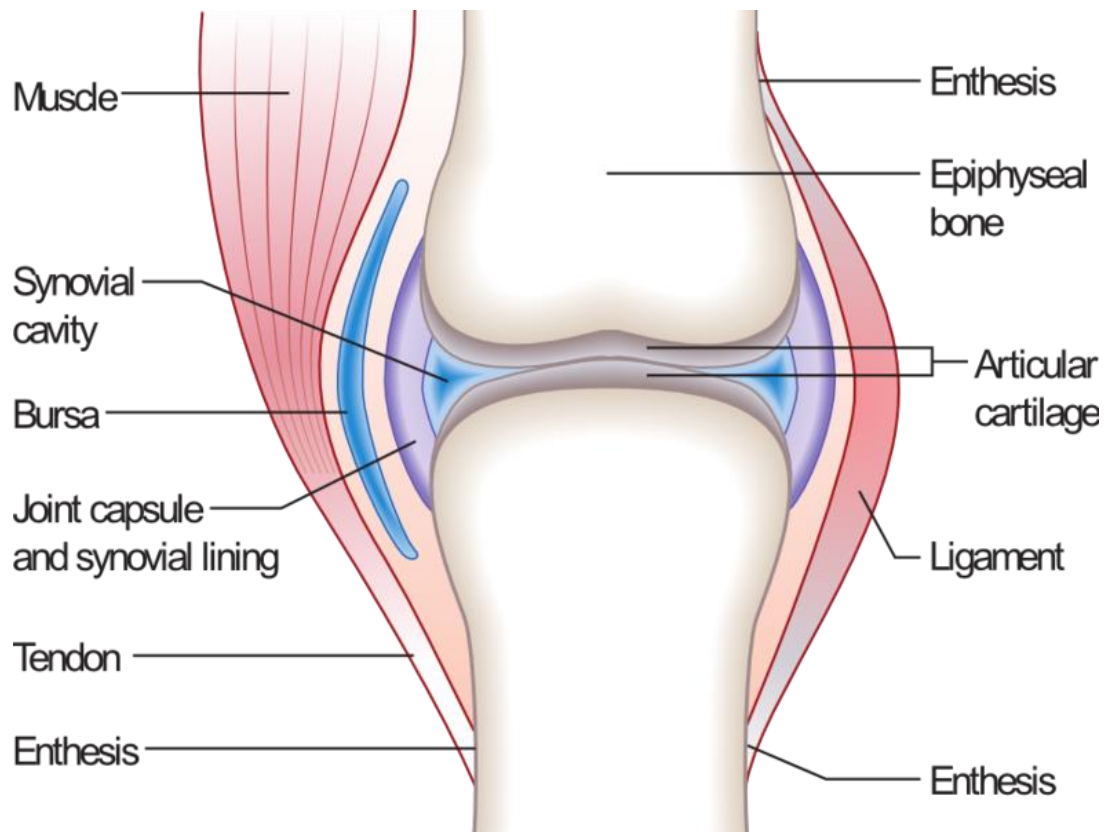


Figure 4-7 A typical Joint (Image source: Madhero88/Wikipedia)

It is difficult to mimic all tissues and tendons of the joint. The proposed method designs the finger joint with three aims: (1) the joint can support the human-like ROM when an external force drives it; (2). The friction is low and acceptable, and (3) the joint is simple and easy to make. So, it uses 1-3mm thickness silicon rubber of rectangular shape to link the joints. The silicon rubber can be inserted through the holes on the bones and fixed by instant adhesive. The silicon is elastic, and it gives a support force to the upper bones, thus reducing the contact surface friction when the finger is moving (Figure 4-8).

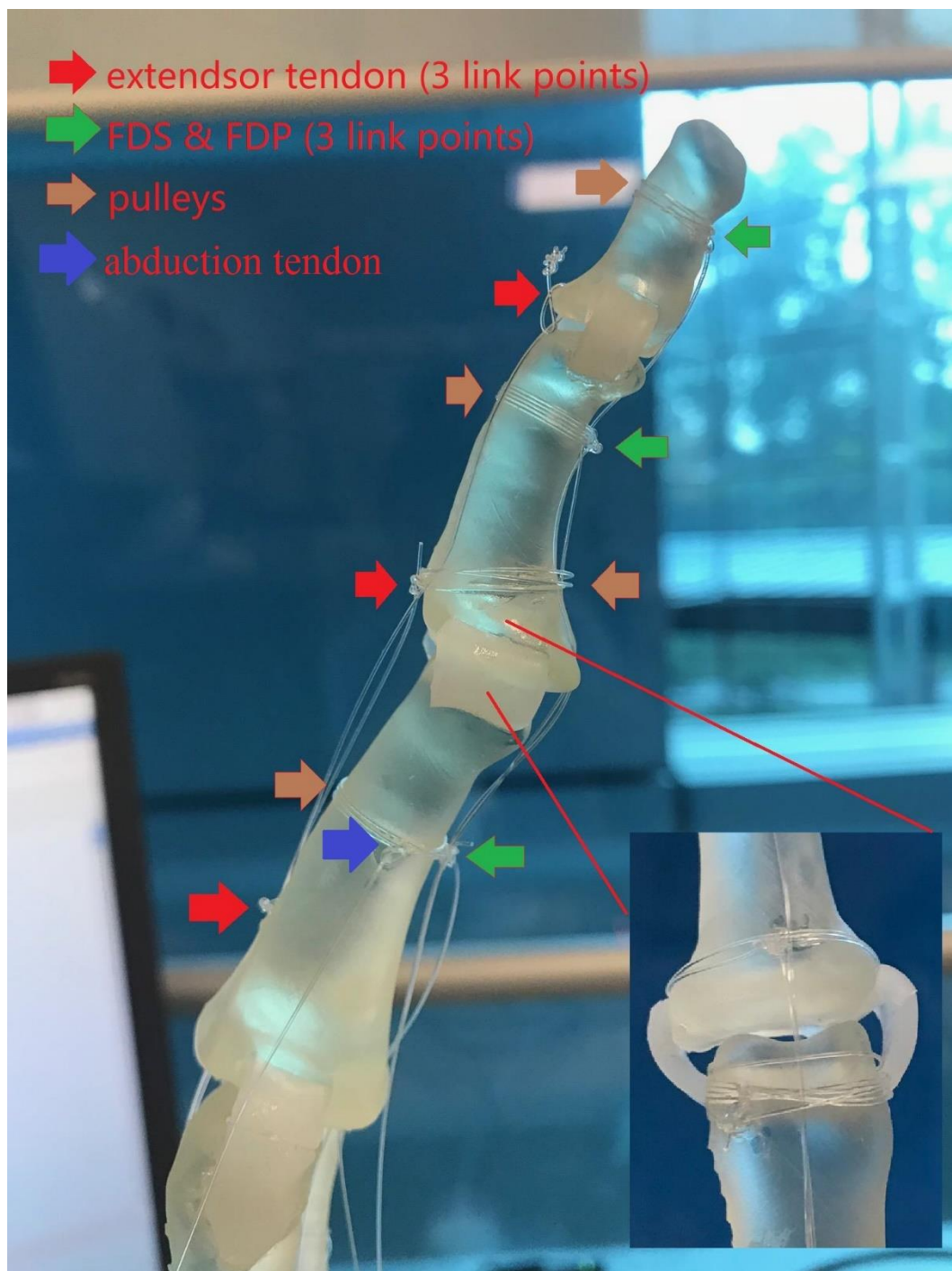


Figure 4-8 Tendons and joints of the finger

Ligaments are made of collagen and provide mobility and stability to the hand. Silicone rubber and laser-cut soft tissue are commonly used for making artificial ligaments. In order to reduce the complexity and cost, this section provides a method that uses a 0.3 mm diameter, 10 lbs Nylon fishing line as the tendon. It uses vertical holes through the bones and line windings as pulley systems to lead and control the tendons.

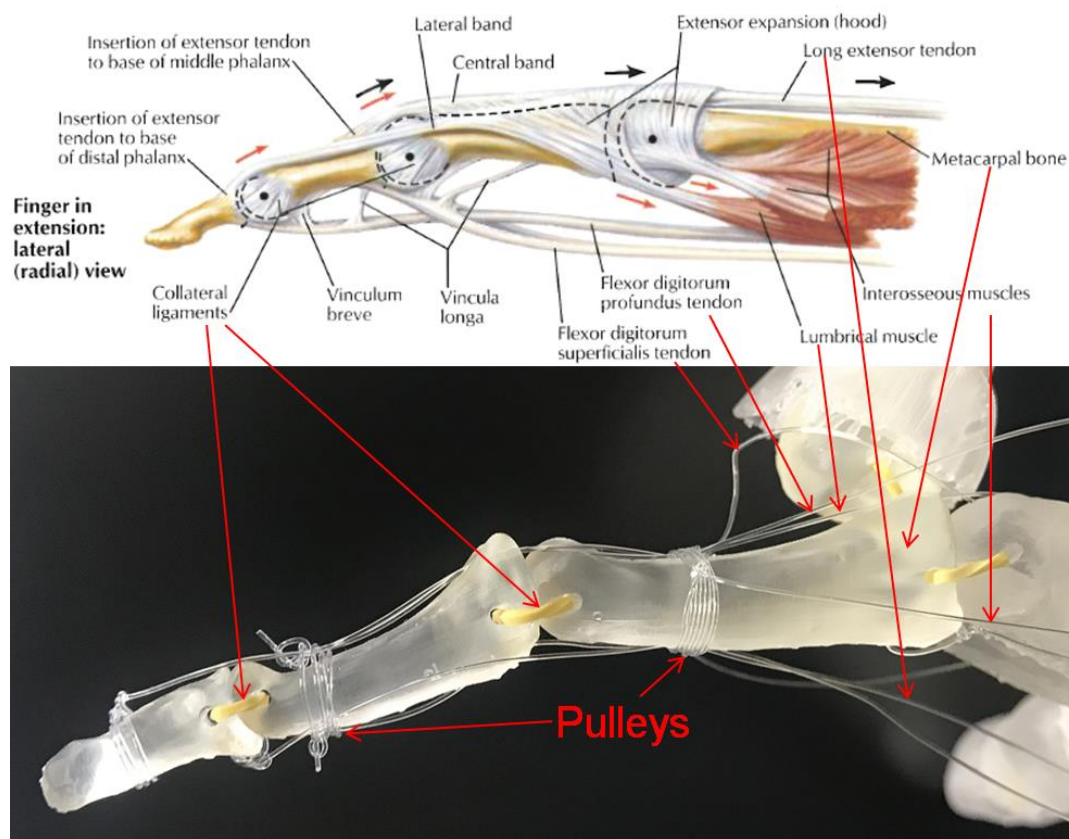


Figure 4-9 Bionic design of the robotic hand

Each finger except the thumb can be fully driven by a 3-layer cascade cable-driven system with eight driven cables and four actuators.

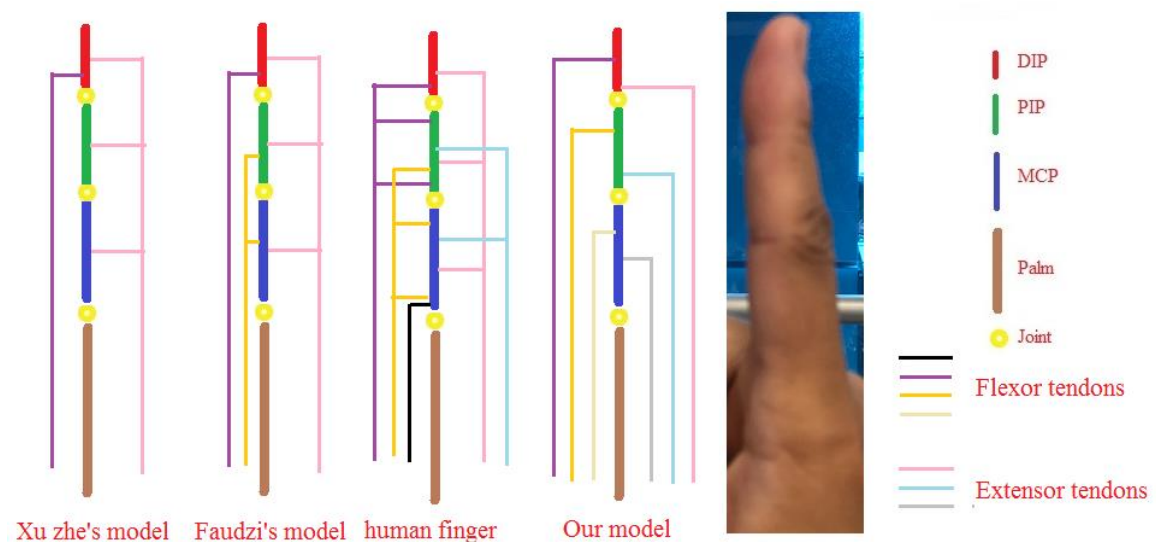


Figure 4-10 Comparison of finger actuation systems

A human finger can be modeled as five main tendons with 12 link points to the bones for the flexion/extension move. This section proposed a new design that simplifies it to a “3 layer cascade cable-driven system” controlled by six cables (Figure 4-10). It uses

0.3mm diameter, 10 lbs Nylon as the robotic finger's tendon, and twines the cable to the bones to simulate the pulley system (brown arrow in Figure 4-8). In order to achieve all four DOFs of the middle finger, the design uses three driven cables to simulate the FDS and FDP tendons for the flexion motion. These three cables are tied to three twined cables (green arrow in Figure 4-8). Another set of three cables are used to simulate the extensor tendon for the extension motion (red arrow in Figure 4-8). Concerning the position of the natural tendon to the bones (Refer to Figure 4-9), 1mm diameter holes are drilled in the 3D model for holding these three cables. Another two cables are used to simulate the abduction and adduction motion (blue arrow in figure 4-10). All cables go through under the pulley system's twined cables. The other side of the cables is tied to the horn of the motors.

In Figure 4-11, three servos are used to control the flexion and extension of MCP, PIP and DIP joints. Another servo is used to control the adduction and abduction (AD/AB) finger's move.

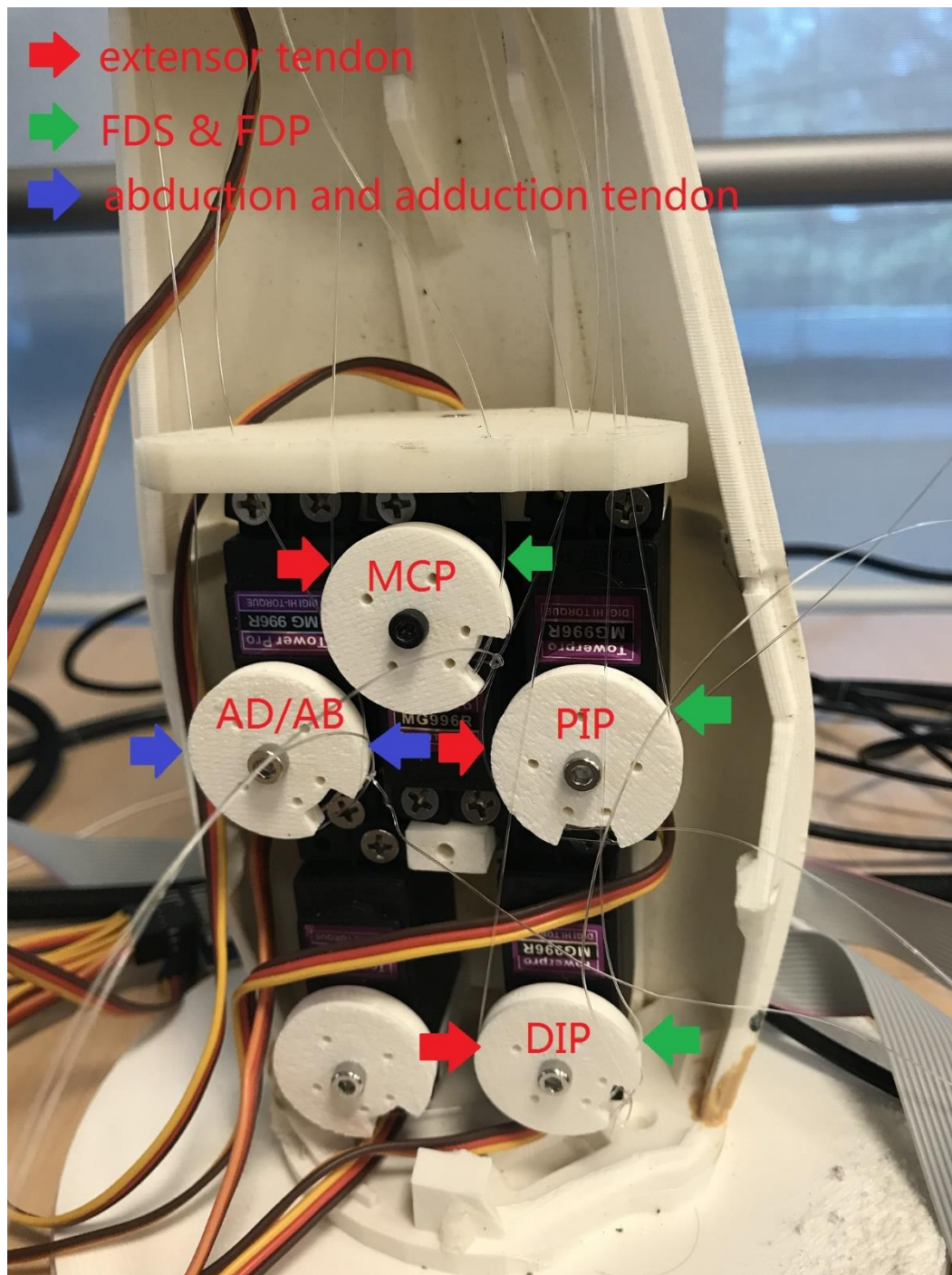


Figure 4-11 Motors and servo bed

4.4.2 Motion control

Based on Landsmeer's model III [142], the basic equation for modeling the tendon displacement (L) can be simplified to a second-order polynomial approximation[143]:

$$L = (b+h\theta) \theta \quad (4-5)$$

where b and h are constants determined by the mechanical system, and θ is the corresponding angle rotation.

The proposed method adapts the basic equation for the “3-layer cascade cable driven system”:

$$L_{pro} = (b_1 + h_1 \theta_{pro}) \theta_{pro}$$

$$L_{int} - L_{pro} = (b_2 + h_2 \theta_{pro}) \theta_{int}$$

$$L_{dis} - L_{int} - L_{pro} = (b_3 + h_3 \theta_{pro}) \theta_{dis} \quad (4-6)$$

L_{dis} , L_{int} and L_{pro} are three displacements of three flexor tendons for rotating distal, intermediate and proximal phalanges, respectively.

Figure 4-12 shows the actuator's force F_{dip+} applies to all three phalanges of the finger to create F_{dis} , F_{int} and F_{pro} . F_{dis} rotates the DIP joint and thus changes the pose of the finger. The proposed method uses two more forces from the driven cables F_{MCP-} and F_{PIP-} to offset F_{int} and F_{pro} and create the balance for pose 2. This method works similarly to the human tendon system in terms of the cooperation of actuators and stoppers [94].

