A Study on Multi-fingered Manipulation System with Flexibility and Task Versatility

多指ロボットハンドシステムの柔軟性と汎用性に関する研究

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Abstract

A great challenge for multi-fingered robotic hand systems is their ability to carry out stable grasping and versatile manipulation. To allow robots to widely operate in human daily environments there is a strong need to develop new systems that can provide advanced task capabilities and high reliability in a simple and low-cost robot hand platform. This system should be effective in different kinds of tasks and for various objects. In addition, to achieve reliable in-hand manipulation in daily environments, it is desirable for the robot hand system to be capable of absorbing some error due to incorrect object recognition. In this thesis, a methodology is presented for the synthesis of in-hand manipulation control in low cost multi-fingered robot hand systems by proposing a control strategy and hardware optimization. The work is presented in three parts.

First, a new elastic contact model is proposed . In conventional research, such a model is available only for spherical fingertips. Previous research from our laboratory discussed the importance of an anthropomorphic fingertip that can change the contact pressure simply by changing the contact angle. However, only an empirical model of anthropomorphic fingertip design is available in conventional research. These empirical equations are impossible to be used in the design stage before the fingertip is made. Therefore, traditional anthropomorphic fingertip design relies on quantitative analysis. In this dissertation, we proposed a new elastic model which could be used to quantitatively predict the performance of fingertips before they are made. The result of an evaluation experiment shows that our model could match the real fingertip. The model enables to calculate the deformation of anthropomorphic fingertips before the construction of any physical prototype.

Second, a new design methodology is proposed by using this new contact model. Using the predictable contact area and deformation information, it could improve the design quality by reducing the error between the expectation and real robot fingertip in the design phase. Furthermore, as there is no deformation sensor available in the market, we also show the application of the deformation model in robot hand grasping for improving the accuracy of object size estimation.

Third, to facilitate the feasible handling behaviours, we developed a compliance posture interpolation controller by introducing the force feedback into the posture interpolation control scheme. With this simple controller, the contact force could be controlled in an easy way during manipulation. Furthermore, to clarify the importance of the flexibility in manipulation, we conducted two kinds of evaluation experiments: 1. Task versatility experiment and 2. Adaptability to inappropriate posture experiment. The result of first experiment shows an effectiveness of soft skin with higher success rate and wider initial grasping position for manipulation. For the second experiment, I tested two cases: 1. The fingertips are too close; 2. The fingertips are too far. For the first condition, the result shows that the contact force could be controlled well. While manipulating a soft material object (the plastic cup in this experiment), the force control strategy could help the robot hand to manipulate the soft object without deforming it. For the second condition, the result shows that the force feedback in the control could help posture interpolation control to keep force closure during manipulation to prevent dropping the object. This approach could take benefits from both the simplicity of posture interpolation control and the reliability of compliance control.

The methods proposed throughout this dissertation provide a simple control strategy and low-cost passive impedance hardware design concept that will allow multi-fingered robot hands to deal effectively with various object manipulation tasks and improve the adaptability to inappropriate object recognition. With this system, we clarified the importance of flexibility in grasping and manipulation. The system is evaluated by manipulation success rate and possible initial grasping position for manipulation. The result shows an improvement by introducing "active" flexibility and passive flexibility into a low cost in-hand manipulation system. In conclusion, the soft skin is very effective for successful manipulation and the force control could improve the manipulation quality for soft objects. The performance of a low cost commercial available robot hand could be improved by the proposed system.

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Symbol	Meaning
q_i	Desired joint angle vector in interpolation control
q_{start}	Joint angle vector at the onset of the motion
q_{final}	Joint angle vector at the end of motion
q_c	Current joint angle vector
t	The time from the onset of the motion
ΔT	Transition time
τ_{des}	Desired joint torque vector
K_p	Proportional gain in PD controller
K_D	Derivative gain in PD controller
E	Young's modulus
σ	Stress of material
ε	Strain of material
P	Compression force
A	Area
L	Original length of soft material
ΔL	Deformation of soft material along pushing force direction
K	Stiffness of virtual spring

f_{ij}	Functions of the envelope curve of fingertip in i, j coordinate
r_c	Contact point of fingertip
${}^{r}f_{ij}$	The function of the fingertip curve after rotation
x_L	The intersect points of x coordinate
z_L	The intersect points of z coordinate
s	Slope of curve
α	Inclination angle of curve / inclination angle of fingertip
κ	Curvature of curve
R	Radius of curvature
$f(\quad)$	Kinematics relationship of robot hand
r	Fingertip position vector
q	Finger joint vector
J	Jacobian matrix
r	fingertip position vector
r_c	Current fingertip position vector
r_f	Desired fingertip positon vector
F	Grasping force
q_f	Desired joint angle vector in force control
K_s	The proportional gain for force control
K_f, K_i	The proportional gain for force control and interpolation control
q_{des}	Desired joint angle vector of combined control
$G(\quad)$	Gravity compensation term
r_0	Centre between fingertips

Chapter 1

Introduction

1.1 Research background

The history of industrial automation is characterized by rapid change in popular and world economics. Industrial robots were identified as unique devices since the 1960s [1] in terms of automatic machine. With computer technology rapidly grew, computer-aided design (CAD) and computer-aided manufacturing (CAM) systems accelerated industrial robots development. As a result of industrial robots development, the accuracy of many manufacturing processes were improved and at the same time required less labour force. Automation of machines became an important research topic and many industries and universities paid more attention to this area. With the growth in the automation technology, the term “robot” became a popular name for expressing a machine which is capable of automatically carrying out a complex series of actions by computer programming [2].