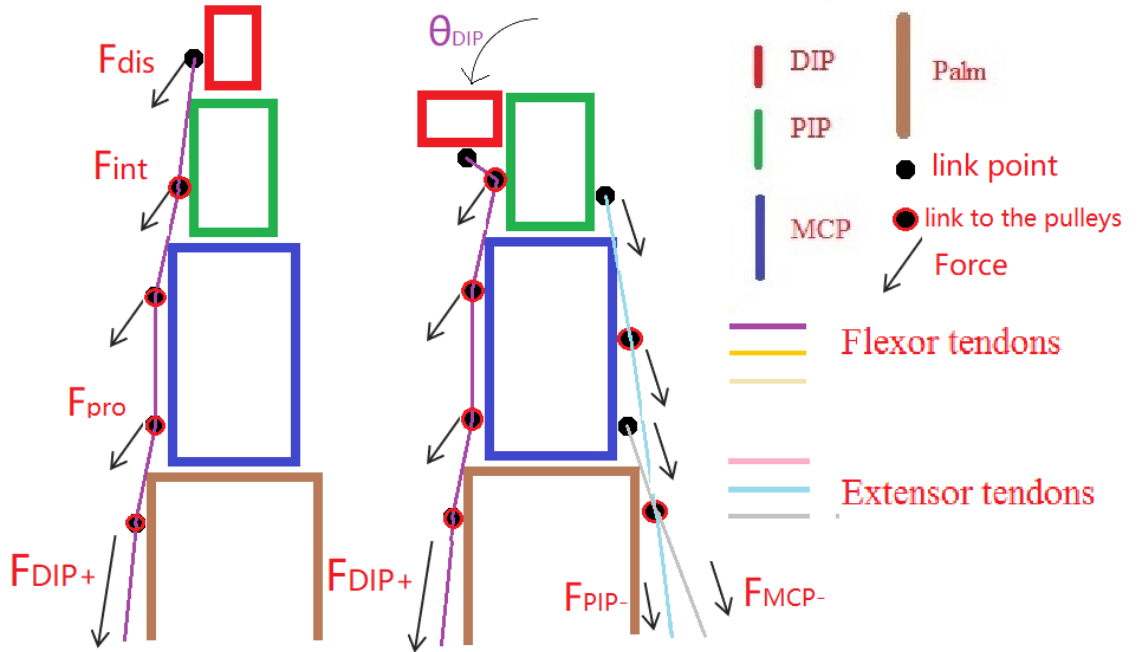


Figure 4-12 Dynamic of our robotic finger (bent the DIP)

4.4.3 Performance evaluation

In order to test the functionality, including the extreme motions, this section primarily

uses nine finger postures to test the flexion and extension motion and two more finger postures to test abduction and adduction motion (Figure 4-13). Pose 1 is vertical, where all three joints have no flexion. Poses 2 - 8 are the different combinations of the joint's flexion. This section introduces pose 9 to mimic the finger in the relaxed situation. It chooses 90 degrees as the standard rotation unit as it is close to the natural hand and easy for calculation. Poses 10 and 11 show the adduction and abduction of the finger.

For the human hand, when the finger is in extreme poses such as pose one and poses eight, it can feel that the tendons are oppositely pulling the fingers to restore to pose nine. From the hand anatomy [94], each finger pose is a balanced result of multiple tendons and vinculum. In order to reproduce these poses, this section uses one dimension control (pull/release) of eight driven cables in different combinations. (Video link: <https://youtu.be/kMEjhcXsOf8>)

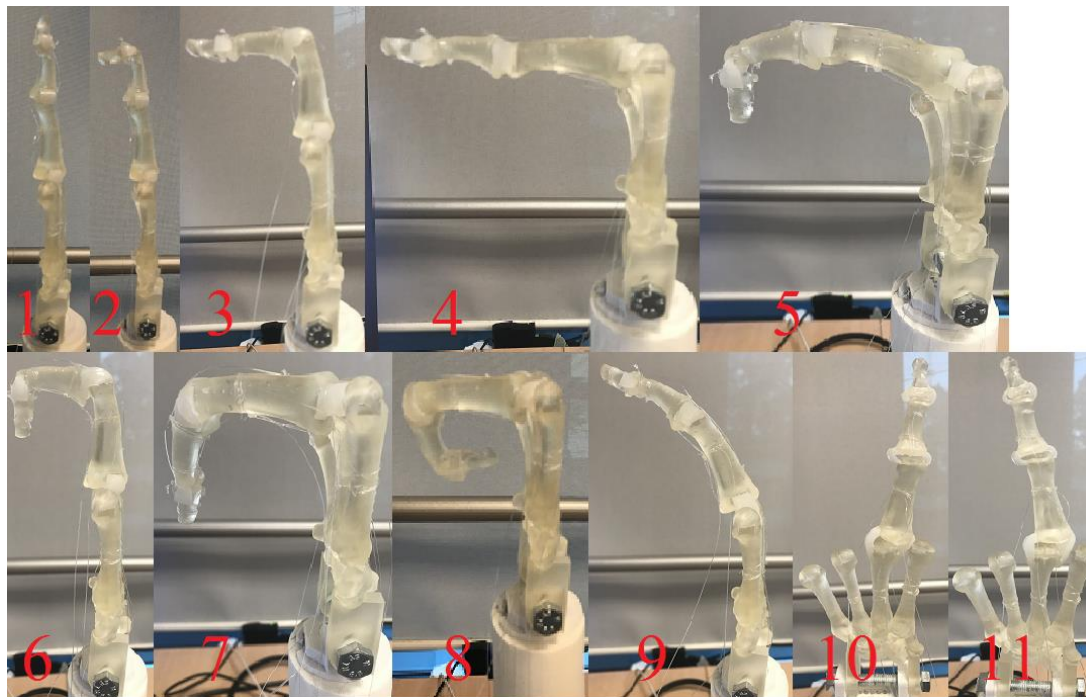


Figure 4-13 11 Pose test result of our robotic finger

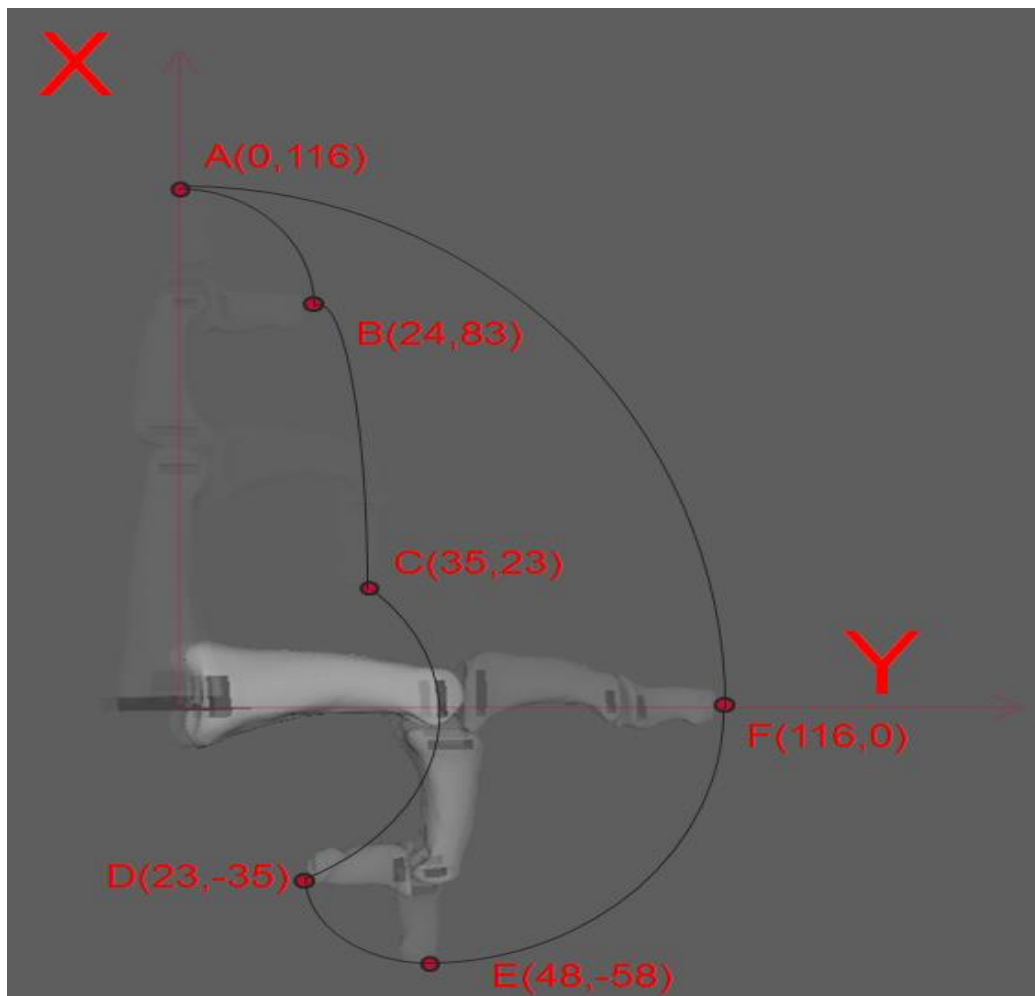
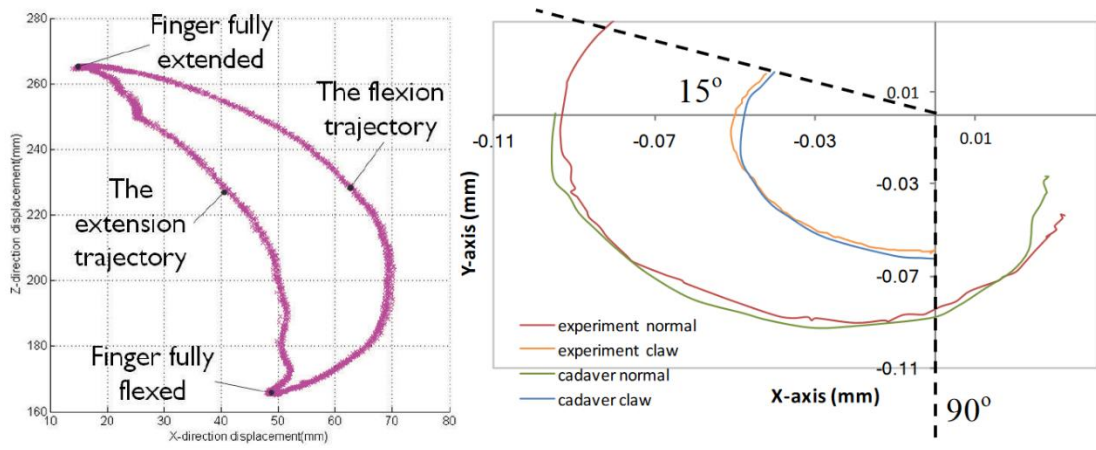


Figure 4-14 Dynamic 2D motion range (bottom) and others (top) [30, 31]

This section builds a 2D coordinate system with the MCP joint as the origin in a virtual environment referenced to [111, 116] to show the motion range of the robotic finger in flexion and extension. Then six limit points from the finger pose are calculated. They are used to estimates the motion range, as shown in Figure 4-14.

Table 4-4 Comparison with other robotic fingers

Name	DoF	Bones	Joint	Pulleys	Actuation	Tendons	Comments
Shadow hand's middle finger[26]	3	Manually made a 3D model	Rigid structure and screws	Hollowed finger parts	Cable-driven, four joints, three two-ways servos	6	Less one DOF than a human finger, skeleton structure is unlike human's
Robotic hand's finger by Zhe Xu[30]	2	From cadaver bones (fixed size)	Crocheted volar plate	Laser-cut tendon sheaths	Cable-driven, two one-way servo	2	Highly biomimetic, less 2 DOF than a human finger
Robotic Finger by A.A.M Faudzi[31]	2.5	From cadaver bones (fixed size)	Silicon rubber	Tubes	Cable-driven, six one-way muscles	6	Three intrinsic muscles and three extrinsic muscles, single EDC
Human finger[94]	4	Real bones	Structured tissues	Tissues	10+ muscles	14	Golden example for our design
Our robotic finger	4	From cadaver bones(Changeable)	Silicon rubber	Nylon cables	Cable-driven, four two-way servos	8	Same DOF and similar ROM as a human finger

This section compares the robotic finger to the other three representative robotic fingers in terms of DOF, bones design, joints, pulleys, tendons and the actuation ways. The detail is given in Table 4-4.

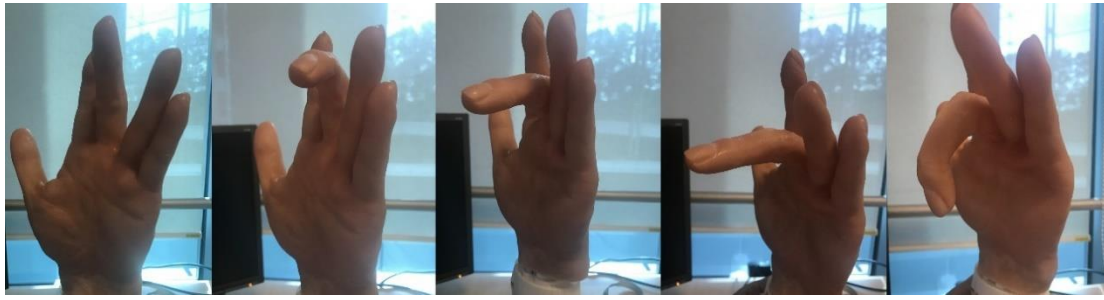


Figure 4-15 High-biometric robotic hand's robotic finger works inside the artificial skin

This section also tests the robotic finger within silicone rubber artificial skin. The result shows that the robotic finger can still make explicit poses under the artificial skin (Figure 4-15). The customized artificial hand skin is made of 0-degree (shore A hardness) silicon in 2mm thickness.

4.5 Experiments with an underactuated actuation system

4.5.1 Overview

This section describes the proposed underactuated system. Tendons, muscles, joints and ligaments actuate the natural hand. Ligaments are fibrous connective tissues that connect bones to other bones and form joints. Tendons are connective tissues as well, but they are attached to muscles and bones. In order to mimic the dynamics of human hands, the proposed actuation system uses cables as tendons, with electric servo motors as muscles to control the motions of the finger.

The underactuated system stems in which each of the three phalanges (i.e., the proximal, intermediate and distal phalanx) of a finger is driven by a cable. All three cables cooperate in completing the movement. Note that there are two tendons, i.e., flexor tendons that bend the finger and extensor tendons that straighten the finger. Consequently, such a design requires two groups of the driven system: one for the flexor tendons, including the flexor digitorum superficialis (FDS) tendon and the flexor digitorum profundus (FDP) tendon; while the other one for the long extensor tendon, as shown in Figure 4-16. With the other two driven cables for simulating the lumbrical and interosseous muscles, eight driven cables and four motors (two cables can share one motor) are used in total to control a finger.

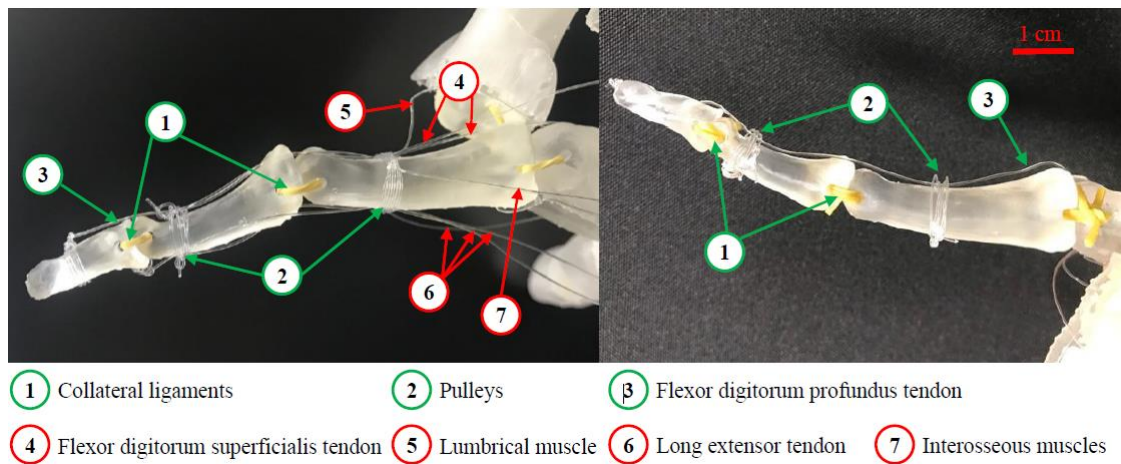


Figure 4-16 Demonstration of the actuation system of the previous design (left) and the simplified one used in this paper (right). The simplification is feasible due to our multi-layer design. The remaining structures are labeled in green.

In this section, the control system mentioned above can be simplified significantly due to the proposed multi-layer robotic hand design. The layers of skin and tissue are made of elastic materials, and the ligaments are resilient rubber bands. They can return to their original shapes automatically after being flexed. Consequently, the bones are also pulled back to their original positions (i.e., via passive movement). Thus, the proposed actuation system removes the cables of the extensor tendon, the lumbrical and interosseous muscles.

Furthermore, the proposed design only keeps the cable attached to the FDP tendon for the flexor tendons. As shown in Figure 4-16, the new underactuated system (marked in green) requires only one cable and one motor for each finger (except the thumb, which uses one more motor to realize abduction and adduction). In summary, the proposed underactuated system has 15 degrees of freedom and 6 degrees of actuation. The design reduces the complexity and size of the system remarkably. Hence, the system can be easily installed on various robotic arms, especially for social robotics like the Nadine robot.

It is noted that the proposed multi-layer structure is a universal design for anthropomorphic hands and is not limited to the above actuation systems. Highly dexterous robotic hands can be obtained with other actuation systems, such as the design that adopts more actuators to achieve various object manipulations described in chapter 6.

4.5.2 Grasping gesture test

This section validates the effectiveness of the proposed design via extensive experiments. (Video link: <https://youtu.be/NCbKIyAAHSs>; <https://youtu.be/9qqFD83CDJM>; <https://youtu.be/o51H04AWq60>; <https://youtu.be/Xfddw24eDkc>; <https://youtu.be/wIs2iSjRBk4>)

The experiment first evaluates the object grasping performance of the multi-layer robotic hand with the grasp taxonomy defined by Feix et al., which consists of 33 human grasp types. A successful grasp is every static one hand posture with which an object can be held securely. Each grasp type is tested ten times, and the experiment uses the success rate as the evaluation metric. Two state-of-the-art robotic hands, including the InMoov hand and Nadine's hand V4, are fabricated for comparison because the models and hardware specifications of the InMoov hand are publicly available. In contrast, Nadine's hand V4 is similar to the proposed design.



Figure 4-17 Comparison of object grasping success rates of different methods. Methods with success rates ≥ 0.8 , in $[0.2; 0.8)$ and < 0.2 are labeled in green, yellow and red, respectively. The proposed robotic hand has the highest success rates for all grasping gestures.

The results of the object grasping test are reported in Figure 4-17. Methods with a success rate greater than 0.8, in $[0.2; 0.8)$ and smaller than 0.2 are labeled green, yellow

and red, respectively. These results show that the proposed robotic hand completes most grasp types with high success rates (rates greater 80%). Furthermore, the performance of the proposed robotic hand is superior to that of the InMoov hand and Nadine’s hand V4 with all 33 grasp types. Note that the number of actuators of the proposed robotic hand is equal to that of Nadine’s hand V4 (i.e., six actuators), which indicates that the success of our robotic hand mainly comes from the deformable multi-layer design.

4.5.3 Ablation study of the multi-layer design

In order to provide an insight into the effectiveness of the multi-layer design, this section further conducts an ablation study in which the robotic hands with different layers are evaluated. Specifically, this section performs the test of 33 grasping gestures with three variants of our design, including a Bone-only design, a Bone + tissue design and a Bone + skin design.

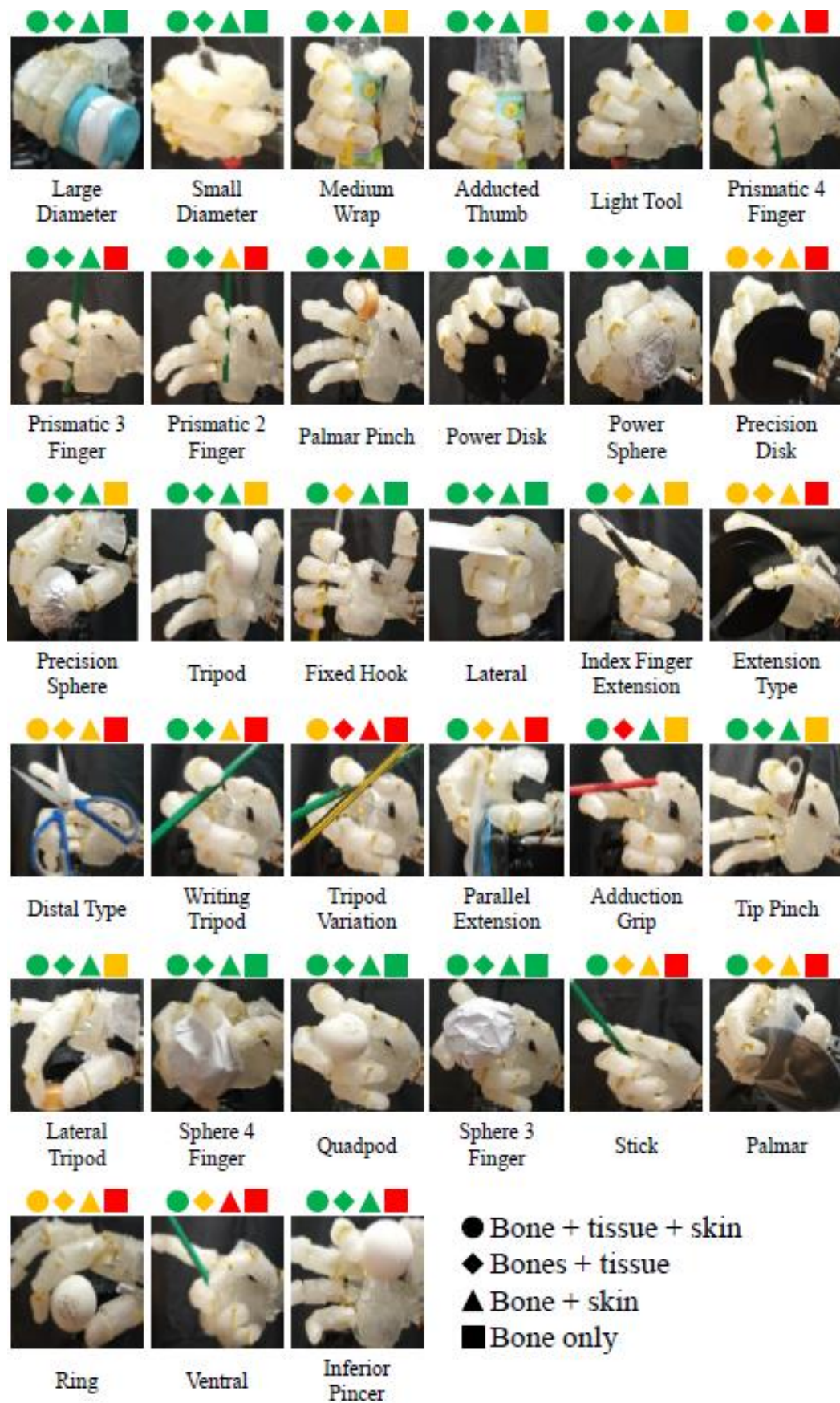


Figure 4-18 Comparison of object grasping success rates of the proposed robotic hands with different layers. Methods with success rates ≥ 0.8 , in $[0.2; 0.8)$ and < 0.2 are labelled in green, yellow and red, respectively. The result validates the effectiveness of each layer in our design.

Figure 4-18 demonstrates the results of the ablation study. The result can be obverse that the bone-only design fails with multiple grasp types, such as “prismatic finger,” “extension,” and “writing tripod.” The test result again validates the opinion that single-layer/structure robotic hands are hard to realize the ability of human hands fully. Nevertheless, with an extra layer of skin or tissue, the proposed design obtains significant performance gains, e.g., the success rate of the “prismatic three fingers” type rises from below 20% to higher than 80%. Moreover, the design with all three layers obtains the highest success rates. Based on these results, it can conclude that the multi-layer design is a feasible solution for anthropomorphic robotic hands.

4.5.4 Deformability of the tissue layer

The tissue layer determines the deformability of the proposed robotic hands. In order to demonstrate that the proposed concentric tube structure from the tissue layer can effectively simulate the deformability of the human hand, here, this section adopts the deformation curve as the measure of deformability and compare the proposed structure with other methods.

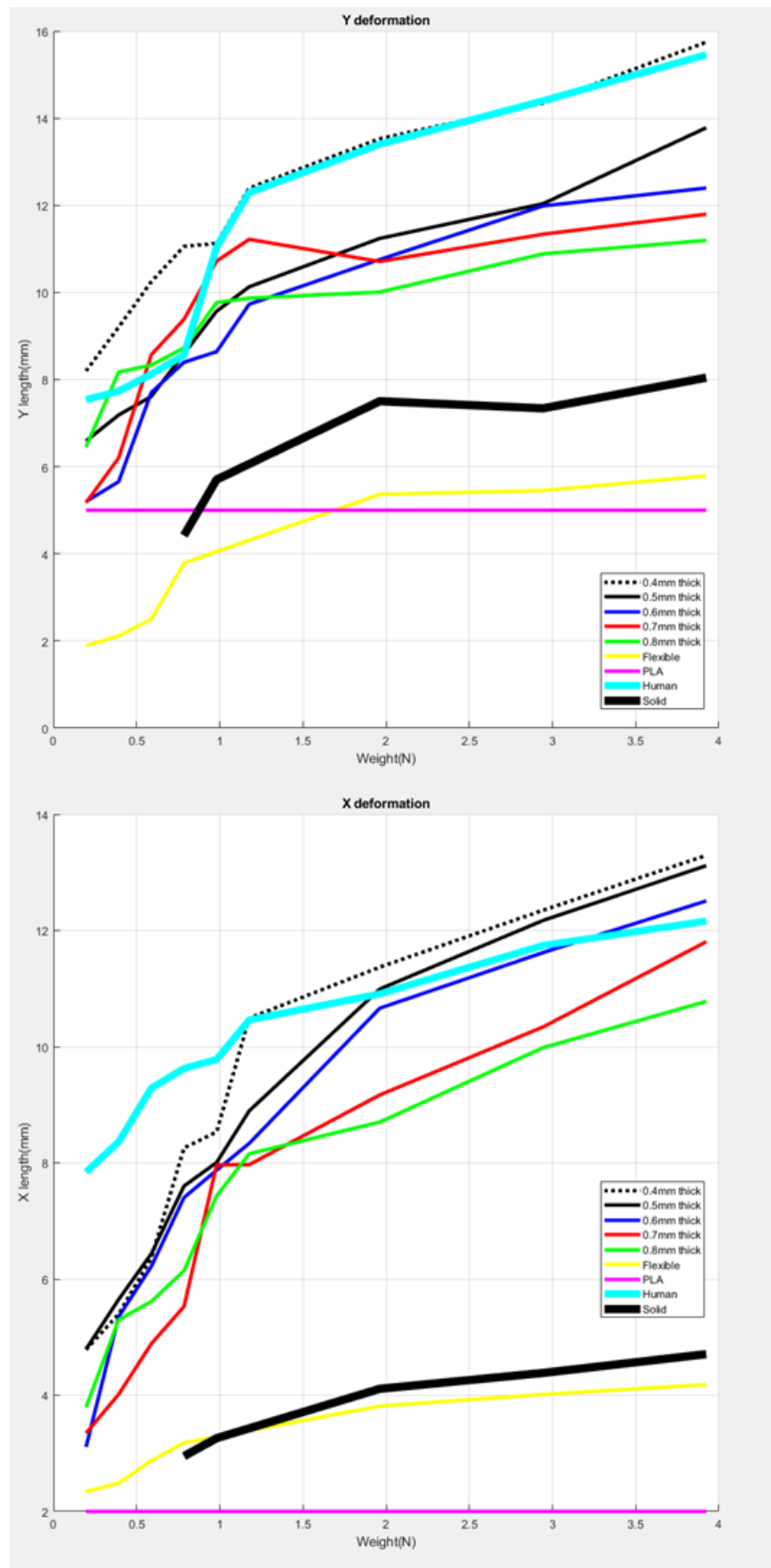


Figure 4-19 Graphical representation of the index finger tissue deformation under pressure

First, this section considers two 3D printing materials for comparison: the flexible

material used by Nadine's hand V4 and Polylactic Acid (PLA) used by InMoov hand. As demonstrated in Figure 4-19, the deformation curves of these two materials are far away from those of the human finger. As mentioned above, the proposed robotic hand's soft material is still more complex than human tissues. Hence, merely using this material with a solid structure cannot achieve desirable deformability. On the other hand, with the tube-based structure, the deformability of the tissue layer is improved dramatically.

More importantly, the experimental results suggest that the proposed design can explicitly control its deformability via setting σ , the thickness of tubes. This section reports the deformation curves of $\sigma = [0.3 \ 0.4 \ 0.5 \ 0.6 \ 0.8]$ in Figure 4-19. It can be observed that the deformability of the proposed robotic hand is inversely proportional to σ . With $\sigma = 0.4$, the proposed method can obtain the tissue layer with the deformation curves approximating the human fingers.

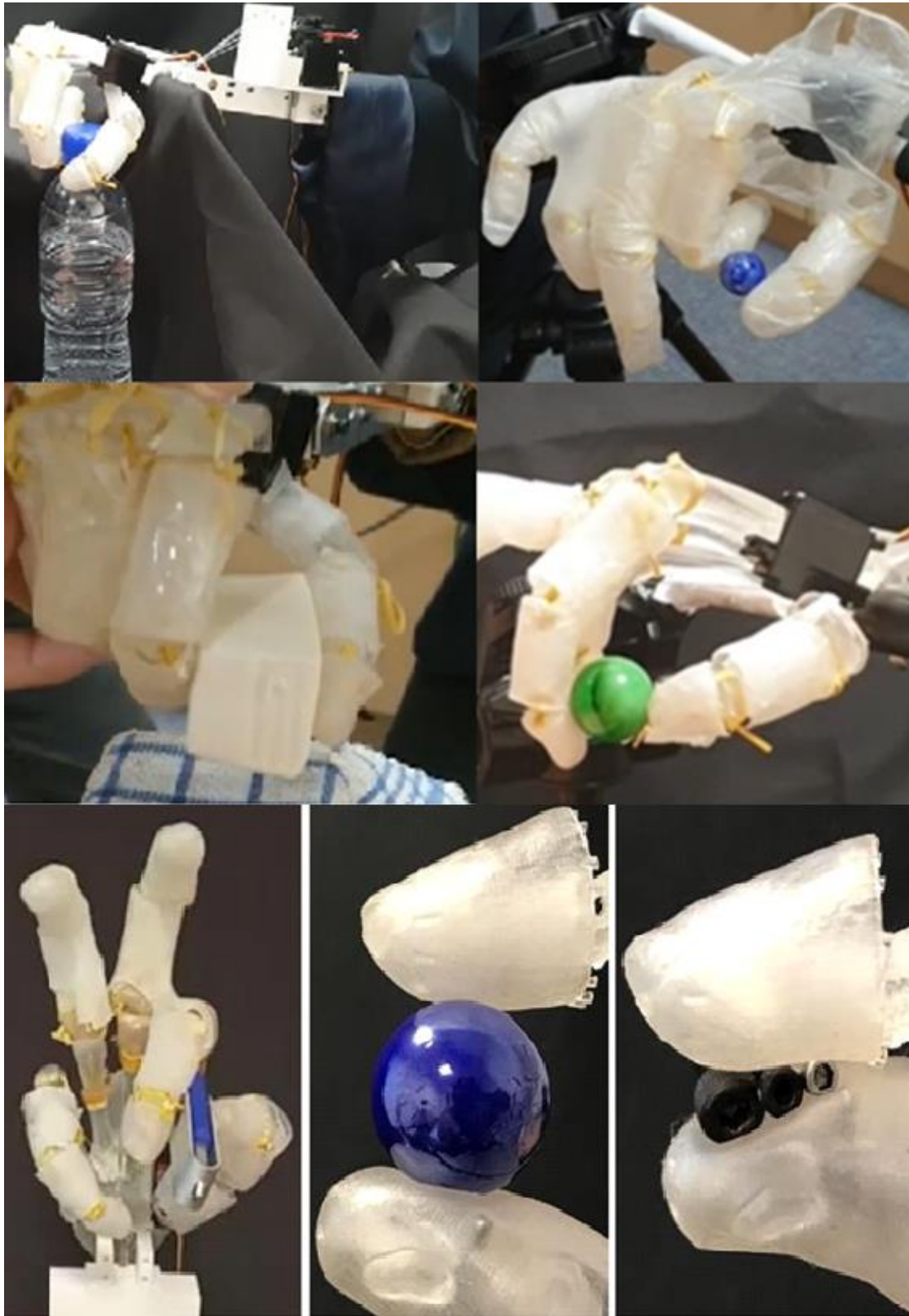


Figure 4-20 Demonstration of our robotic hand in pinching unique objects. The proposed design can pinch (via side-pinch or fingertip-pinch) various objects stably.

As emphasized before, the robotic hand's deformability is key to grasping various textures and weights objects. In order to validate this, this section also conducts five experiments on grasping unique objects, including InMoov hand, Nadine Hand V3 & V4, and the

proposed robotic hand without the tissue layer for comparison. The five experiments are listed as follows, and the experimental results are summarized in Table 4-5:

Table 4-5 Comparison of the deformability of various anthropomorphic hand designs. A design fails in a task is marked with (, otherwise with ✓.

	InMoov Hand	Nadine Hand V3	Nadine Hand V4	Ours without Tissue	Ours
Task A: Side pinch silken tofu	(	(	✓	(	✓
Task B: Side pinch marble	(	(	✓	(	✓
Task C: Side pinch water bottle (in g)	250	200	50	200	450
Task D: Fingertip pinch screws	(	(	✓	(	✓
Task E: Press and pick up the M1 screw cap	(	(	(	(	✓
Maximum deformation length (x : y, in mm)	2 : 5	2 : 2	4.78 : 5.79	2 : 5	13.3 : 15.7
Sliding resistance (in N)	0.96	0.93	2.16	1.18	3.43
Plane rotation resistance (in N)	0.25	0.25	1.18	0.15	1.77

Task A: Side pinch a fragile silken tofu block. This task is introduced to demonstrate the benefits of soft and deformable materials since rigid hands like our hands without the tissue layer will crush the tofu block.

Task B: Side pinch smooth marbles with a diameter of 16 mm and 24 mm. This task is designed to validate that our deformable contact surfaces can provide considerable friction to grasp objects.

Task C: Side pinch a water bottle. This sub tale records the maximum weight each hand can hold. From the results, the proposed robotic hand can pick up a water bottle of 450

g, which is larger than the baseline.

Task D: Fingertip pinch screws. This section conducts a task to validate the two-finger caging model of our robotic hand. This task uses three types of screws, i.e., M1, M2, and M3. It is noted that our hand can pinch three types of screws (one for each type) simultaneously.

Task E: Press and pick up an M1 screw cap with the fingertip. The task demonstrates the single finger caging model of the proposed robotic hand. Only the proposed robotic hand and the natural human hand can complete this task.

Figure 4-20 demonstrates several examples of the proposed robotic hand in grasping unique objects. Besides, this section reports three contact-related metrics in Table 4-5, including the maximum deformation length, the horizontal sliding resistance and the resistance of rotating the contact tangent plane. These results can conclude that the proposed robotic hand does obtain superior deformability compared with previous methods. Furthermore, the comparison between ours and ours without the tissue layer validates that the tissue layer is the critical factor in our performance gains.

This section also does more pinch tests for unique objects such as 15mm and 25mm diameter marble, super soft silk tofu, and a water bottle weighing 490g. In comparison, traditional robotic hands with a rigid body such as the Inmoov hand and Nadine hand V3 fail to pinch marble and tofu in the same test. The maximum weight of water bottle they can hold is 250g for Inmoov hand and 180g for Nadine hand V3.

4.5.5 Ablation study of finger design

Last but not least, this section proposes to analyze the functionality of the underactuated system. First, five different solutions for joint connection are compared in Table 4-6. The most significant advantage of using rubber bands as ligaments is that they provide the restoring force after flexion (about 3.1 N for a 4 mm rubber band). The proposed actuation system can remove the cables for completing the extension.

Table 4-6 Comparison of the joint connectors in various anthropomorphic hand designs

Connector	Type	Maximum Restoring Force	Force Transmission
Fishing line	Ligament	0	1 Bowden cable for flexion & extension
Crocheted ligament	Ligament	0	1 cable for flexion and 1 cable for extension
Solid pin	Hinge	0	1 cable for flexion and 1 cable for extension
Flexible pin	Hinge	0	1 cable for flexion and 1 cable for extension
Rubber band (this design)	Ligament	1.5 N with 2 mm rubber band	1 cable for flexion, extension achieved via the restoring force
Rubber band (this design)	Ligament	3.1 N with 4 mm rubber band	1 cable for flexion, extension achieved via the restoring force

Next, this section records the trajectories of fingertips during flexion to investigate whether they can fit the trajectory of the human finger. The proposed system can be implemented with different configurations, e.g., with different attaching knots and displacements of strings. Therefore, as demonstrated in Figure 4-21, the section realizes five different system designs and includes the design from InMoov hand as the baseline for comparison. Configurations of these designs are summarized in Table 4-7.