Many areas already make extended use of robotics technology, such as medical care, aerospace, entertainment, military, disaster recovery, etc. The functional requirements of the end-effector of such robots became wider. Considering a scenario in which a robot should support an elderly person and help him to finish some daily activities such as cooking, feeding food to him and washing dishes after the meal, the end-effector of this robot has to be able to grasp objects with various shapes and perform flexible manipulation, for example rolling or sliding motions. Therefore, a simple gripper that can only open and close is no longer sufficient as the end-effector for such applications.

Robot hands were developed as general purpose end-effectors that exhibit characteristics similar to the human's hand in order to achieve various skills, in particular stable grasping and dexterous manipulation [3]. In order to perform the tasks in human like ways, the human hand is often considered as a model for the specifications that robotic hands should fulfil, especially, in terms of degree of freedom and joint arrangement. It means that a great number of actuators and sensors should be integrated within the robot hand in a very compact space. It is also implies that the control of these robot hands became complex with such feedback information.

With the rapid increase of social problems, such as an ageing society or labour force reduction in developed countries, the development of robots is expected as a means against labour shortages. In here, the role of the robot hand is important because in the near future robots should work with and in the same environment as humans. Therefore, I now feel that the research of robot hands for improving their performance is more urgent and became a critical issue for realizing useful robots that can really conducive widespread robot applications

1.2 Conventional Robot hand development

The design of an articulated robotic hand can be performed according to many possible design concepts and options depending on different purposes, e.g. prosthetic robot hands are designed to achieve basic grasping with low-weight mechanisms [3]-[7], while hands for industrial applications are designed to handle specific parts [8][9], and the reliability is one of the core target in the mechanical design and control system in such kinds of robot hands. "Grippers" [10][11][12] are widely employed in industrial robotic manipulators that perform repetitive task. These grippers can only execute limited manipulation tasks for specific objects [13][14]. Due to these limitations, in the case that a humanoid robot is expected to be capable of dexterous manipulation with various objects, research efforts have been dedicated to the development of anthropomorphic robot hands for mimicking the characteristics of a human’s hand.

In the late 1970s Okada [15] developed a three- fingered robot hand with 11 degrees of freedom (DOF), driven by a tendon system. A nut opening motion was demonstrated with this robot hand. In the early 1980s, two major projects about multi-fingered robot hands were launched, JPL Hand (Salisbury Hand) [16] developed by the Stanford/Jet Propulsion Laboratory, which has 3 fingers with 9 DOF, and the UTAH/MIT Hand from Massachusetts Institute of Technology, which has 4 fingers with 16 DOF [17]. These two robot hands show a milestone for later robot hand research. After that, some important architectures for robotic hands have been designed and developed in a number research institutes all over the world, for example Deutsches Zentrum für Luft- und Raumfahrt (DLR) hand(s) [18], Robonaut2 hand [19], LMS Hand [20], Karlsruhe hand[21], University of Bologna (UB) hand [22], Gifu hand [23], NAIST-Hand [24], Southampton Hand [25], Keio Hand [26] and many others. Most of these robotic hands have a high number of DOF and complex control architectures. Therefore a high manufacturing cost is needed in these research-orientated robot hands [13]. A few of them have been sold on the market such as the Standord/JPL hand. Besides these research-orientated robot hands, there are some commercial available robot hands on the market, such as the Barret hand [11], SARAH Hand [27], Shadow hand [28], DLR/HIT Hand [29], MechaTE robotic hand [30], Allegro Hand [31], etc. An overview of representative robot hands is given in Figure 1-2.

Different kinds of robot hand

Gripper type | Anthropomorphic type

Shunk grippers [10] | Shadow hand [28]

Figure 1-1 Two kinds of robot hand

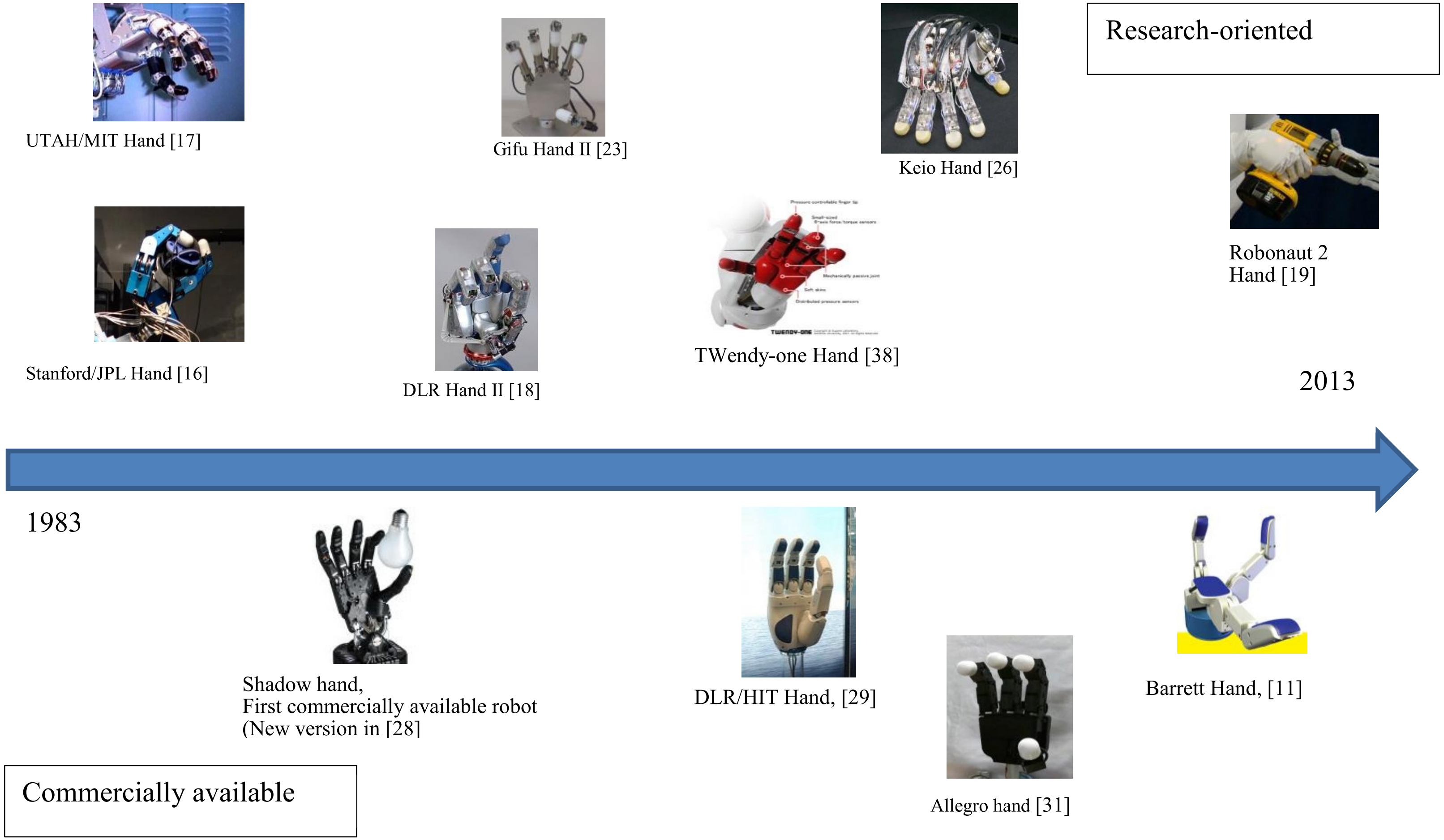


Figure 1-1 Some representative robot hand

Over the last few decades, soft robot hands were proposed for improving the grasp stability of the robot hands [32][33]. This concept changes the traditional design concept by introducing passive flexibility into robot hand. Traditionally, the adaptability of robot hand was presented by force control with rigid robot hand. The use of rigid components in conventional robot hands is because the manipulation situation is relative easy to be modelled. It requires high control accuracy with suitable trajectory planning of robot hand finger, and the practical environment should fulfill the assumptions in the model. Different of it, soft robot hand development pursues high stability instead of high accuracy. Two major approaches are used in soft robot hand development as: passive impedance joints [34][35] and soft fingertip[36][37]. In some robot hand, these two approaches are implemented simultaneously [38].

The development of the passive impedance joint is an effective approach for improving the stability of robot hand grasping and manipulation by its backdrivablility. As soft robotics technology was paid more attention to gradually, some flexible actuation was used in robot hand design, such as pneumatic actuation [35], hydraulic actuation[39], tendency actuation[34] or spring actuator[38]. However, these architectures require high costs of manufacture. Furthermore, for the hydraulic/pneumatic actuation and spring actuator, their structure is too complex to maintain. Their parts are often made by custom order, which means that it is difficult to be found in the market when the robot hand needs to be maintained. Tendency actuation is relative old technique in robot hand development and it has been used until nowadays [12]. It could provide flexible movement of fingers and relative low cost. However, the wire limited the workload of actuation.

(a) Tension actuation[34] (b) Pneumatic actuation[35] (c) Actuator with Spring[38]

Figure 1-3 The approaches for providing impedance actuation

The implementation of soft fingertip is considered as another approach for presenting passive flexibility. Although it provides relative small flexibility, the manufacturing cost could be reduced significantly. However, when the whole fingertip made by soft material, it limited the possibility for installing sensing element into the fingertip for control system because the deformation will affect the sensing ability. The skin pads can be quickly assembled with robot hand through reliable, structural coupling [41]. Therefore, I decided to only use soft skin implementation to present passive flexibility in this dissertation.

Furthermore, once I decided to use soft skin to present low cost and limited passive flexibility, I also have to consider the suitable control strategy of robot hand to cover the inadequate flexibility and stability.

To control the robot hand, the control system of robot hand could be considered as two levels: low level control (control scheme of robot hand in hardware development) and high level control (control strategy for generating the trajectories of fingers). In the viewpoint of robot hand manufacturer, they are concerning the low level control which is focusing on how to communicate the motor and sensor with computer, how to actuate the joint for obtaining the required response of a single joint movement. An example is given in [42], the transmission systems of tension-actuation. They paid more attention about the relationship between the tension output and the input displacement of a joint. From the viewpoint of robot hand user, they are concerning the result of high level control which is focusing on some special tasks such as stable grasping or dexterous manipulation. Some control law is proposed for different purpose such as grasping force control, object position control, etc.

In 1980s, [43] proposed dynamic control strategies for the control of robotics manipulator, by given the target position, velocity and acceleration of end-effector, it is possible to generate the desired torque for the actuator to present these end-effector performances. In [44], grasping matrix is proposed for transforming the contact force at fingertip to the resultant force/moment vector exerting on object, thus, the control target could be set to the object instead of fingertip. After that, many related works are proposed by different research institutions such as hand Jacobian, form and force closure [45], passive and active closures [46]. These concepts could be seen as constraint analysis in terms of force equilibrium at the centre of mass of the object. Based on form/ force closure concept, [47] applied active force closure to analyse grasping force and optimise the whole hand grasping. In [48], the essential characteristics of passive grasping were understood by studying of passive force closure condition of grasping.

Most of these researches of grasping mentioned above are given in terms of fingertip force. Normally, manipulation is expected after grasped the object, it is desirable to consider other factors such as manipulating ability and fingertip trajectory. Various control algorithms for robot hands were developed in these several decades.

Hybrid position/force control and impedance control are two major groups for controlling robot hand to present manipulation with grasping force. Hybrid control method [56] controls the force and position simultaneously by a selection matrix to separate the force direction and position direction. Impedance control method [49] controls the force indirectly through specification of the mechanical impedance of the grasped object against external forces (A detail discussion about the force control is addressed in chapter 4). Besides these two major methods, there are some control methods by using dynamics [36][50]. These trajectory-following methods need pre-designed fingertip trajectory for each specific manipulation, thus the task versatility of these methods is limited by the quality of trajectory generator.