Table 4-7 Ablation study on the finger design. Maximum forces are measured from fingertip (in N), and ranges of motion are measured by the rotation angle of DIP (in degree)

Design	Cable Link Method	Joint Connector	Pulley Solution	Maximum Force	DIP ROM
1	Through-hole and knot	4 mm rubber band	2 holes through the phalanx (2 mm beneath the surface of phalanx)	18.973	[0, 95]
2	Through-hole and knot	4 mm rubber band	2 holes through the phalanx (3 mm beneath the surface of phalanx)	8.652	[0, 90]
3	DIP attaching knot	2 mm rubber band	2 holes through the phalanx (1 mm beneath the surface of phalanx)	10.301	[0, 90]
4	DIP attaching knot	2 mm rubber band	1 hole through the phalanx (1 mm beneath the surface of phalanx) 2 nylon string windings	23.348	[0, 100]
5	Inside knot	Pin joint	Hollow body	3.345	[0, 70]
6	Through-hole and knot	4 mm rubber band	4 nylon string windings	19.306	[0, 100]

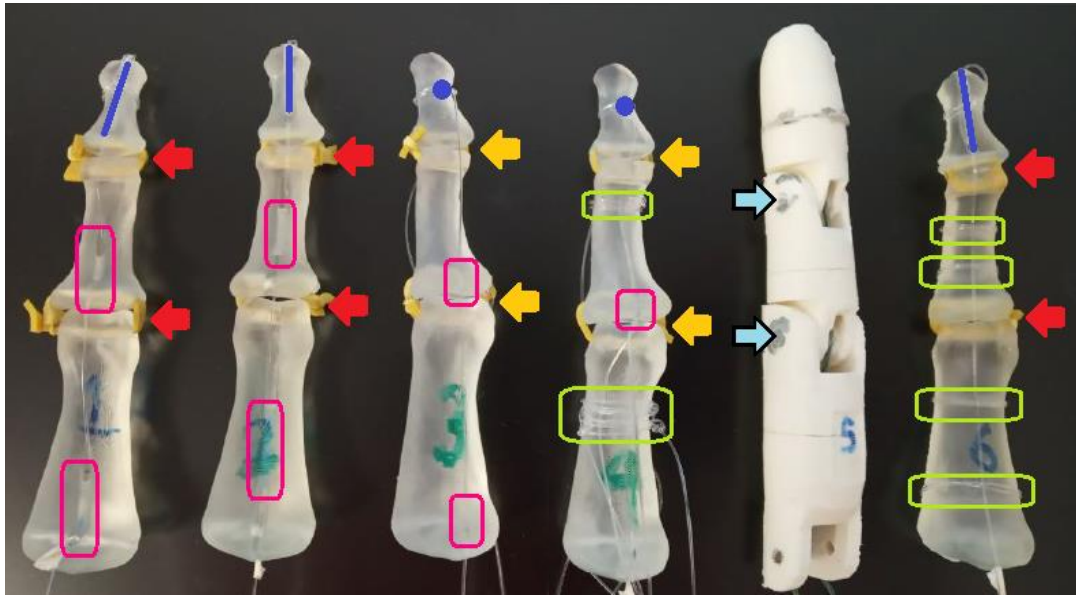


Figure 4-21 The six designs of fingers. Design 5 comes from InMoov [14]. Blue dot: Driving cable and distal phalanx attaching point (knot). Blue line: Through-hole and knot. Yellow arrow: 2mm thick rubber band. Red arrow: 4mm thick rubber band. Blue arrow: Pin joint. Red Box: Hole through phalanx. Green box: Nylon string windings

Trajectories from the lateral view of the six designs are reported in Figure 4-22. It can observe that the flexion of the baseline (Design 5) is limited, as its minimum y coordinate is more significant than that of the human finger by a large margin. On the contrary, all our five designs are more flexible and better replicate the human finger. Designs 2 and 6 have similar deformation curves. Therefore, this section further measures their maximum pull strength and DIP range of motion (ROM) to decide optimally. With the same servomotor, the maximum pull strength of Design 6 is 19.306 N, while that of Design 2 is only 8.652 N. Design 6 also achieves the maximum DIP ROM ([0, 100]) among all variants. Therefore, Design 6 is considered the optimal choice for implementing our underactuated system.

The six designs of fingers and below are their details.

Design 1: Pulley consists of holes bored through the base of phalanges, exiting the bases of the phalanx at a horizontal angle, while the entry is positioned above, at an angle of approx. 70° to the horizontal.

Design 2: Driving cable runs through grooves (width 2mm) going down the middle and proximal phalanges length. The driving cable is sandwiched between the groove base and a curved barrier located at the center of the phalanx.

Design 3: Driving cable runs through small circular gaps (diameter 1mm) at the middle

and proximal phalanx base. These gaps exist at the bottom surface of each phalanx.

Design 4: Driving cable runs through nylon string coils tied onto the middle and proximal phalanx surface.

Design 5: Pin-joint mechanism with driving cables within the hollow shell.

Design 6: Driving cable runs through thinner coils of nylon string, the coils fixed in place by holes bored through the phalanx.

The six designs are subjected to 2 tests to determine their efficacy: a grip strength test and a motion test.

For the grip test, the tested finger is fixed onto a stand. The driving cable of the tested finger design would be subjected to a constant load of 3.6 kg (load amount chosen as it is the load the finger would generally experience when driven by a servomotor). An electric force scale with an attached hook is fixed onto the stand above the finger. During the test, the finger curls around the hook of the force scale. The test is repeated five times for each design, and the average reading is recorded (Table 4-8).

The tested finger is fixed onto a stand in front of a marked grid in the motion test. The coordinates of the tip of the distal phalanx are recorded with every 2 mm interval of driven cable pulling. The obtained points are then plotted on a graph through Matlab to be compared with the motion of a real finger put through the same test.

Table 4-8: Measured fingertip grip strength of the different designs, using a 3.6 kg load.

Readings(kg)	1	2	3	4	5	Average
Design 1	1.790	1.970	2.020	1.930	1.960	1.934
Design 2	0.865	0.875	0.895	0.910	0.865	0.882
Design 3	1.075	1.010	1.080	1.045	1.040	1.050
Design 4	2.410	2.300	2.445	2.440	2.305	2.380
Design 5	0.360	0.330	0.335	0.330	0.350	0.341
Design 6	1.970	1.940	2.000	1.970	1.960	1.968

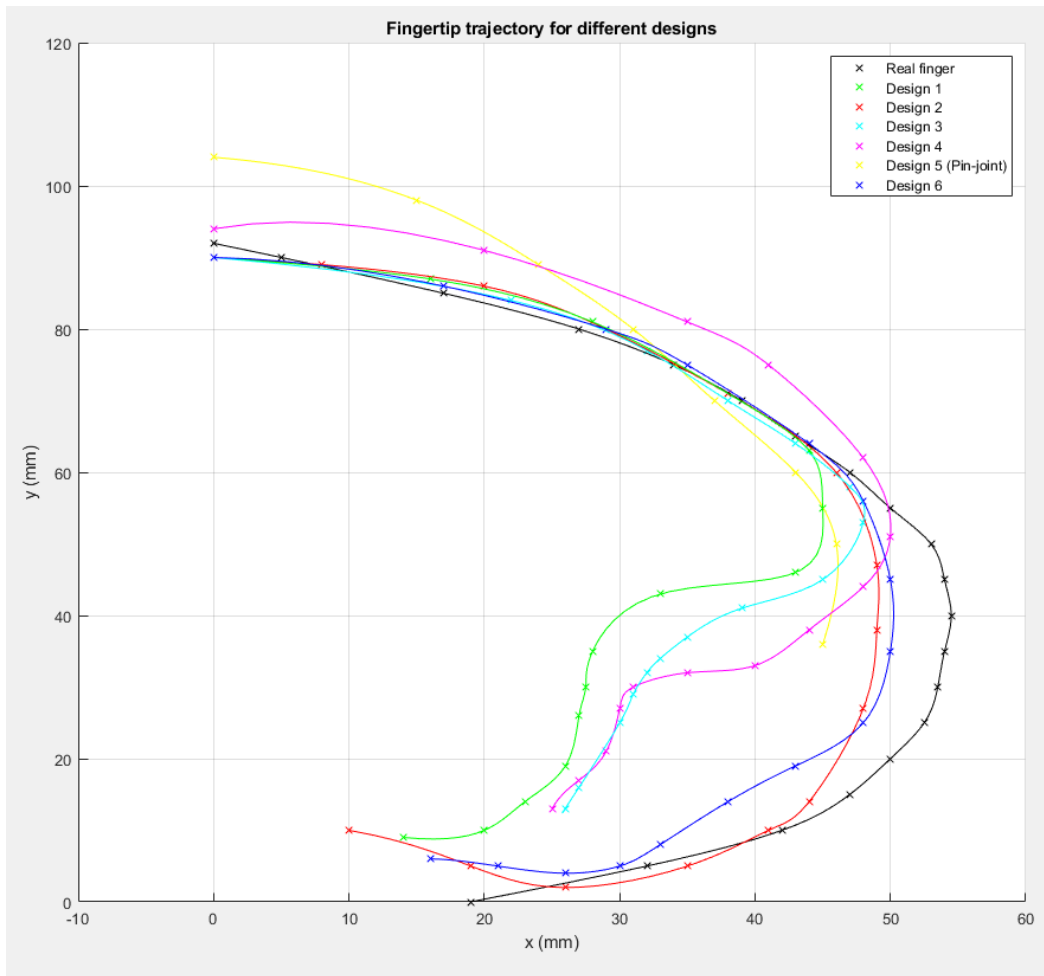


Figure 4-22 Fingertip trajectories during flexion with different designs of the underactuated system. These trajectories are captured from the lateral view. Design 5 is from InMoov's hand.

The results show that Design 4 has the highest average grip strength (2.30 kg), while Design 2 best emulates the motion of a real finger. However, Design 4 does not correctly recreate the finger motion, and Design 2 has the second-lowest average grip strength (0.882 kg). The best compromise between the two qualities is achieved in Design 6, which has the second-highest average grip strength (1.968 kg) and emulates a real finger's motion well. The test result can be attributed to using nylon string windings as pulleys like Design 4 and repositioning the windings to recreate the pulley positions in Design 2. The reduced average grip strength from Design 4 to 6 can be attributed to the thicker rubber band joints in Design 6, leading to more energy used to overcome elastic potential energy in that design. Based on experiments, the rubber band's flexibility regresses after 3 months.

4.6 Summary

This chapter proposes a fast and systematic method to fabricate multi-layer robotic hands.

The core of the proposed method is the skin-tissue-bone, multi-layer design inspired by the anatomy of the human hand. The fast template matching method can generate the 3D bone models of the target hand. At the same time, the tissue layer's concentric tube-based structure ensures that the fabricated hand is of high deformability. With the multi-layer design, the proposed method significantly reduces the cost and complexity of the actuation system. The experiment in section 4.4 shows that the robotic finger can achieve all 11 standard finger gestures like a human middle finger with a full-actuation system. In section 4.5, extensive experiments with the standard object grasping types, as well as with unique objects, demonstrate that the proposed design is superior to previous robotic hands.

Compare to the customized low-cost robotic, the multilayer deformable robotic hand keeps the feather of customizable, fast fabricate and low in cost. It also has soft surface and deformable body. The disadvantage is it require manually assembly after 3D printing.

This chapter could provide a new baseline for fabricating anthropomorphic robotic hands based on 3D scanning and 3D printing. In the future, this research plan to add soft sensors into the hollow chamber of the tissue layer to help to increase the accuracy of object grasping and manipulation. It also plans to devise an actuation system with more freedom to complete complicated motions besides flexion and extension.

Chapter 5 Object Grasping of Humanoid Robot Based on YOLO

5.1 Introduction

This chapter presents a system that is able to achieve autonomous grasping for humanoid robots such as the Inmoov robot and the Nadine robot. The system consists of a visual sensor, a central controller and a manipulator. This system modifies the open-sourced object detection software YOLOv2. It is also associated with the visual sensor to detect the category of the target object and the location with the help of a depth camera. It also estimates the target's dimensions (i.e., the height and width) based on the bounding box technique. After that, it sends the information to the central controller (a humanoid robot), which controls the manipulator (customized robotic hand) to grasp the object with the help of inverse kinematics theory. The experiments show that the system can detect the object and drive the robotic hands to grasp the target object ¹³.

Currently, robot technology is making it possible to introduce more automation services to our daily life. Intelligent and interactive robots could assist us in the home or office. One of the most critical tasks is to fetch objects. However, autonomous grasping is still not a completely solved problem in robotics. In order to archive autonomous grasping, robots should have abilities to recognize the target objects and determine the location of objects.

Moreover, robots need to adjust their motion trajectory based on the information of the target objects, such as location and category. Nevertheless, there are still many uncertainties that need to be further studied. Therefore, how to deal with uncertain facts and improve the success rate of grabbing is an efficient problem. Generally, the uncertainties in the grasping process mainly include the uncertainties of the target object's shape, the object's pose, the contact point of the manipulator, and the object's

¹³ Part of this work is published in “Tian, L., Thalmann, N. M., Thalmann, D., Fang, Z., & Zheng, J. (2019). “Object Grasping of Humanoid Robot Based on YOLO.” In Proceedings of Computer Graphics International Conference (pp. 476-482).”

quality.

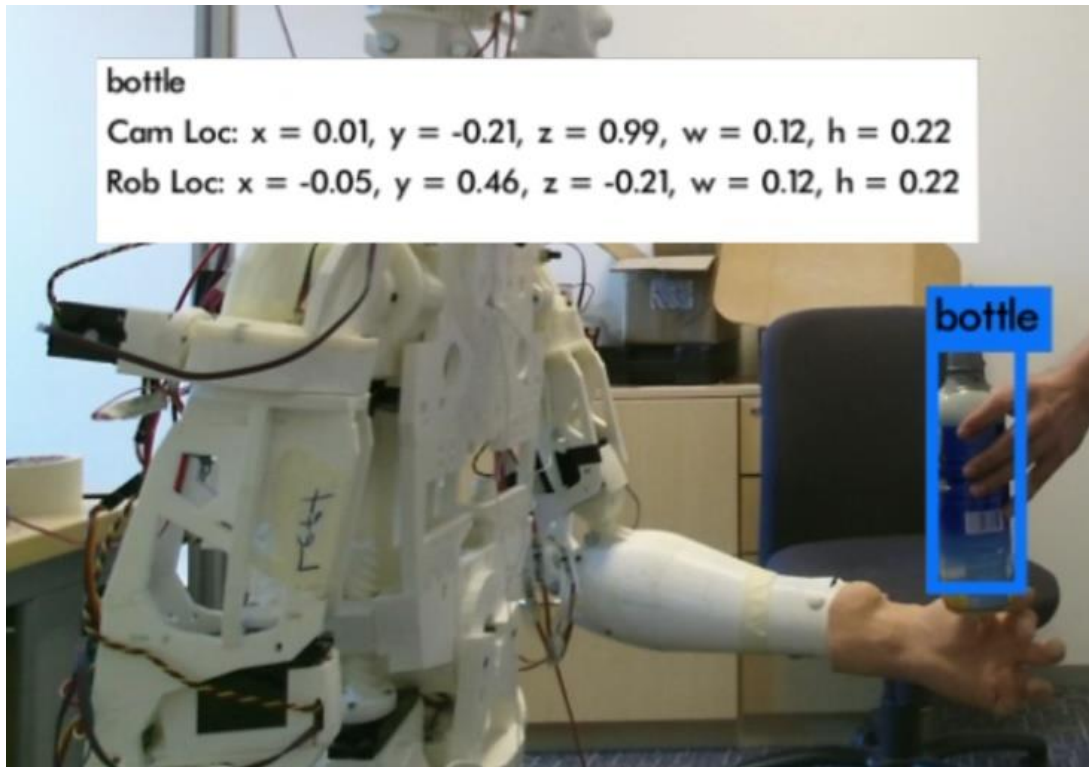


Figure 5-1 Autonomous grasping with real-time object detection

In order to solve this problem, the proposed system first collects the necessary information about the target. Then, it does path planning for the arm based on the target's position. Finally, it actuates the robotic hand to grasp the target by preset grasp pose according to the categories and size of the targets. Figure 5-1 shows the screenshot of the proposed object detection software. The water bottle has been detected and highlights within the blue rectangular box. The “x,y,z” after “Cam Loc” indicates the 3D coordinate of the bottle regarding the Kinect II™. Moreover, the “x,y,z” after “Roc Loc” indicate the 3D coordinate of the bottle after transformation regarding the robot’s position. “w” and “h” indicate the width and height of the detected object.

5.2 Object detection

5.2.1 Object perception in the RGB image

How to grasp the object remains a challenging task. Therefore, the target objects need to be recognized and localized accurately for safe grasping in a natural environment. This chapter defines the task of grasping as fetching objects from a static place, and the system architecture of the proposed visual-based perception system is shown in Figure 5-2. Firstly, the system collects depth and RGB images from KINECT II. A CNN-based

object detection method named YOLO is adapted to extract CNN features, detect objects, and recognize objects based on the RGB images. The objects are marked by rectangular boxes and labeled using the object category. Then, the corresponding regions are cropped from the depth image according to the rectangular boxes, including the target objects. Finally, in the depth-images, object segmentation is designed to obtain the pixels belonging to the target objects, which is used to calculate the location of objects.

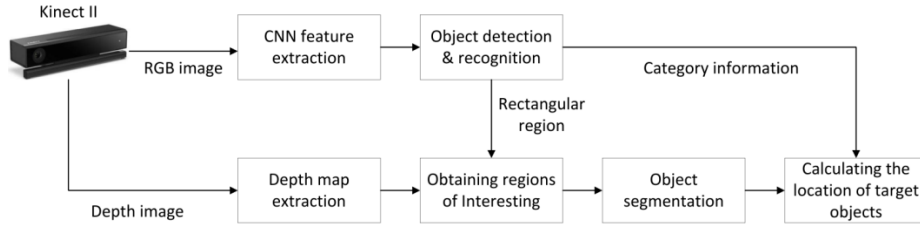


Figure 5-2 The architecture of our proposed visual-based perception system

Next, introduce the details about object perception for social robot grasping. In vision-based grasping, an exciting object should be perceived in the current image at real-time speed. In order to facilitate real-time object perception, the proposed method adopts You Only Look Once (YOLO) [13] to detect and recognize interesting objects.

YOLO is a unified pipeline, which treats object detection as a regression problem. YOLO uses global image features to detect objects. It can output spatially separated bounding boxes and corresponding class probabilities simultaneously. Because the pipeline of object detection is a single network, it can be optimized end-to-end directly. Moreover, YOLO can process images at a real-time speed. The pipeline of YOLO is shown in Figure 5-3. This framework consists of three steps: (1) resize the input image to 544×544 , (2) run a CNN-based network, and (3) output the results by the confidence of the network model.

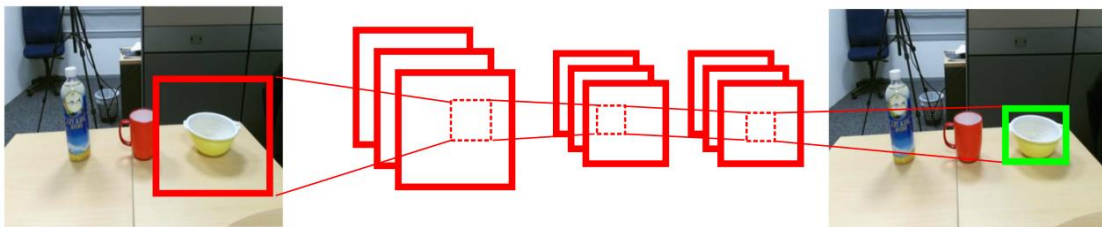


Figure 5-3 The pipeline of YOLO: (1) resize the input image to 544×544 , (2) run a CNN-based network, and (3) output the results by the confidence of network mode.