In order to accomplish various tasks, [51] proposed a posture interpolation strategy by introducing the static griping classification of human, to generate the finger trajectory automatically and implement on TWendy-one hand [38]. However, this approach is strongly relating to the hardware flexibility.

1.3 Design methodology of robot hand

As the development history of robot hand, in order to reproduce human hand function, the main design target remains the functional emulation about human's hand which represents the human's behaviours on the end-effector of multi-fingered robot hand [52]:

- Prehension: i.e., the ability of grasping and holding different size and shape object in the hand.
- Apprehension: the ability of understanding the environment through active touch.

We are considering that the human hand is both an output and input device [53]. As an output device, the hand should be able to apply forces to environment in order to obtain stable grasps or perform manipulation procedures. As an input device, it should be able to explore an unknown environment in order to get information though interaction between human and environment.

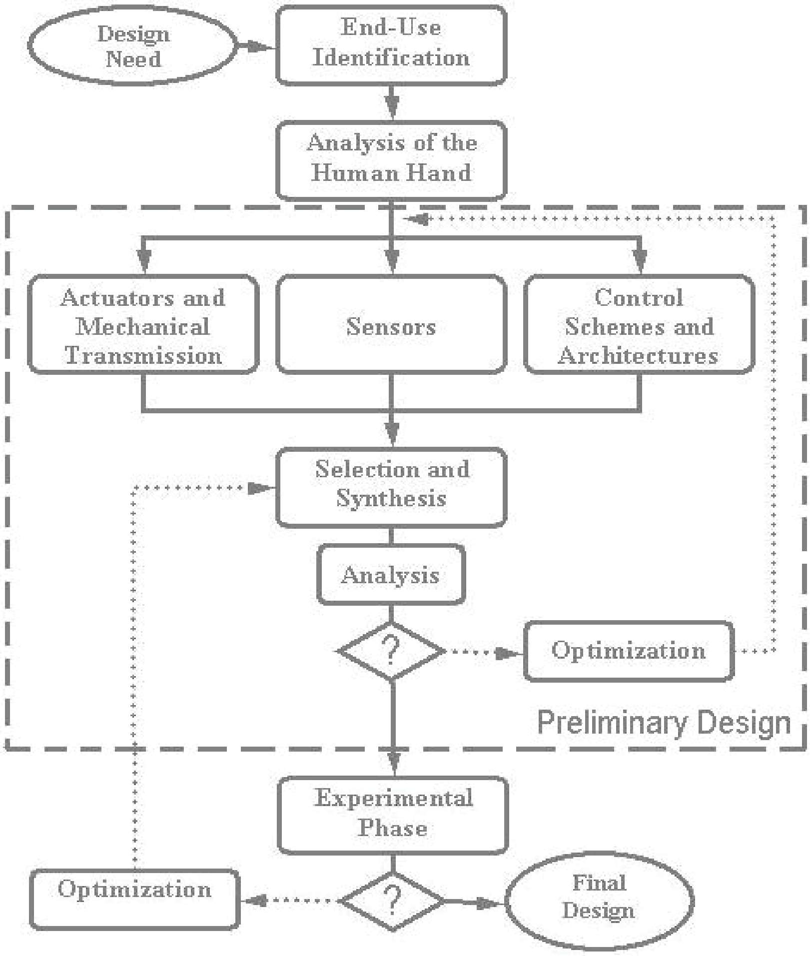


Figure 1-4 Design process for robotic hands [13]

Since that it is difficult to quantify the effective degree of dexterity of a robotic system, as a widely accepted definition states that the dexterity of a robotic end-effector is a measure of its capability of changing the configuration of the manipulation object from an initial configuration to a final one, arbitrarily chosen within the device workspace.

As the above reason, for developing robot hand system, two concerns are addressed in conventional robot hand development [52]:

- Kinematics: concerning the presence of the main morphological elements

(principal upper fingers, opposable thumb and etc.)

- Contact surfaces: extension and smoothness of the contact surfaces, aspect the reflect on the capability to locate contacts with objects all over the surface of the available links and on the presence of external compliant pads.

In last sub-section, some conventional robot hand examples are addressed. However, a systematic design methodology of these robot hands is often missing in the related work of these robot hands. Considering a systematic design methodology is benefit for the robot hand developer to design and build the robot hand effectively, the design methodology of robot hand is also discussed in this dissertation. [13] summarised the process of robot hand development and addressed a general robot hand design methodology of multiple finger robotics hands by modifying the product design methodology from [54]. The flow of this methodology is shown in fig. 1-4.

At the first phase in this process, the application of the robot hand is identified depending on technological and market requirement, such as prosthesis purpose, humanoid robotics, industrial manipulators, etc. Once the application of the robot hand is identified, the structure of the robot hand should be roughly determined. Since human's hand is universal grasping mechanism with great flexibility in manipulation, it is often considered as a great biological mechanism reference which is capable for presenting dexterous movement. The second phase is considered as the study of anthropometric characteristics of human hand. Some study about human's grasping taxonomy and kinematical characteristics is introduced into robotics engineering field [55][56]. After the architectures of the robot hand is determined, the actuation way and structure, sensing and control system should be considered. In here, the actuator, sensor and other component should be selected and synthesised depending on the requirement, such as payload of robot hand, resolution of sensing system or manufacturing cost.

- Some parameters should be considered in actuator selection: the number of required motor, the dimension, torque, speed, respond time, etc.
- Some parameters should be considered in sensor selection: sensitivity, hysteresis, bandwidth, etc.

This synthesis process leads the determination of the geometrics and material for robot hand. The kinematic chain of mechanism should be also determined for optimising the robot hand design before the construction of a physical prototype. Some CAD/CAE tools are helpful for deciding the design. The control architecture is designed in this phase could evaluate the controllability and reachable workspace of the designed robot hand. After this preliminary design is conduced, a prototype can be built for evaluation experiment and validation. A feedback loop is often needed to improve the design with experimental information.

This design methodology could provide a general design process of robot hand with the focus on the kinematics performance of robot hand. However, from the viewpoint of robot hand application, we want robot hand to accomplish some specific tasks such as grasping or in-hand manipulation. Therefore, the contact between robot hand and the object should be concerned as I mentioned at the beginning of this sub-section. In particular, the unpredictable deformation of soft robot hand will affect the manipulation accuracy. In the traditional robot hand development, the contact problem is considered as trajectory planning problem instead of development problem. As this influence of contact is strongly related to the stiffness of the soft robot hand, the shape and hardness of robot hand material are also affecting the stiffness of robot hand. It is beneficial if we can keep the concern about the contact when we are designing the robot hand system from the viewpoint of grasping and manipulation application. Therefore, I considered a possibility to introduce contact model into the robot hand design methodology.

1.3 Objectives and Approach

As the research target throughout this dissertation, I consider to develop a simple and low-cost robot hand manipulation system which could provide high flexibility and task versatility. According to this target, we have to solve some problems both in hardware and software.

1.3.1 Clarifying passive flexibility

In the previous robot hand development, the focus is located on the mechanism design of finger structure in order to mimic human finger behaviour. Considering the fingertip is often used for interacting object in manipulation, the contact surfaces should be considered in robot hand design. However, this field is often ignored in conventional research about robot hand design. Although there are some experimental researches about contact status [57]-[59], the focus of them is on material properties rather than robot hand design. To design a soft fingertip, the quantified contact performance should be considered because we do not know the empirical factors before we made the fingertip. Furthermore, since that these is not deformation sensor available in the market, the influence of the design is often difficult to be evaluated. Although there is some available tools could be used to assist analysing the deformation in design phase, such as Finite Element model or Magnetic Resonance method. These approaches are inconvenience to deviate a mathematical optimisation for the design because the relationship between the factors and the performance is not clear.

Furthermore, different from material research, the robot hand fingertip is often designed as complex shape with variable cross-section. And the position of contact point between fingertip and object will lead different deformation because of different cross-section of fingertip even though there is same material. Therefore, it is difficult to determine the design by the given contact requirement. In order to quantitatively design the passive flexibility of the fingertip, as the first objective, I consider a mathematical contact model for clarifying the relationship between these design factors such as geometrics, softness, etc.

1.3.2 Design of hardware compliance

Even though we can understand the deformation of the fingertip, the design target is strongly depending on the application purpose of robot hand (the requirement of robot hand). How to use the deformation to design a fingertip is still a problem. For example, when we want to design a fingertip which could provide large contact area change from pulp to tip, the curvature of the shape and non-uniform thickness is also able to provide contact area change. As some fingertips which are needed to implement tactile sensor, non-uniform thickness will lead non-uninform sensitivity of the sensor. Therefore, a general design methodology could be benefit instead of a certain product design. In here, I paid more attention about the general design methodology instead of giving a solution to show what the best design is. As the second objective, I consider using the contact model in design phase for demonstrating the evaluation and prediction of the performance when we are design the robot hand with soft fingertip.