Next, briefly introduce YOLO. The input image is divided into a 7×7 grid. If a grid cell includes the center of an object, that grid cell is used to detect that object. Bounding box

and class probabilities are predicted using that grid. YOLO has 24 convolutional layers, followed by two fully connected layers. It uses a 1 x 1 layer followed by 3 x 3 convolutional layers, and stride convolutions replace the max-pooling layers.

5.2.2 Object segmentation from the depth image

Having good segmentation information can help grasp. It can help the social robot to estimate the location of target objects. Unlike previous methods, which only use RGB images, the proposed method takes advantage of a previously developed concept “depth cues” to get the pixels belonging to target objects [144]. In order to segment the target objects from the depth image, the background and the desk plane are needed to remove.

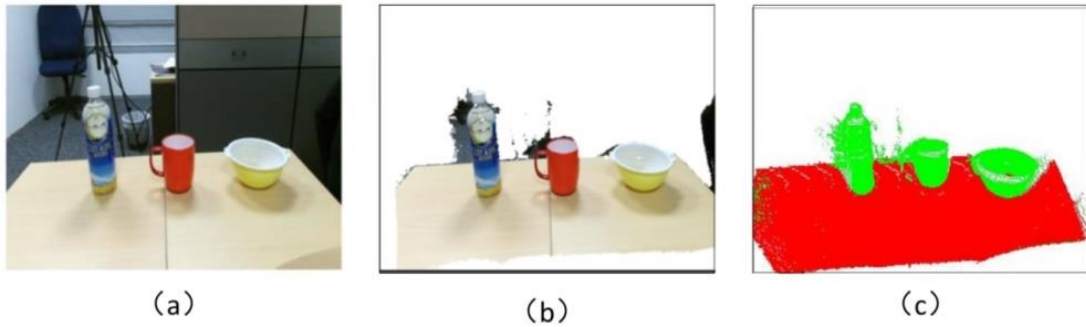


Figure 5-4 Illustration of object segmentation in Kinect RGB and depth image

Because the length of humanoid robot arms is about 0.8m, the background information can be filtered by a fixed threshold θ as Eqn.5-1.

$$RGB(p) = \begin{cases} 0, & depth(p) > \theta \\ RGB(p), & other, \end{cases} \quad (5-1)$$

where $RGB(p)$ and $depth(p)$ represent the RGB value and the depth value of pixel p ; $\theta = 1000$ is the threshold. For removing the background. It means that the RGB value of pixels whose depth values are larger than 1m will be set to 0. The distance-based filter can restrain the background. The sample is shown in Figure 5-4(b). To segment objects, the depth map is also filtered as Eqn. 5-2.

$$depth(p) \begin{cases} 0, & depth(p) > \theta \\ depth(p), & other, \end{cases} \quad (5-2)$$

Next, get the pixels belonging to the desk. The plane of the desk is the biggest one in Figure 5-4(b) because the background has been removed in the last step. In order to detect the plane, the first step is how to transform the depth image to point cloud data.

IR camera intrinsic parameters, focal length and the principal point can be used to finish the transforming task[145]. The algorithm for converting the depth image to point cloud data is as Algorithm 5-1.

Algorithm 5-1: Transform the depth image to point cloud data

```

1:  $\phi=1000$ ; //Meter to MM
2: for vDepth = 1 to height
3:   for uDepth = 1 to weight
4:      $z = \text{depth}(\text{vDepth}, \text{uDepth})/\phi$ 
5:      $x = (\text{uDepth} - \text{cxd}) * z / \text{fxd}$ 
6:      $y = (\text{vDepth} - \text{cyd}) * z / \text{fyd}$ 
7:      $\text{pointcloud}(\text{vDepth}, \text{uDepth}, 1) = x$ ;
8:      $\text{pointcloud}(\text{vDepth}, \text{uDepth}, 2) = y$ ;
9:      $\text{pointcloud}(\text{vDepth}, \text{uDepth}, 3) = z$ ;
10:   end
11: end

```

Where fxd, fyd are the focal length and cxd, cyd are the principal points. After obtaining point cloud data, the proposed method adopts a RANSAC[146]-based plane fitting method to efficiently discover planes in point cloud data. The plane fitting method can get the largest set of points that fit to plane. The plane equation is defined as:

$$ax + by + cz + d = 0 \quad (5-3)$$

Where a, b and c are plane parameters and d is the distance from the origin to the plane. From the point cloud data, three points are selected by RANSAC, which can calculate the parameters of the corresponding plane according to these points. Then a distance threshold is set to enlarge the plane. The distance threshold is set to 0.0 in our method. The sample of the plane segmentation is shown in Figure 5-4(c). According to the segmentation result, the corresponding depth pixels of the desk plane are removed. Finally, obtain the target objects in the depth image. Based on the object detection in the RGB image and the object segmentation in the depth image, the object location (x_c, y_c, z_c) in the camera space can be calculated by averaging the location information of pixels belonging to the target objects.

5.2.3 Object location in the robot space

As illustrated above, the location of the target objects is obtained in the camera space. Aim to grasp the target objects, the location of the target objects should be transformed to the corresponding value in the robot space shown in Figure 5-5. The joint of the right arm is set as the origin of the coordinate plane in the robot space. Furthermore, the formulation of the affine transformation is defined as Eqn. 5-4.

$$\begin{pmatrix} x_r \\ y_r \\ z_r \\ 1 \end{pmatrix} = Trans(\delta x, \delta y, \delta z) Rotz(\gamma) Rotx(\beta) Roty(\alpha) \begin{pmatrix} x_c \\ y_c \\ z_c \\ 1 \end{pmatrix} \quad (5-4)$$

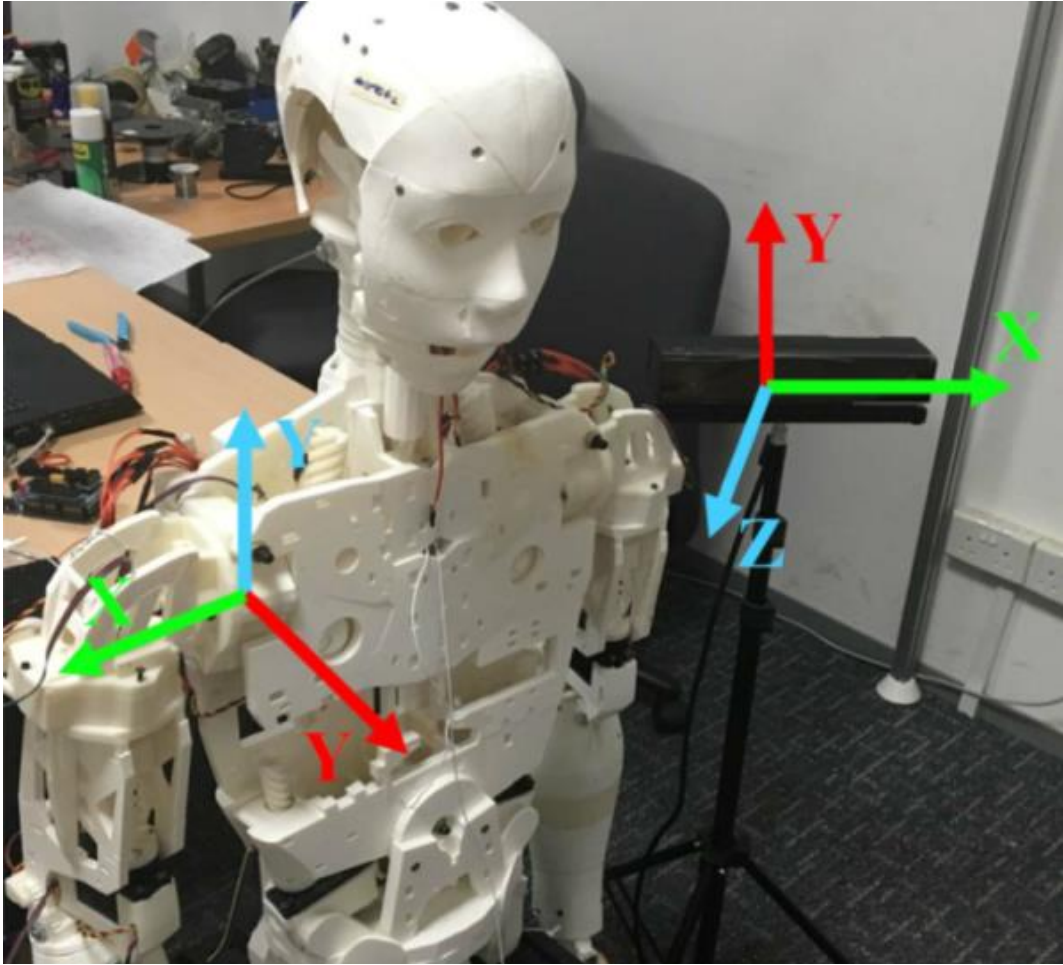


Figure 5-5 The camera space and the robot space

Where (x_r, y_r, z_r) and (x_c, y_c, z_c) represent the locations in the robot space and the camera space respectively; $Rot\Delta(\text{angle})$, $\Delta \in (x, y, z)$ is the transformation matrix for a Δ -based planar rotation about the origin through an angle. $Roty(\alpha)$, $Rotx(\beta)$, $Rotz(\gamma)$ and $Trans(\delta x, \delta y, \delta z)$ are defined as:

$$Rot_y(\alpha) = \begin{bmatrix} \cos(\alpha) & 0 & \sin(\alpha) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(\alpha) & 0 & \cos(\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5-5)$$

$$Rot_x(\beta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\beta) & -\sin(\beta) & 0 \\ 0 & \sin(\beta) & \cos(\beta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5-6)$$

$$Rot_z(\gamma) = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5-7)$$

$$Trans(\delta x, \delta y, \delta z) = \begin{bmatrix} 1 & 0 & 0 & \delta x \\ 0 & 1 & 0 & \delta y \\ 0 & 0 & 1 & \delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5-8)$$

5.3 Path planning and motion control

5.3.1 Inverse kinematics

The Denavit-Hartenberg parameters (also called DH parameters) are the four parameters associated with a particular convention for attaching reference frames to the links of robot manipulators [147]. As the Inmoov robot's arm has five DOFs, the kinematics calculation frame assignment is needed. Table 5-1 is the Denavit-Hartenberg notation parameters obtained for each joint and link connections. The transformation matrix is Eqn. 5-9 [148].

Table 5-1 D-H notation parameters for link connection

Joint	a _i	α _i	θ _i	d _i
1	a1	90	θ1	0
2	0	90	θ2	d2
3	0	90	θ3	d3
4	0	90	θ4	0
5	0	0	θ5	d5

$$A_n = \begin{bmatrix} \cos \theta_n & -\sin \theta_n \cos \alpha_n & \sin \theta_n \sin \alpha_n & l_n \cos \theta_n \\ \sin \theta_n & \cos \theta_n \cos \alpha_n & -\cos \theta_n \sin \alpha_n & l_n \sin \theta_n \\ 0 & \sin \alpha_n & \cos \alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5-9)$$

After getting the target object's position, the next task is to control the hand to approach the object. It is a typical inverse kinematics problem. It means that when a desired

reachable position in the 3D space is given, each DOF's angle can be calculated to move the robotic hand to the given location. It may have multiple solutions for one destiny position. The method proposed in [148] uses Eqn. 5-10 to calculate inverse kinematics of robot arm to get the solution with the least possible movement.

$$\Delta\theta = J^T(JJ^T + \lambda^2 I)^{-1}\vec{e} \quad (5-10)$$

5.3.2 Grasping pose

“Wrap” is a commonly used hand pose that grips the object by the thumb and other four fingers [17]. It can be used to hold cylinder objects with a diameter of 3 - 12 CM. This chapter chooses this pose to test the robotic hand as it has a lower motion accuracy requirement than other poses. After getting the location 3D coordinate of the object, it first controls the hand to approach the target object and then moves the thumb and fingers to form the wrap pose to hold the target object (Figure 5-6).

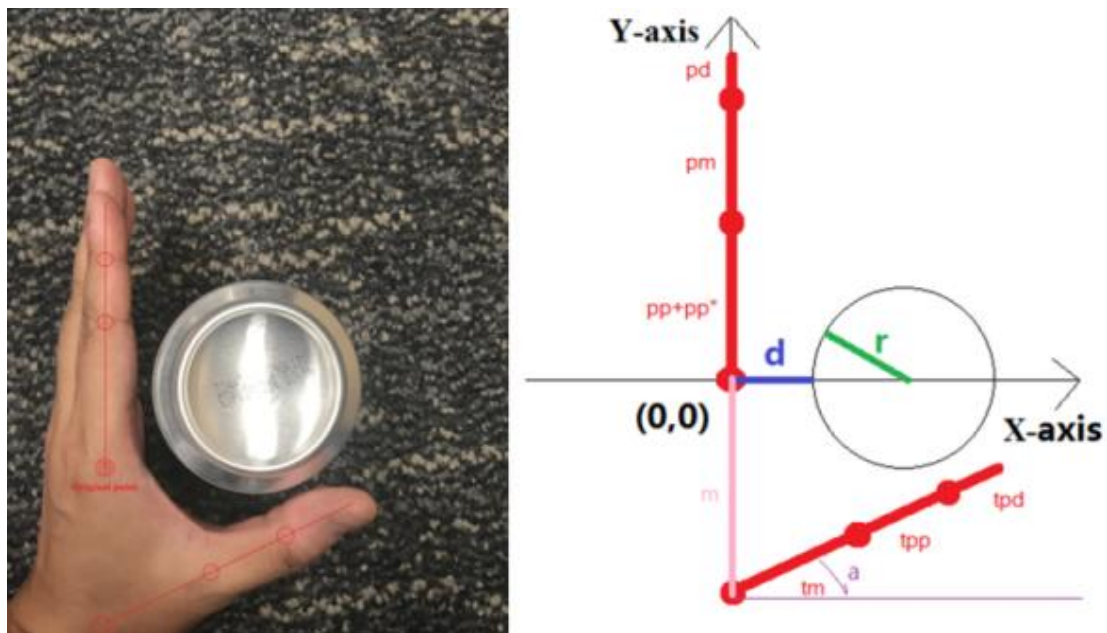


Figure 5-6 Diagram for wrap pose

pd – distal phalanx; pm – medial phalanx; pp – proximal phalanx;

tpd – thumb distal phalanx; tpp – thumb proximal phalanx; tm – thumb metacarpal; PP* – web height from the metacarpophalangeal joint; d – the distance from palm to the target object. r - radius of the target object estimate based on the width of the bounding box

5.4 Experiments

5.4.1 Experiment setting

YOLO requires a high-speed processor to handle the mega quantity of calculation, while the Inmoov robot's controller, Arduino Mega 2560TM, only has 256K memory. Therefore, the experiment establishes the object detection software in a desktop computer linked with Kinect II.

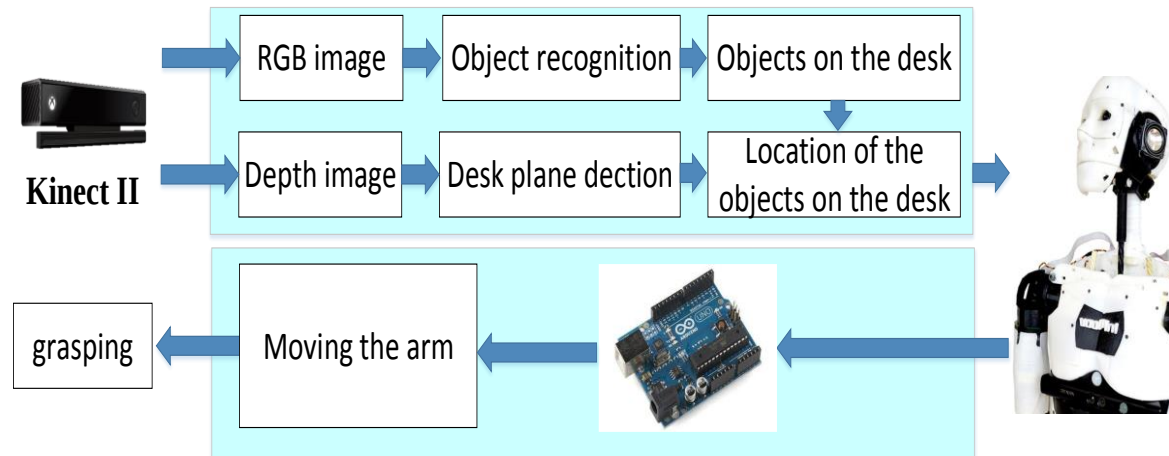


Figure 5-7 Flow chart of our method

The above Figure 5-7 displays the designed framework for the demo of locating the objects on the desk. Firstly, the objects in front of Kinect II are detected and recognized using the RGB image. Then the desk plane (or background) is detected and removed in the depth image. Finally, the location of the objects on the desk is computed according to the depth information of the objects.

5.4.2 Grasping test with a humanoid robot

Since the first appearance of Virtual Humans in the early 1980s, many types of research related to grasping plans have been conducted in a virtual environment [115]. A virtual robot is designed based on “Anthropometric Body Modeling” [116]. The virtual robot is a 3D model with the same scale as the real robot or an adult woman. The animation control parameters of each joint are manually set to match the motor control parameters, so the motion of the real robot is replicated by the animation of the virtual robot under the same control parameters. As a result, the proposed method can adequately test any grasping actions in the virtual robot before applying them to the real robot. The way of grasping is based on the “heuristic grasping decision”[149]. The motions of the Nadine

robot are pre-set at this stage. Some facial emotions are also added. Four intermediaries' actions are shown in Figure 5-8.



Figure 5-8 Four intermediaries' actions of Virtual Nadine

In order to determine the effectiveness and accuracy of the robotic hand, the robotic hand's ability to recreate specific grasping motions is tested with a humanoid robot Nadine. All test gestures are defined in the grasping taxonomy designed by Thomas Feix [33]. The proposed method designed a customized compact actuation system with only six actuators compatible with the Nadine robot (Figure 5-9). Various objects were positioned within the robot's grasp before actuating the finger to recreate the grip. Some trials and errors were required to recreate the grasps accurately.

The robotic hand was most successful in recreating “power grasps” (large and small diameter objects as seen in figure 5-10). Although the hand was victorious in performing most of the defined grasps, the limited 6 DOF offered by the hand meant that some of the grasps were not accurate recreations. For instance, grasps that involve pinching between the thumb and a finger might have the points of contact at the fingertip and the thumbnail as opposed to the fingertip and the thumb tip (as seen in the writing tripod grip). Additionally, grasps that call for the actuation of only some of the phalanges in the finger because each finger only has 1 DOF. Additionally, the robotic hand lacks the necessary DOF for the fingers to orient themselves away or toward each other, making the adduction grip difficult.