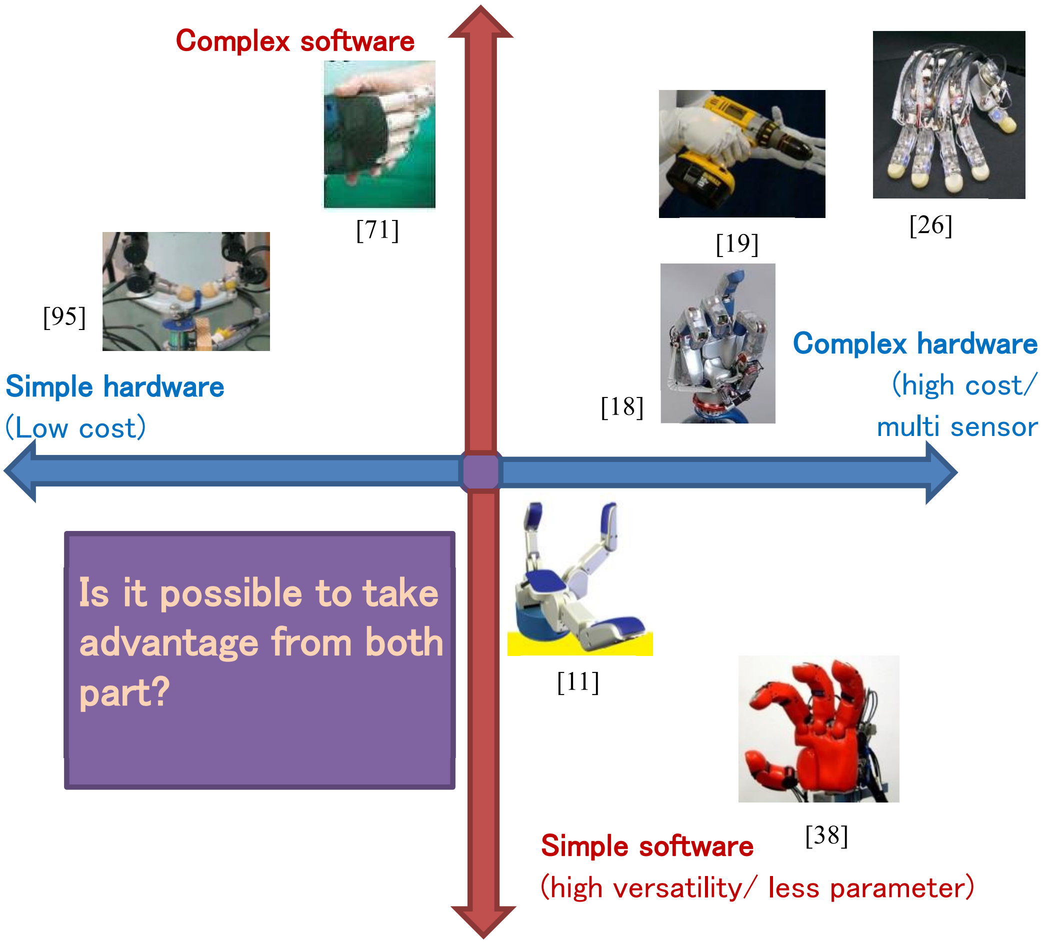


Figure 1-5 The objective of current research

1.3.3 Simple and robust control for accomplishing various manipulation task

As above mention, TWendy-one[38] using combination of soft skin and impedance joint for implementing hardware compliance. By this hardware compliance, the simple position control strategy is work for various manipulations. It is difficult to say that such simple position control is also work in general robot hand system which without impedance joint. For the other conventional researches [60]-[62], numerous information is needed for the controller such as vision information, grasping matrix or complicated calculation. Considering the benefit of TWendy-one's simple control strategy which the fingertip movement can be controlled without specific motion planning, grasping matrix or complex calculation, the trajectory is automatically generated by the initial position and final position. It makes us to consider how to apply such simple control strategy to other robot hand which without impedance joint. As the third objective, I tried to improve the posture interpolation controller by introducing compliance property. By such improvement, I considered that the new controller could take both benefit from the simplicity of posture interpolation control and the flexibility of force control.

As the resultant throughout this dissertation, I am exploring a possibility to develop a reliable manipulation system which could present versatile manipulation by the combination of simple flexible hardware and simple flexible controller.

1.4 Chapter Summary

This dissertation is organized as follows.

In Chapter 2 I will introduce a multi-fingered robot hand platform I used in this dissertation, which consist of robot hand base, communication equipment and operation system. After that, as the control strategy, the interpolation idea of TWendy-one is addressed. Furthermore, an integration of TWendy-one's posture interpolation idea and Allegro Hand is introduced. At the end of this chapter, a pre-experiment is conducted for showing the performance of posture interpolation control in Allegro Hand.

In Chapter 3 I will summarize and compare various types of robot hand fingertip. In this chapter, the important factors of the fingertip for grasping will be clarified by grasping property experiment. Based on this investigation and experiment, a contact model is made with such factors. In the same chapter, a design methodology is proposed by using this contact model. The evaluation experiment is conducted for verifying my model and the fingertip performance.

In Chapter 4 I will present a posture interpolation based force- position control method to improve the manipulation performance. A simple force strategy is introduced and the result of force controller will be combined to posture interpolation control for generating a force-position control method. Two kinds of experiment are conducted for evaluating the proposed system both in task versatility and inappropriate posture adaptability.

In Chapter 5, I will conclude the works and main contribution though this dissertation. The effective of flexibilities for robot hand to accomplish grasping and in-hand manipulation will be discussed. Finally, some possible future works will be highlighted.

The flow of this dissertation is presented in fig.1-6.