Figure 5-9 Installation with Nadine Robot. The servo bed is linked to the forearm frame of the robot

Both the InMoov robot and Nadine robot are tested for verifying the proposed system. The results showed that both robots could grasp the objects as per plotted motions. Figure 5-10 provides four screenshots of the robot grasp test. (Video link: <https://youtu.be/o1Kpb2Rs-AI>; <https://youtu.be/ndwsruEvmFY>)

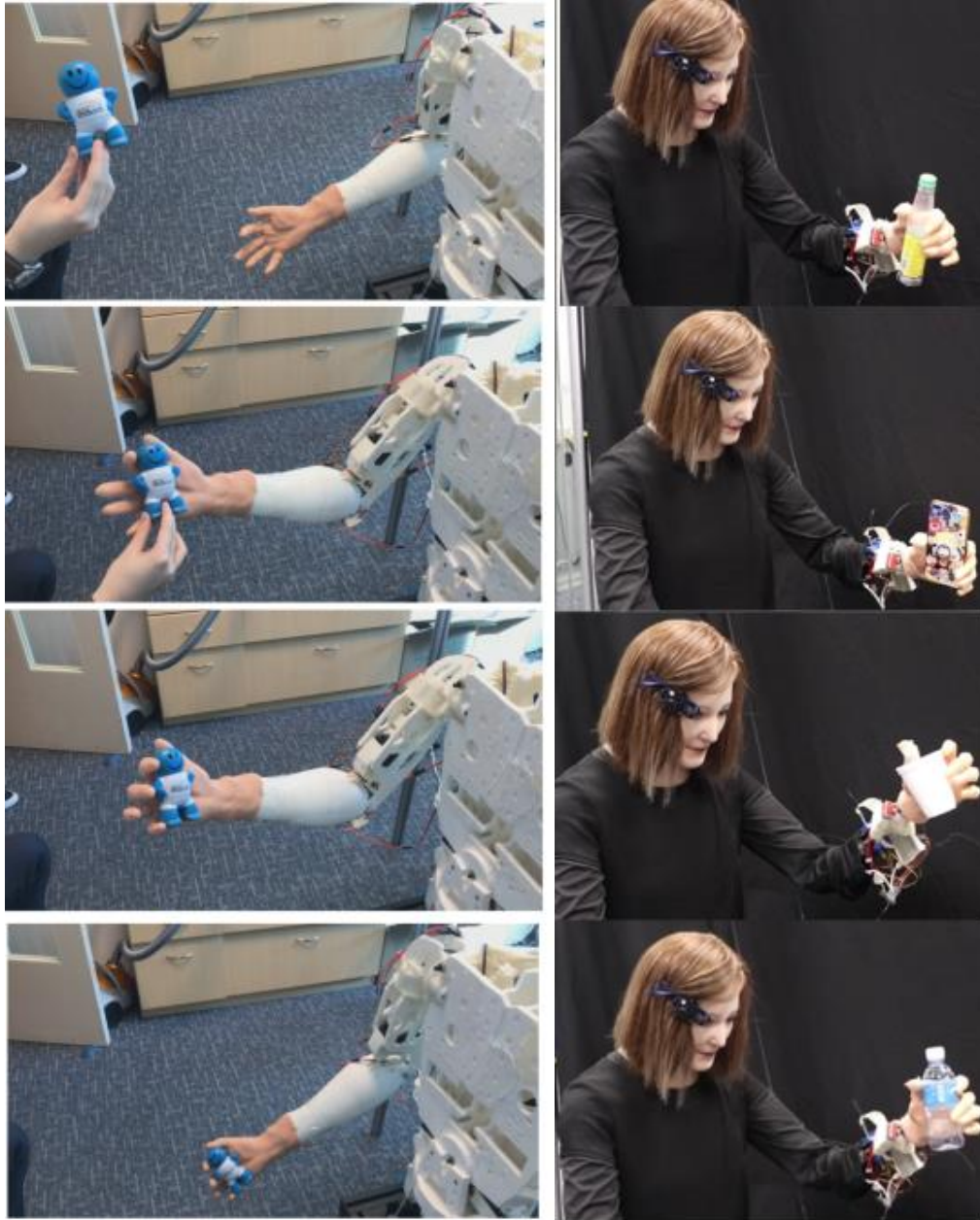


Figure 5-10 Grasping test with humanoid robots

5.4.3 Real-time grasping

This chapter also did the real-time grasping test with the InMoov robot. The results showed that the robot could grasp the objects autonomously in real-time. Figure 5-11 provides three screenshots of the robot grasp test.

The procedure of our method is as follows:

Run the vision detection software on the controller PC. The linked Kinect II will start to detect the area in front of it.

1. When a pre-programmed target appears, the software will send the object's category, location, and size to the humanoid robot (Figure 5-1). In the testing, the tester puts a goblet in front of the robot with the human hand. The software works fine in this case.

The humanoid robot will do the motion plan for the hand and fingers to grasp the target object (Figure 5-11). In testing, the robot raises the left arm and hand to approach the cup and eventually grasp the cup with a wrap pose. (Video link: https://youtu.be/_ktm98wDwC0)

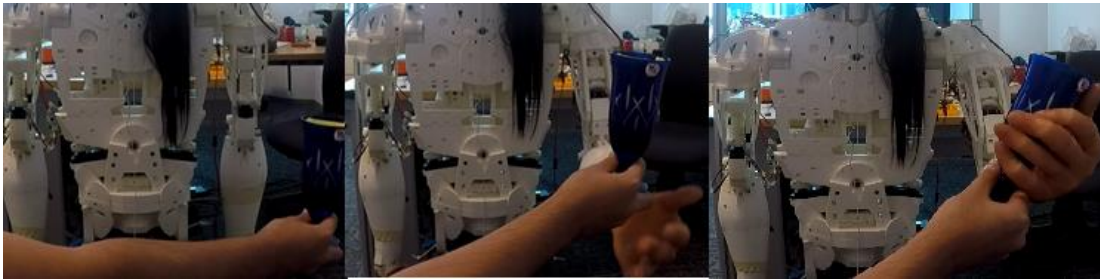


Figure 5-11 Grasping test with Inmoov

5.5 Summary

This chapter has described a manipulator grasping system, including a communication mechanism among the central controller, the visual sensor (Kinect II), and the manipulator through the robot operating system. The object detection software YOLO is modified to provide more data for grasping. After an object is placed within the visual field of the visual sensor, it will be recognized, and its 3D coordinates and size will be outputted. According to the position relationship between the visual sensor and the manipulator, the central controller converts the coordinates of the graspable point into control instructions and sends them to the manipulator. The manipulator moves to the designated position and grasps the object according to the control instructions.

Compared to other solutions with multiple cameras or multi-view camera, the proposed system needs fewer data and only one visual sensor [150, 151]. Therefore, it provides a cost-effective solution, which makes it useful in practice.

Chapter 6 A Gesture-based Approach for Complex and Continuous Manipulation Using Anthropomorphic Robotic Hands

6.1 Introduction

This chapter proposes a gesture-based approach with the purpose of mimicking the dexterity of the human hand for grasping and in-hand manipulation. In order to deal with activities of daily living in unstructured environments, the human hand is one of the best examples for design a robotic hand, while in-hand manipulation is an excellent method to show the dexterity of a robotic hand. However, the majority of existing robotic hands have difficulty in duplicating the human hand's in-hand manipulation, including object translation, rotation, and other more complex manipulations such as continuous rotation, spinning a pen around the thumb and rotating Rubric's cube. The difficulty is due to the lack of a method for duplicating a human hand's actions to a robotic hand. This chapter analyzes and decomposes complex manipulations into continuous gestures and implemented them by interpolation method. The experiment show that with the proposed approach, a specially designed robotic hand is capable of multiple in-hand manipulations, including rotation, turning, and transition for different object shapes such as slim cylinder, big cylinder, sphere and cuboid, etc. The proposed manipulation method has many potential applications in humanoid robots robotic hand, prosthetic hand and industrial areas¹⁴.

The robotic hand is a movable and programmable mechanical structure aiming to partially or fully mimic the human hand. As early as 1774, the Jaquet-Droz family built an automate named "the writer," who can write any custom text up to 40 letters long [152]. After that, during these about 250 years, although the invitation computer saved

¹⁴ Part of this work is published in "Tian, L., Li, H., Wang, Q., Du, X., Tao, J., Chong, J., Nadia Thalmann, N. M., Thalmann, & Zheng, J. (2021) "Towards Complex and Continuous Manipulation: A Gesture Based Anthropomorphic Robotic Hand Design." IEEE Robotics and Automation Letters."

a lot of work required dealing with programmable, there is still no robotic hand design capable of 100% duplicate the human hand's functionality [12].

Designing a mechanical structure that fully mimics the dynamic of the human hand is a challenge problem. In 2019, a later version of the Shadow Dexterous hand was used for solving Rubik's cube by in-hand manipulation in a video [133]. On the one hand, this video showed that the traditional design of the robotic hand is capable of human-like manipulation; on the other hand, there is still a significant gap in the aspect of deformation finger/palm and the way of the finger motion. It is challenging to use only rigid material to simulate the natural hand's dexterity. Besides, the sensory and actuation systems of the human hand are too complex and too high efficiency to duplicate.

Based on previous work on multi-layer robotic hands [153], this chapter changes the actuation method, increases the DOF, and provides a new simplified design of anatomically correct robotic hands. This design aims to provide a customizable robotic hand mechanical structure that can significantly duplicate the human hand's dexterity with a simple actuation system (13 electrical servo motors) and short fabrication and assemble duration (20 hours). The artificial tissue and bone layers can be 3D printed by a 3D printer, and the artificial skin layer can be made with silicon rubber quickly (Refer to Figure 6-1).



Figure 6-1 The robotic hand part consists of 4 materials: 3D printed bones, 3D printed elastic tissues, nylon cable and Bowden cable with pipes. Left top: Artificial tissue. Left down: servo bed with 13 servo motor

Besides testing the robotic hand by 33 gestures from grasp taxonomy, manipulation is an excellent way to verify the functionality of a robotic hand. Not only is duplicating human hand functionality an ultimate goal, but the human living environment is also built to a “human hand-friendly” environment. It could go bottom-up, defining manipulation as the union of several different types of manipulation: pick-and-place, mechanical assembly, and in-hand manipulation [154]. In [155], “Within prehensile hand manipulation” is a sub-category of human manipulation task and can be further divided into 12 types. Almost all human activities of daily living can be classified into one or more grasp gestures or manipulation types [156-158].

The dexterity of robotic hands has kept improving for many years, so it is necessary to develop higher standard testing methods to verify their functionalities [33, 125, 159]. Based on previous research on grasping and in-hand manipulation, a new test procedure is concluded with three levels for testing a robotic hand. Level 1: Grasping targets using 33 gestures from grasp taxonomy and 11 gestures from Kapandji test. Translate and

rotate standard shape objects (cylinder, sphere and cuboid etc.) with different sizes in three axes. Level 2: Continuous and Composed Manipulation (CCM) such as contiguous rotation of a cylinder (pen), a sphere (open a bottle cap) and a cuboid (rotate and turn a Rubik's cube) etc. Level 3: CCM with changing the center of gravity of the robotic hand, such as crawling with a finger and climbing a ladder. CCM with changing the center of gravity of target object such as toss and spin an object. The test result of these 3-level tests is shown in section 6.3.

6.2 Proposed Method

6.2.1 Mimicking the human hand DOF

Fully duplicate the human hand's 21 DOF would lead to a bulky and complex actuation system [28, 32, 160]. In contrast, the underactuation method will reduce the number of actuators but lose independent control for each joint [26, 30]. Previous research showed that the distal-interphalangeal (DIP) and proximal-interphalangeal (PIP) joints are working like an under-actuated system [81]. In this proposed design, each finger uses one Bowden cable to control DIP and PIP joints simultaneously. This chapter further studies the maximum range of motion (ROM) required to achieve 33 gestures from grasping taxonomy and reduce the two least important DOF from the ring finger's metacarpophalangeal (MCP) joints. As a result, this robotic hand's dynamic model also has 15 movable joints but only eight independent DOF plus five underactuated DOF (refer to Figure 6-2).

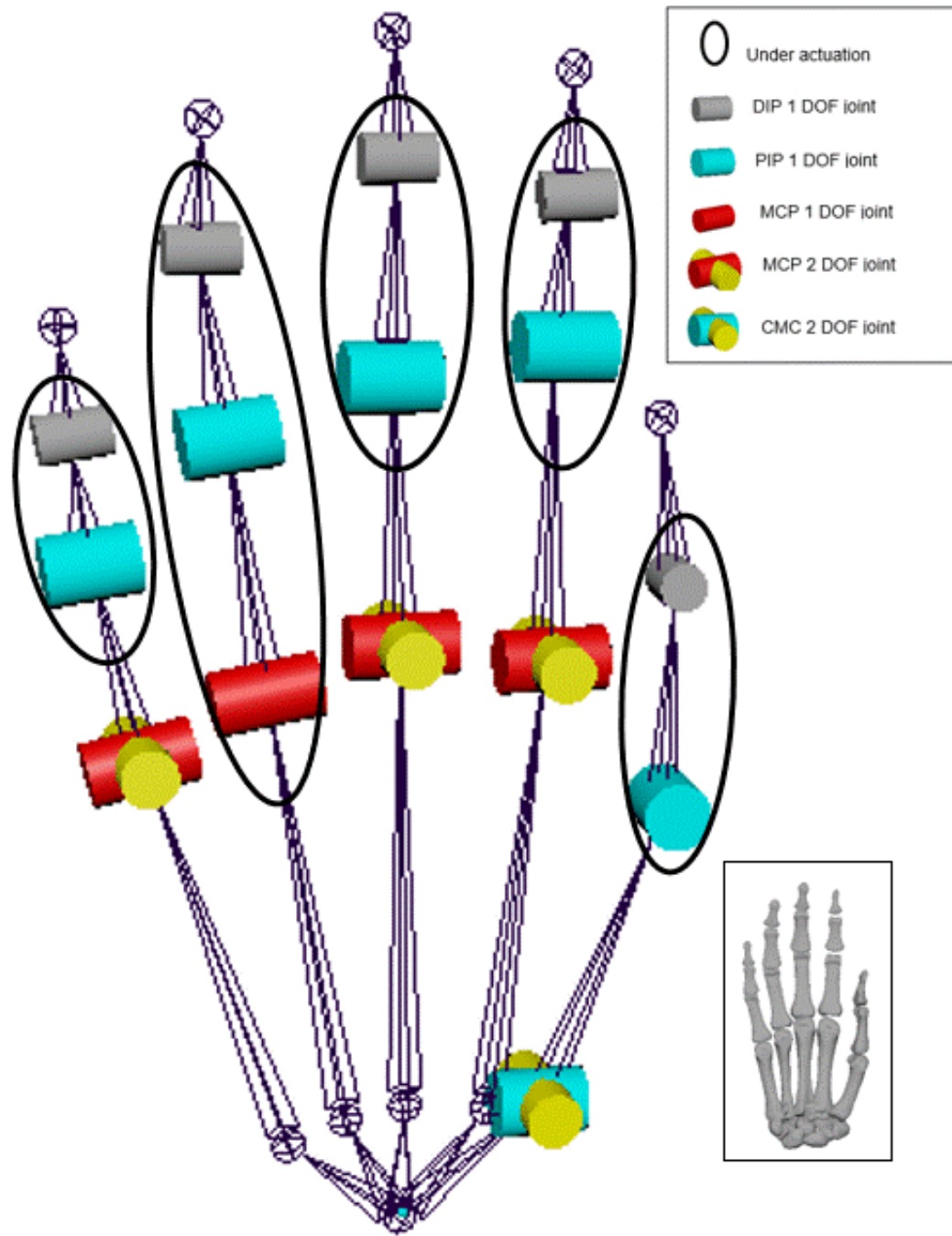


Figure 6-2 The simplified 13-DOF model of the proposed Nadine hand V6

The proposed method uses the elastic 3D printable material, RS-F2-ELCL-01, with 50A shore hardness and 3.23 MPa tensile strength for artificial tissue. For artificial bone, the proposed method uses the rigid 3D printable material RS-F2-GPCL-04, which has 2.8 GPa tensile strength. Both materials are 3D printed with a “Form2” 3D printer. In order to simulate human hand skin, the proposed method uses PlatSil Gel 10™ (10A shore hardness), directly “dry-peeling” the artificial skin from a human hand.

Based on previous research, this robotic hand’s bone structure and artificial tissue layer are generated by Python script with CAD software (Maya™) without manual work [85,

132]. The proposed script code saves a lot of manually 3D modeling time and proves a precise and duplicable solution for any size of input hand 3D model.

Due to the Bowden cable's rigid character, this design uses it as the tendons, which allows “pull and push” movements by applying tension and compression, and converts it to flexion and extension at the joints. Hence for drive DIP and PIP, this design would only include the Flexor Digitorum Tendons (FDT) responsible for flexion and extension. The Bowden cable used in this section is the 1 x 7 strands, 0.75mm diameter thin Bowden cable. It allows more stable flexion and extension at the DIP and PIP joints, where the bones are small and require less force to move. The flexion and extension of the MCP joints are mainly achieved by Lumbrical muscles (LUM) in natural hands, while this group of muscles is replaced by a thick 1 x 19 strands, 1.25mm diameter Bowden cable. Thicker Bowden cables would have a higher modulus of rigidity, which means that greater force can be applied than the thinner cable during finger extension. It would allow the MCP joints to be extended while DIP and PIP joints are flexed. The Flexor pulley rings are designed onto the phalanges bones. They are printed with the bones as a whole piece. Finger adduction and abduction are controlled by a pair of Interossei muscles (INT), while it was mimicked using the 1 x 7 Bowden cable in our design. The cable is looped around the top of proximal phalanges. This design aims at the most significant sideway moment when the cable is being pulled. In order to further increase the sideway moment, the INT Bowden cable route to its adjacent metacarpal bones by modified Tendon Sheath (MTS) and a cross made for Index and Small finger. This design uses fishing wires (0.34 mm D, 17 LBS straight tension, 15.5 LBS knot tension) as Collateral Ligaments (CL) to link the bones. A plastic tendon sheath (TS) is used for holding the FDT and LUM. The articular cartilage (AC) is modeling as a sphere to reduce friction and create a smoother MCP joint (Refer to figure 6-3).

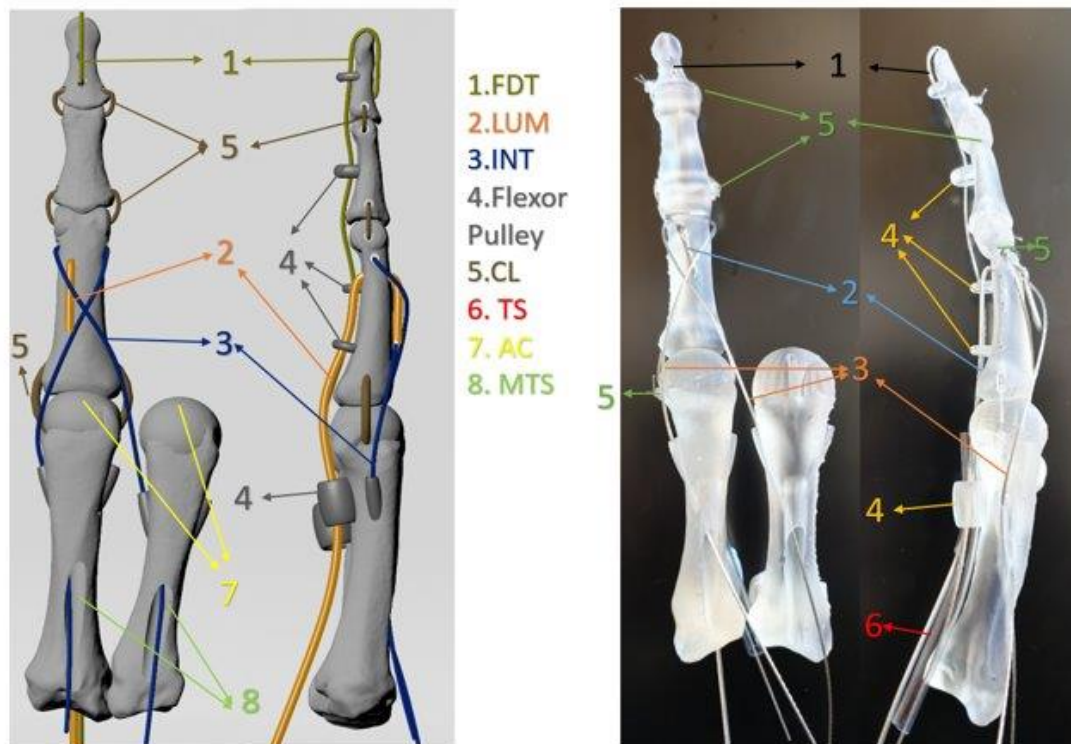


Figure 6-3 Finger Mechanical design (FDT: Flexor Digitorum Tendons, LUM: Lumbrical muscles, INT: Interossei muscles, CL: Collateral Ligaments, TS: Tendon Sheath, AC: Articular cartilage, MTS: Modified Tendon Sheath)

Similar to the finger, the thumb is actuated by three Bowden cables which simulate Flexor Pollicis longus (FPL), Flexor Pollicis Brevis (FPB) and Adductor Pollicis (Refer to Figure 6-4).

All Bowden cables are linked to servo motors as actuators. This design uses 13 MG996R (torque: 11 kg/cm) as actuators (refer to figure 6-1). The robotic hand model is compared with two other state-of-art robotic hands in Table 6-1. For the advantages of the proposed design, it realizes 90% of the grasping ROM by only 13 actuators. Bowden cable support both pull and push action, which save control tendons. And the materials are cheap.

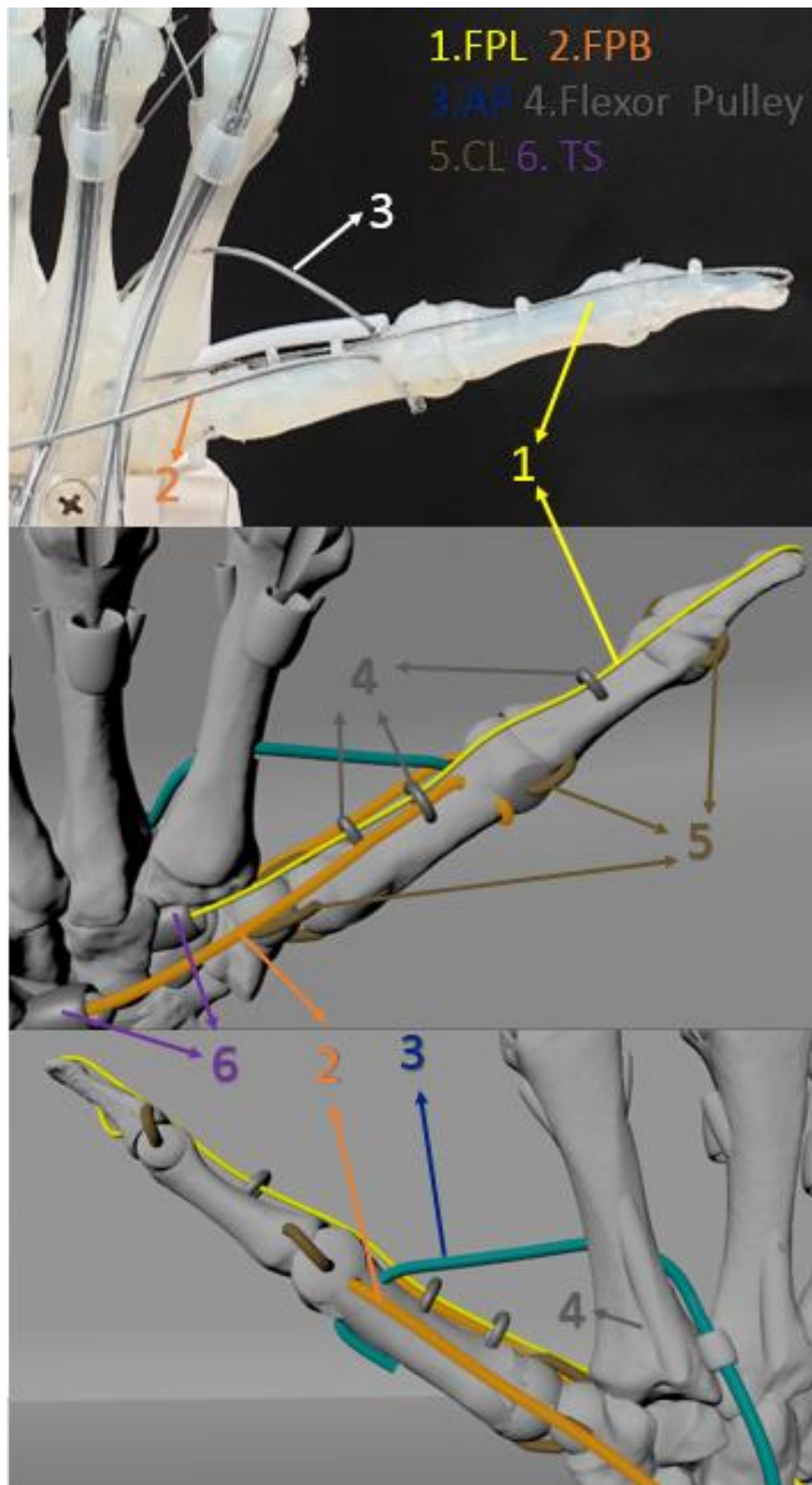


Figure 6-4 Thumb Mechanical design (FPL: Flexor Pollicis Longus, FPB: Flexor Pollicis Brevis, AP: Adductor Pollicis, Flexor Pulley, CL: Collateral Ligaments, TS: Tendon Sheath)

Table 6-1 Comparison of hand models

Robotic hand	Anthropomorphic Hand[30]	Human-like robotic hand[31]	The proposed Robotic Hand
Bones	3D printed, ABS	Molded, resin	3D printed, resin
Actuator	Servo, Nine MX-12W, one AX-12A	Pneumatic McKibben actuators	Servo, 13 MG996r
Tendons of finger	FDP and EDC (Extensor Digitorum Communis)	FDP, FDS, EDC, LUM and INT	FDP, LUM and INT
Driven Cable	Soft cable	Soft cable	Bowden cable
Ligaments	Crocheted ligament	Silicone ligament	Fishing wire
Tendon pulleys	Laser-cut elastic silicone	Polyethylene tubes	3D printed together with the bones
Tissue and skin	Fingertip cap only	Not included	3D printed, elastic resin and silicon skin
Test Method	15 gestures from Taxonomy	Motion Range of finger	50 Benchmarks and CCM

6.2.2 Representation of gesture by finger joint rotation

Without considering the object's weight, the key to grasping action is to complete a hand gesture. Both Cutkosky and Feix's grasp models are image-based, which is difficult to understand and duplicate fully. This chapter proposed using human hand 15 joints rotated angles to represent a hand gesture and labeled all 33 gestures from grasping taxonomy [33] (Refer to figure 5-5 for one example). As a result, each gesture can be represented by the 15 joints rotate angle, which contains 20 ROM. Theoretically, any gesture can be duplicated by a robotic hand if it fulfills the required 20 ROM.

The size of the hand and the grasped object will affect the results. The human hand used in this test is 180 mm in length. Furthermore, the size of grasped objects is from [33]. This chapter compares the human hand ROM, human hand ROM for achieving all grasping taxonomy and our robotic hand ROM in Table 6-2. This robotic hand duplicate 80% human maximum motion range and 90% taxonomy required motion range. It causes a bit of difference in human pose duplication, but the proposed robotic hand can still duplicate all 33 poses from the taxonomy (Refer to Figure 6-8).

Table 6-2 Comparison of hand ROM

Finger	x	Human ROM [161, 162]	Human ROM for taxonomy	The proposed robotic hand ROM
Thumb	IP	0 – 90	0 – 84	0 – 70
	MCP	0 – 70	0 – 70	0 – 75
	CMC	0 – 53	0 – 48	0 – 61
	<i>Add. /Abd.</i>	-40–50	0 – 50	0 – 50
Index	DIP	0 – 80	0 – 70	0 – 70
	PIP	0 – 120	0 – 100	0 – 100
	MCP	0 – 90	0 – 90	-15 – 82
	<i>Add. /Abd.</i>	-20 – 25	-20 – 22	-8 – 26
Middle	DIP	0 – 80	0 – 80	0 – 90
	PIP	0 – 120	0 – 106	0 – 80
	MCP	0 – 90	0 – 90	-7 – 95
	<i>Add. /Abd.</i>	-20 – 25	-20 – 20	-6 – 15
Ring	DIP	0 – 80	0 – 73	0 – 70
	PIP	0 – 120	0 – 120	0 – 90
	MCP	0 – 90	0 – 90	-5 – 95
	<i>Add. /Abd.</i>	-20 – 25	-18 – 6	-
Little	DIP	0 – 80	0 – 80	69
	PIP	0 – 120	0 – 110	100
	MCP	0 – 90	0 – 90	-4 – 90
	<i>Add. /Abd.</i>	-20 – 25	-14 – 20	-9 – 28

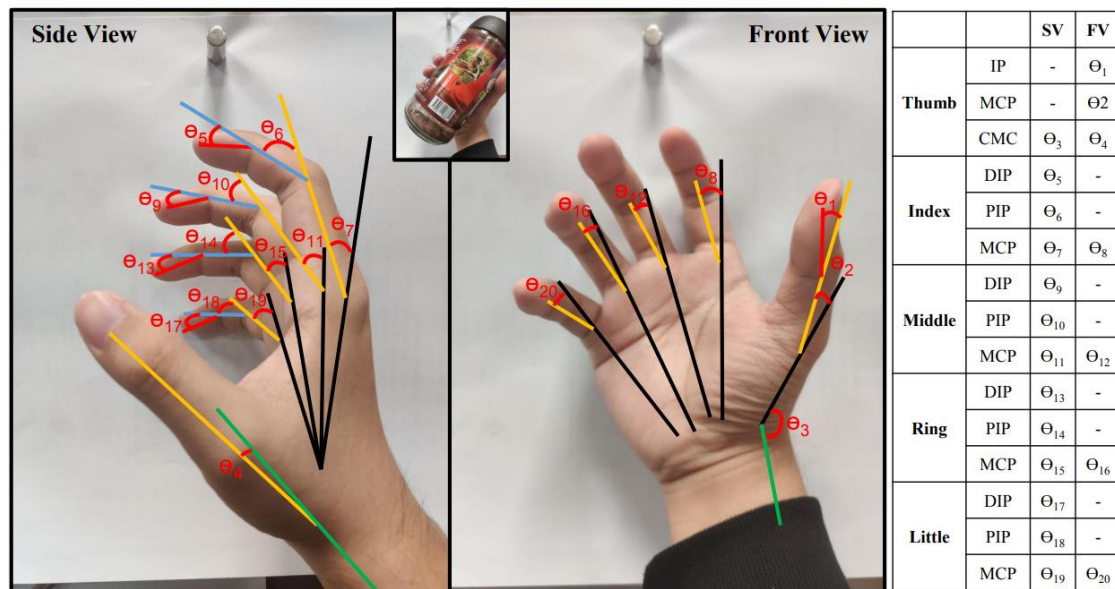


Figure 6-5 Measuring 20 angles of joint rotation for an exemplar gesture. Best viewed on a high-resolution screen. (SV: Side view, FW: front view)

6.2.3 Continuous and composed manipulation

Both hand taxonomy and in-hand manipulation refer to an action with a fixed grasping touchpoint. However, many hand actions require changing the grasping touchpoints. This chapter raises a new concept, “continuous and composed manipulation (CCM),” which refers to a meaningful hand action containing more than one gesture and manipulation. All CCM can be divided into separate grasping gestures and in-hand manipulation. For example, rotating a pen 180 degrees can be divided into 1) palmar pinch (index & thumb), 2) pitch - rotates from 0 to 90 degrees and form Adduction grip, 3) Tripod grip, 4) pitch - rotate 91 to 180 degrees and form Palmar pinch (middle & thumb), 5) prismatic two fingers, and 6) back to Palmar pinch. In order to duplicate a CCM by a robotic hand, the proposed method uses interpolation to generate path planning for each finger to accomplish the CCM. Refer to Figure 5-6 (tendon excursion diagram for rotating a pen by 180 degrees). The above process can be repeated to get a 360 degree rotation.

Besides in-hand manipulation, CCM can also duplicate other hand motions related to change in the center of gravity. The experiment section does an initial test for hand gobble motion (crawl, change orientation and climb), toss and spine an object.

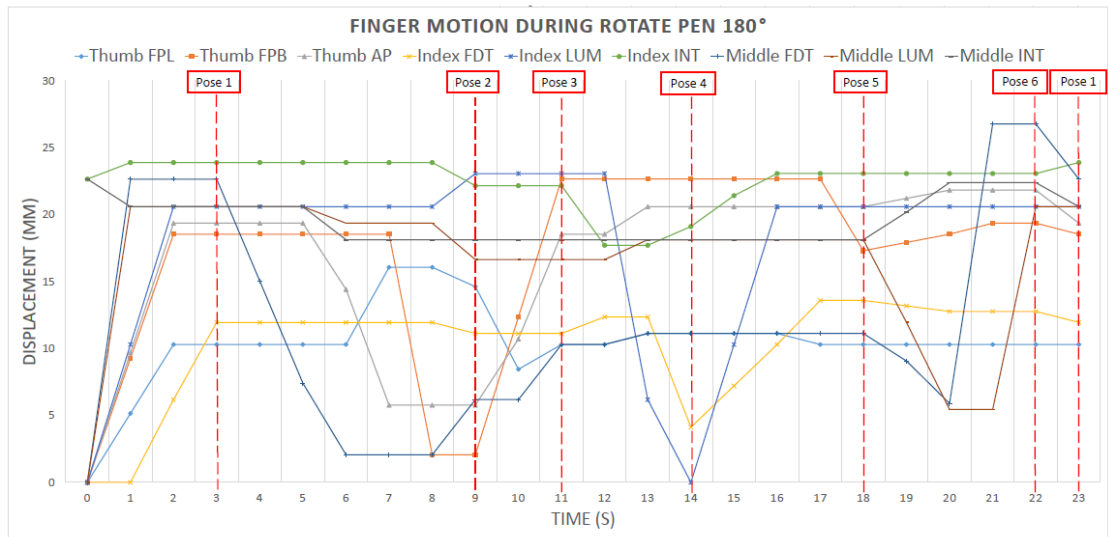


Figure 6-6 Tendon excursion diagram for rotating a pen 180 degrees

6.3 Experiments

6.3.1 Effective motion range

The trajectories of each finger are recorded and plotted in a 3D space (Figure 6-7).

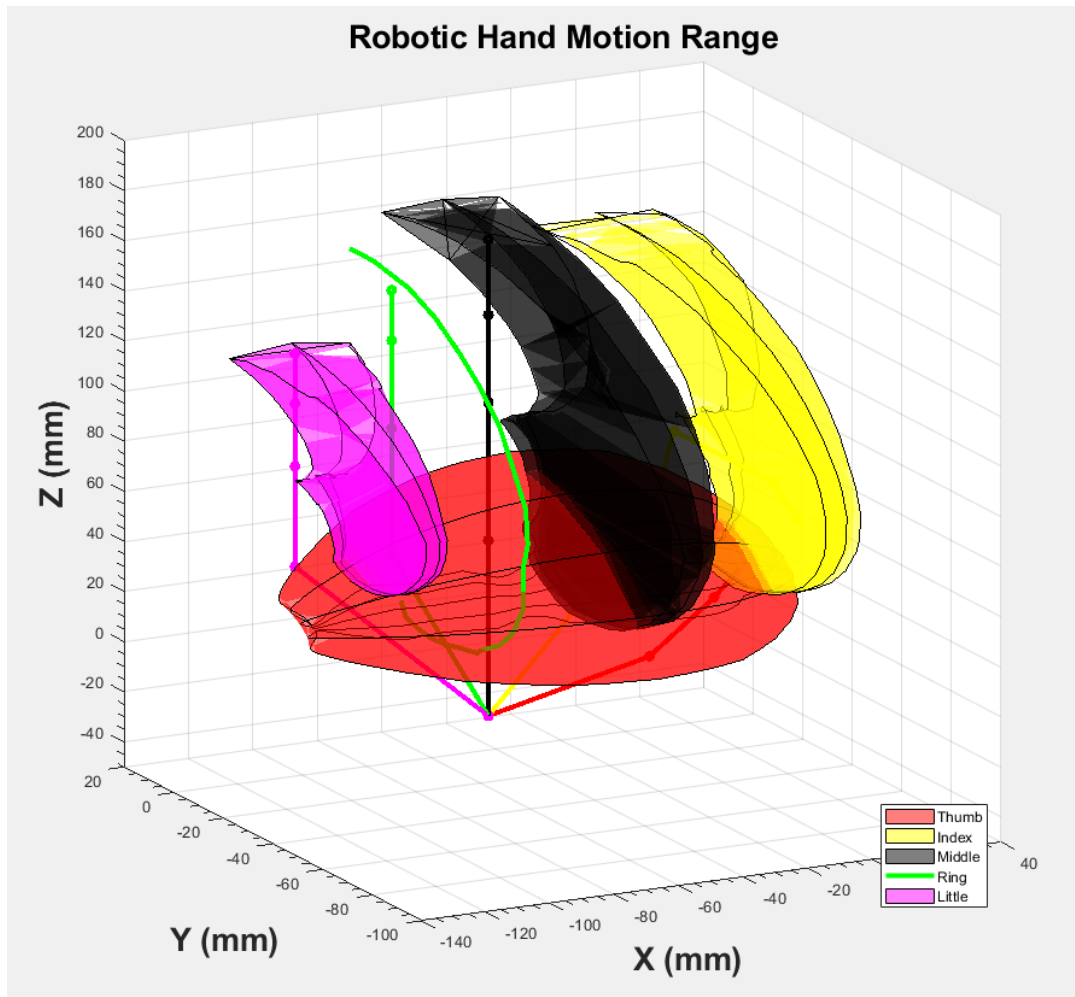


Figure 6-7 Motion range of proposed robotic hand

In order to illustrate the relationship between tendon excursion and the corresponding joint angle, this chapter samples the trajectories of the index finger and fits them with a first-order function:

$$\Theta_{\text{joint}} = AE_{\text{tendon}} + B \quad (6-1)$$

where Θ_{joint} is the finger joint rotated, E_{tendon} is the excursion of corresponding control tendon, and A and B are constants.