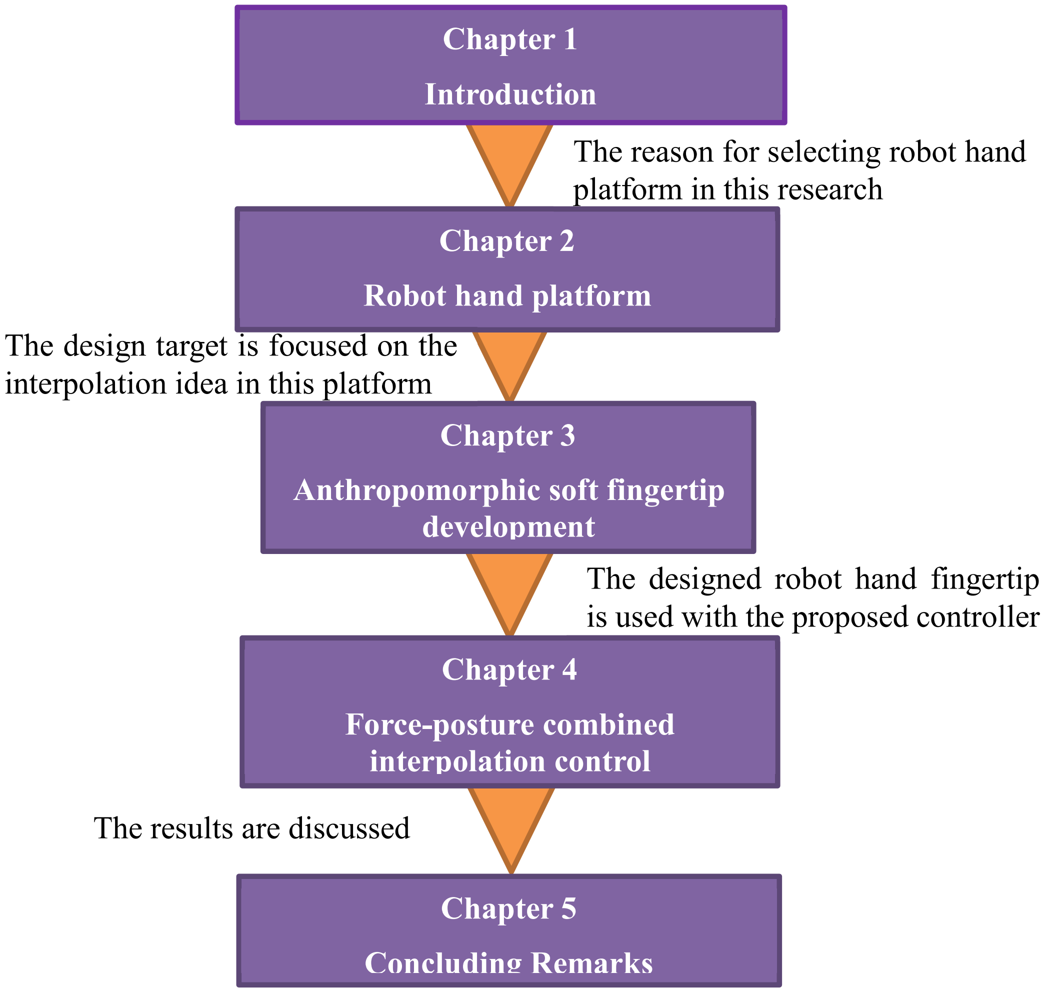


Figure 1-6 The flow of this dissertation

Chapter 2

Robot hand Platform

In the previous chapter, I described the conventional robot hand system development and discussed the limitation of current robot hand design methodology. At the same time, I also introduced TWendy-one hand, a conventional robot hand system which was proposed from our laboratory. In this robot hand system, a posture interpolation control strategy was proposed by simply interpolate the pre-defined postures and generate the finger movement automatically. In addition, the mechanical impedance joint and soft skin was also implemented in TWendy-one hand for providing passive flexibility in order to absorb the error in posture interpolation control. On the other hand, it is hard to ensure that these linear trajectories would be successfully implemented on the other type of robot hands, especially the robot hand without mechanical impedance. In this chapter, a review of this control idea is addressed and also how to integrate these ideas into inexpensive commercial available robot hand platform also discussed with pre-experiment.

This chapter is consisted by two parts: Section 2.1 described an introduction of the robot hand platform I used in current research. In section 2.2, I tested the performance of conventional control approach in this robot hand platform. At the end of this chapter, the results of this pre-experiment are discussed.

2.1 Robot hand platform

The manipulation system is consisted of two parts: software controller and robot hand hardware. As the based platform I used throughout this dissertation, the introduction of platform is separated into two parts.

2.1.1 Posture interpolation control

(a) Posture interpolation idea for manipulation

In daily environment, various tools are designed for human with different shapes. In order to allow robots hand to use such tools, the robot hand should be able to handle or manipulate such objects/ tools like human does. In conventional research about the control, the trajectory planning is often needed for providing the position control of end-effector [63][64]. In order to provide the feedback of these controllers, some essential information such as object position or contact position is needed. Those information proved to be difficult to extract from the subject handling the object. Furthermore, some assumptions are needed to be made such as point contact, no slip, etc. Such assumptions are often making the control inapplicable in daily environment.

In our laboratory, [51] proposed a posture interpolation controller for TWendy-one robot hand. It is a position control strategy for generate in-hand manipulation by a set of pre-defined fundamental grasping postures. By the transition between theses pre-defined static grasping postures, the trajectory of the fingertip could be automatically generated without any additional trajectory generator.

(b) Static fundamental grasping postures

From the viewpoint of bioengineering or rehabilitation, the behaviour of a human's hand can be considered as a series of combinations of fundamental postures and motion patterns. Based on it, various studies were conducted for clarifying the behaviour of human's hand, [65] investigated finger's movement of human and summarised a set of moving pattern depending on the arrangement of muscle and tendons. [66] proposed a classification of grasping posture according to the contact status between human's hand and object. From the definition of this classification, the static grip of human's hand is classified into three groups: digital grip, palmar grip and symmetrical grip.

(c) Human manipulation behaviour survey

In addition to the definition of static grasping postures classification, in the same research of [51] a relevant survey was previously conducted in order to investigate the manipulation behaviour of human's hand by TWendy-one research team. According to this study, we understood that some posture transitions are not commonly seen in our life. For example, human does not do manipulation from "Spherical palmer prehension" posture to "cylindrical palmar prehension" posture because they are used to grip different object shapes. Similarly, the "Panoramic pentadigital grip" posture is relying on a wide separation of fingers with the thumb in maximal counter-opposition. Therefore, this posture is normally used for holding a big sized object and it is rarely transited to other postures.

Based on this grasping definition and manipulation survey, 16 kinds of grasping styles have been designed for TWendy-one robot hand (it is shown in fig. appendix). Furthermore, a interpolation controller was proposed for generating the manipulation motion automatically by initial grasping posture and final grasping posture input, the concept is shown in fig.2-1.

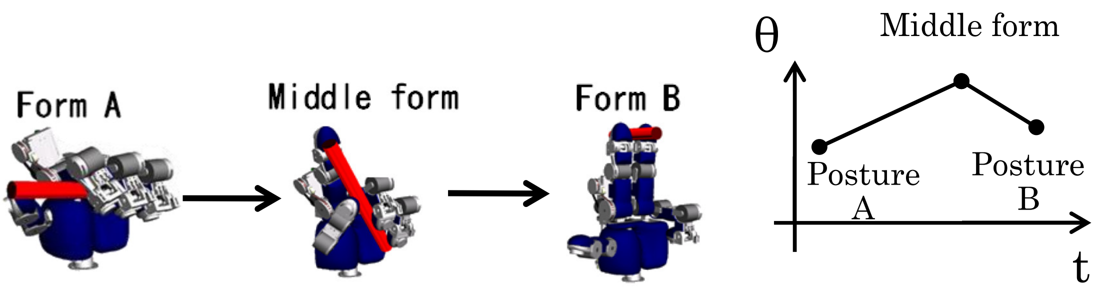


Figure 2-1 Posture interpolation with TWENDY-Hand [51]

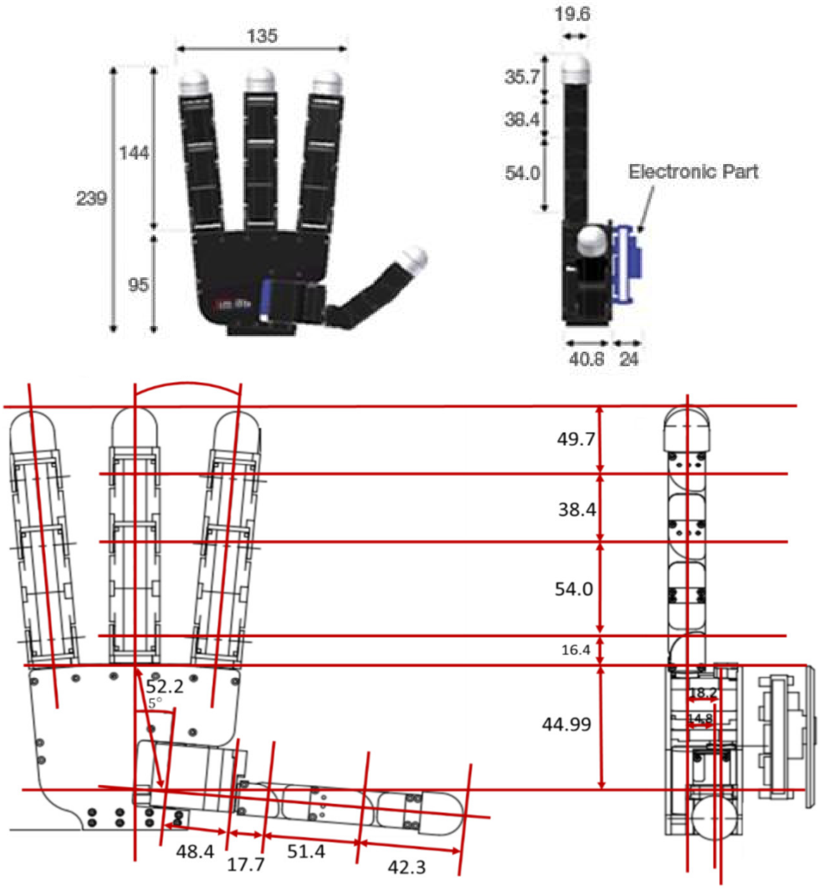


Figure 2-2 The original fingertip of Allegro Hand (source from [31])

2.1.2 Robot hand

Considering the complexity of the actual tasks that human performed in their daily environment, multi-fingered robot hand is preferred for realising versatile manipulation instead of gripper. Comparing a custom ordered multi-fingered robot hand, using a commercial available robot hand as a platform can give a general and low-cost solution when we are considering developing a manipulation system. Moreover, low cost and maintainability are two attracting points for robot hand user when we hope the robot hand to be widely used in our daily environment.

From chapter one, I investigated many conventional robot hands, considering our requirement such as cost, simple structure and multi-fingers, I selected Allegro hand as hardware platform from commercially available robot hands in current market.

Table 2-1 Allegro hand specification (source from [31])

Number of Fingers	Four fingers, including thumb	
Degrees of Freedom	4 fingers x 4 = 16 (Active)	
Actuation	Type	DC Motor
	Gear Ratio	1:369
	Max. Torque	0.70 (Nm)
Weight	Finger (except thumb)	0.17 (kg)
	Thumb	0.19 (kg)
	Total	1.08 (kg)
Joint Resolution	Measurement (for joint angle)	Potentiometer
	Resolution (nominal)	0.002 (deg.)
Communication	Type	CAN protocol
	Frequency	333 (Hz)
Payload	5 (kg)	
Power Requirement	7.4VDC (7.0V - 8.1V), 5A Minimum	
The shape of fingertip	Hemi-spherical tip with cylindrical body	
Material of fingertip	Silicon Rubber	
Hardness of fingertip	Shore A 40	

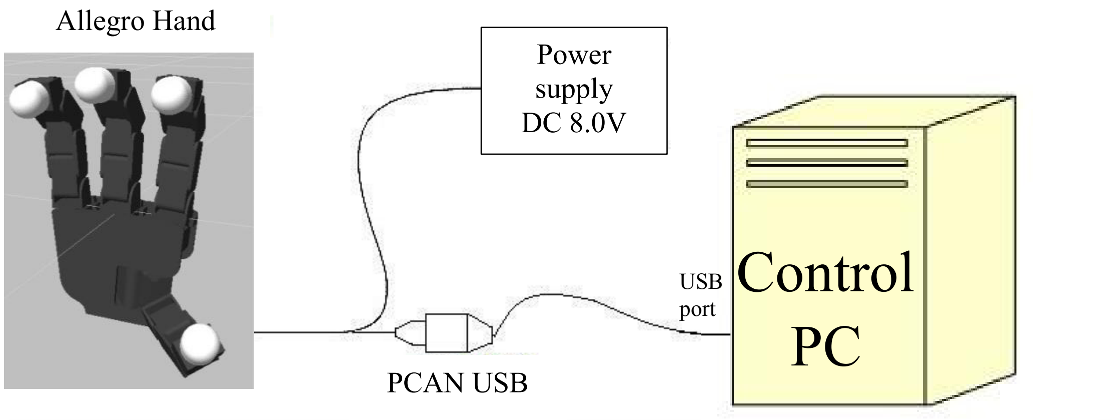
(a) Allegro Hand

Allegro Hand [31] is a commercial available robotic hand which has four fingers, 16 degree of freedom (DOF.), with independently current based torque controlled joints. All joints are actuated by DC motors and the angle values are measured by potentiometers in each joint. Therefore, it could present three dimensions fingertip movement as the basic behaviour of human's hand. The dimension of Allegro hand is shown in fig 2-2. The technical specification is listed in table 2-1. On each finger, the shape of fingertip is designed as hemi-spherical tip with cylindrical body and no any additional sensors on the fingertip. The fingertips are made by silicon rubber with Shore-A 40 hardness.

(b) Communication between