The proposed robotic hand index finger bones distal, middle and proximal phalange lengths are 22.2, 24.2 and 41.9 mm. The values of the A, B coefficient of determination are shown in Table 6-3 below.

Table 6-3 value of A, B coefficient of determination

Joint	Tendon	A	B	R ²
DIP	FDT	2.982	10.238	0.981
PIP	FDT	4.037	-15.143	0.975
MCP	LUM	3.115	-25.059	0.961
Add./Abd.	INT	2.133	7.679	0.996

6.3.2 Robotic hand Level 1 test

In order to evaluate the performance of the robotic hand, this chapter first performs a level 1 test for the robotic hand. All 62 test cases are tested for ten times separately, and all success rates are equal to or greater than 90%. Refer to Figure 6-8 for details.

6.3.3 Robotic hand Level 2 & 3 test

Level 2 and 3 tests are then done for the proposed robotic hand to evaluate this robotic hand's performance. Refer to Figure 6-9 for details. (Video link: https://youtu.be/iZ0FznwMG_o)



Figure 6-8 Row 1-5 The robotic hand presents the 33 grasping taxonomy tasks. Row 6 presents the achievement of 11 Kapandji tests. Row 7-9 presents translation and rotation cylinder, cuboid and sphere along X, Y and Z-axis.

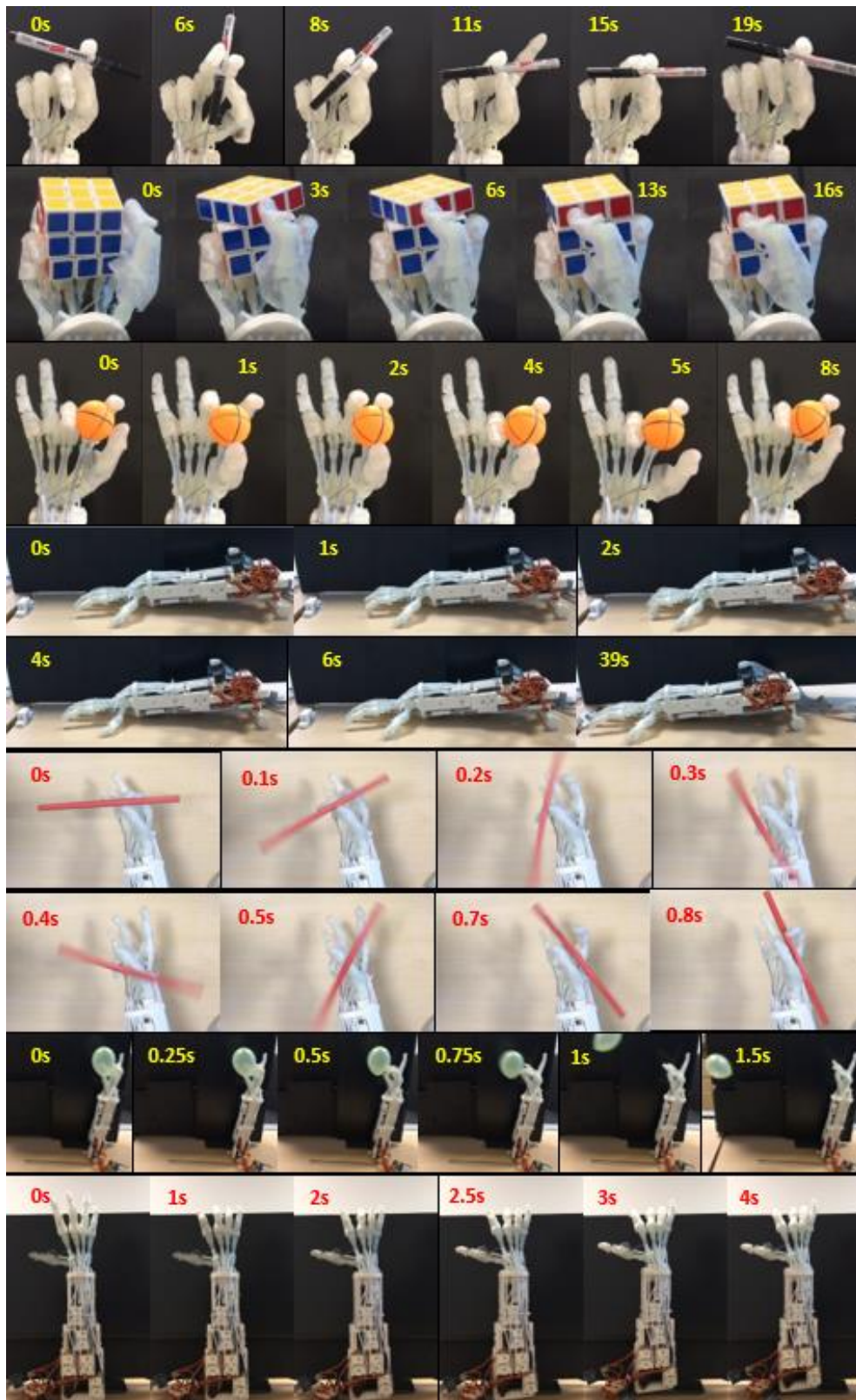


Figure 6-9 Row 1 The robotic hand presents the rotation of a pen 180°. Row 2 presents the turning of the first layer of Rubik's cube. Row 3 presents the rotation of a Ping-Pong. Row 4-5 presents crawling forward. Row 6-7 presents spinning a 3D printed thin cylinder. Row 8 presents shooting a balloon. Row 9 presents climbing up

6.4 Summary

This chapter has proposed a gesture-based framework, the core of which is the set of base gestures and their ROMs. Given the widely used gestures as the bases, this chapter devises the simplified 13-DOA robotic hand to provide the essential functions for achieving them. It also demonstrates that complex manipulation tasks can be subdivided into multiple base gestures and adopts the key-frame interpolation method to complete the tasks. The robotic hand is evaluated on the CCM benchmark and demonstrates its remarkable dexterity. The gesture-based framework and the three-layer CCM benchmark can provide a considerable baseline for future studies.

Chapter 7 Conclusion and Future Work

7.1 Conclusion

This research hypothesizes that the anatomically correct approach is a promising way to design the anthropomorphic robotic hand. A general-purpose robotic hand that can work in an unconstructed environment will significantly accelerate the research of robotic, automation, service, and medical areas. This thesis has detailed the design process and built the prototype of two robotic hands. The goal of this research is to answer the question of how to design robotic hands that highly mimic the salient biological features of a human hand with the latest developed technologies.

This thesis has studied the related work in chapter two. It reviews the past research works in four aspects: robotic hands, 3D modeling hands, actuation system, object detection, and grasping. Although there are many existing designs of robotic hands created in the past 20 years, the design of advanced robotic hands has not fully taken advantage of cutting-edge technologies.

With the help of the latest 3D scanning and 3D printing technologies, this research has developed two design methods and fabricated two different robotic hands. Chapter three presents a design method that for building low-cost, customizable 3D printed robotic hands which can partially simulate a human hand. The robotic hand is 3D printed out and then tested with the Nadine robot. The test result shows that it successfully performs 16 grasping gestures. This design method provides a fast and simple way to fabricate 3D printed rigid and soft-surface robotic hands.

Chapter four proposes a method for making a soft body, multi-layer 3D printed robotic hand. It aims to provide a deformable and multi-purpose robotic hand. The human hand's tissue and skin play essential roles during grasping. The robotic hand is 3D printed with the latest SLA 3D printing technologies. The robotic hand's deformable test result shows that the robotic hand has similar deformability as a human hand. This feature enhances the grasping ability of the robotic hand when it grasps some objects

such as Tofu and marble balls.

With the latest actuation materials, this research designs two types of actuation systems. The soft cable-driven system can actuate the two proposed robotic hands with six actuators and 16 DOFs. The experiment showed that the proposed robotic hand could have significant grasping gestures as a mighty and dexterous human hand. The second method is a full actuation system for a robotic finger. The experiments show that this system is able to generate all 11 postures of the finger.

With the latest object detection techniques and control theories, a method for path planning and motion control of robotic hands is developed in chapter five. Then the research tests the proposed robotic hands with humanoid robot Nadine and InMoov. The experimental results show that the robots could approach and grasp the target object like a human with the help of object detection software YOLO.

In chapter six, the research proposes a new gesture-based approach for complex and continuous manipulation for a robotic hand. The experiments show that the proposed robotic hand is capable of many human-like in-hand manipulations such as playing a Rubik's cube, rotating a Ping-Pong ball and turning a water bottle cap.

In summary, this research has the following contributions:

- While existing methods of building a robotic hand require a lot of manual work and the final products are usually quite different from the human hand, the proposed method is simple and low-cost, and can build personalized robotic hands via 3D printing with biomechanical information. For example, the fabrication cost of a robotic hand including the actuation system is under US\$100. The parts, including the bone structure, rubber band joints, and fishing line-driven cable, can be 3D-printed or quickly found. The total assembling time is under 12 hours.
- The proposed method of creating deformable tissue provides a fast and simple way to fabricate the robotic hand's tissue part, which helps to improve the flexibility of the robotic hand.

- The proposed solution of autonomous grasping provides an integrated solution to the object detection and grasping problem. It works with different humanoid robots and various environments.
- The concept of complex and continuous manipulation (CCM) can test the dexterity of different kinds of robotic hands. The proposed interpolation method is a new and promising way to deal with the CCM problem.

The limitations of this research are:

- All robotic hand designs of this research are based on multi-material. Thus, it leads to complex manual production progress.
- The object detection software, YOLO, can only provide a rough bounding box of the detected object, which limits the accuracy of the grasping plan,

7.2 Future work

According to the limitations, there are two future works that are planned to extend this research.

- Design a single-material anthropomorphic robotic hand to realize the human hand's functionality by single 3D printable material. The robotic hand 3D model is combined with bones, ligaments, tendons, pulley systems and tissue (Refer to figure 7-1). The first trial 3D printed result is shown in figure 7-2. Single material robotic hands will significantly reduce the fabrication and assembly cost.

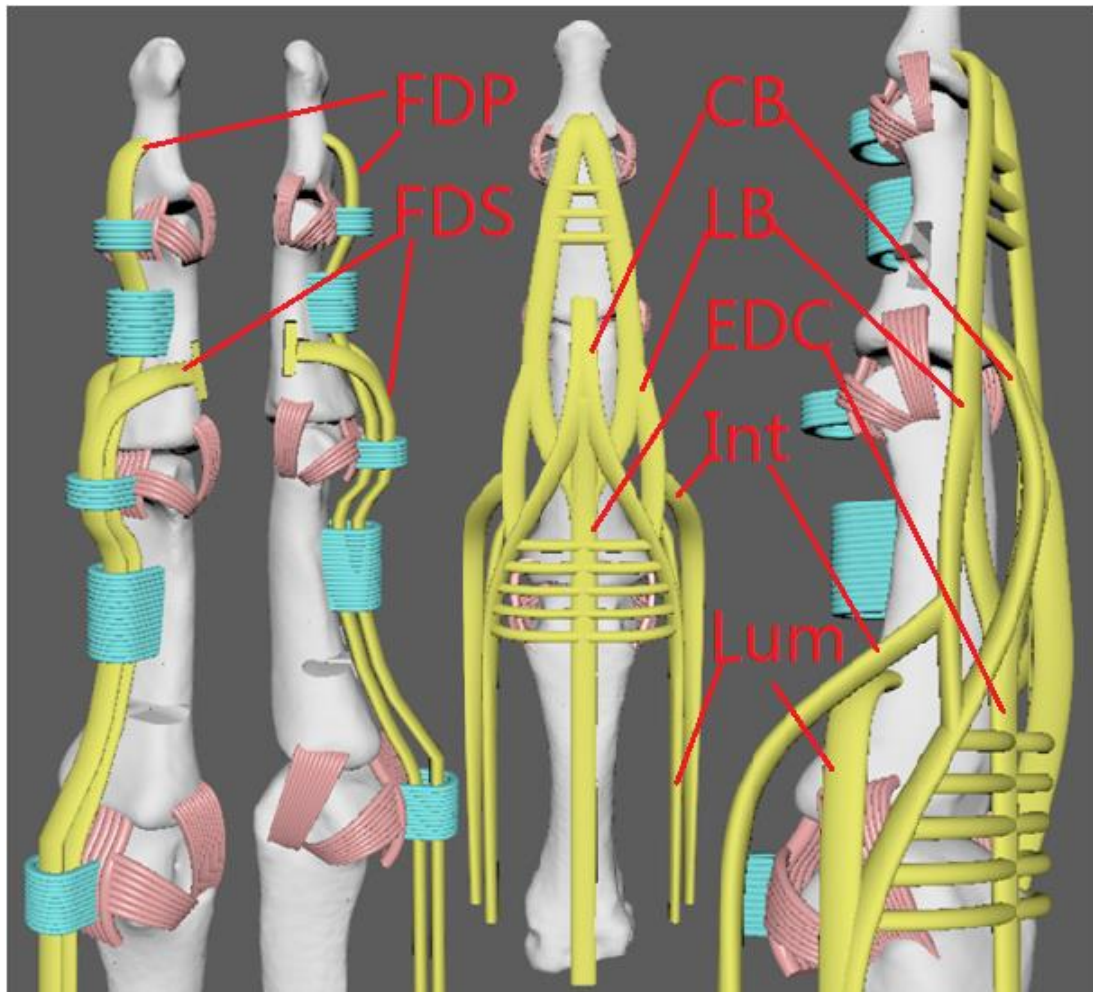


Figure 7-1 3D model of one-material robotic hand



Figure 7-2 Front and back view of our 3D printed robotic finger

- Improve the autonomous grasp system with a more robust perception system. The current solution detects and locates the object with Kinect II and YOLO. YOLO could detect the object and indicate the object with a bounding box (Figure 7-3). However, the precise grasp needs more geometry information of the object. With the help of next-generation perception technologies, the target objects can be classified into a standard 3D shape, such as a cylinder or a sphere, based on their categories. The other work is to design a new grasping solution based on a more precise perception result.

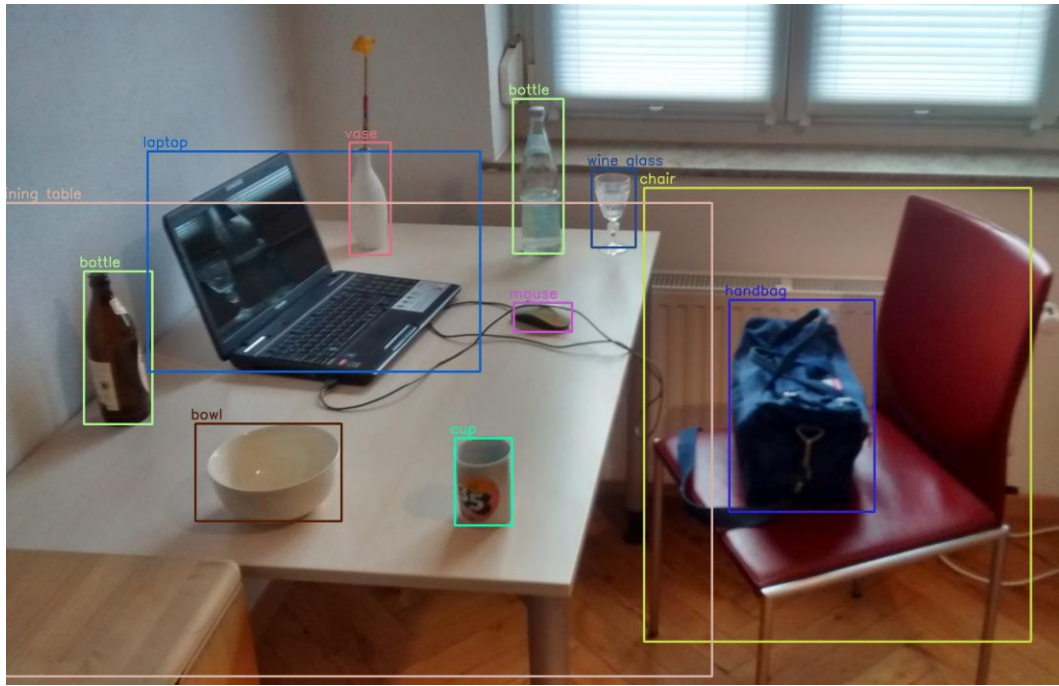


Figure 7-3 YOLOv3 (source: https://en.wikipedia.org/wiki/Object_detection)

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Appendix

Table A-1 Ratio of dimensions of hand and length (HTL=180mm)

No.	Name	Ratio	Result(mm)
1	TLT	0.318	57.23
2	TLP	0.152	27.352
3	TLD	0.166	29.877
4	ILT	0.38	68.486
5	ILD	0.137	24.722
6	ILP	0.13	23.46
7	ILM	0.113	20.304
8	MLT	0.417	75.009
9	MLD	0.14	25.248
10	MLP	0.146	26.195
11	MLM	0.131	23.565
12	RLT	0.388	69.854
13	RLD	0.138	24.828
14	RLP	0.129	23.25
15	RLM	0.121	21.777
16	LLT	0.311	55.967
17	LLD	0.124	22.303
18	LLP	0.102	18.41
19	LLM	0.085	15.254
20	HLT	1	180
21	TBD	0.112	20.199
22	TBP	0.16	28.72
23	TDD	0.096	17.253
24	TDP	0.123	22.092
25	IBD	0.089	16.096
26	IBM	0.105	18.936
27	IBP	0.114	20.514
28	IDD	0.076	13.676

29	IDM	0.092	16.517
30	IDP	0.103	18.515
31	MBD	0.089	16.096
32	MBM	0.105	18.831
33	MBP	0.108	19.357
34	MDD	0.076	13.676
35	MDM	0.095	17.148
36	RBD	0.082	14.728
37	RBM	0.096	17.358
38	RBP	0.103	18.515
39	RDD	0.071	12.729
40	RDM	0.088	15.885
41	LBD	0.076	13.676
42	LBM	0.088	15.78
43	LBP	0.1	17.989
44	LDD	0.069	12.414
45	LDM	0.081	14.623
46	LDP	0.088	15.78
47	MDP	0.117	21.146
48	RDP	0.115	20.725
49	WB	0.323	58.177
50	TCD	0.355	63.857
51	TCP	0.48	86.476
52	ICD	0.287	51.654
53	ICM	0.331	59.544
54	ICP	0.376	67.75
55	MCD	0.289	51.97
56	MCM	0.335	60.386
57	MCP	0.363	65.33
58	RCD	0.265	47.656
59	RCM	0.31	55.757
60	RCP	0.341	61.333
61	LCD	0.249	44.816

62	LCM	0.281	50.602
63	LCP	0.321	57.756
64	WC	0.924	166.324
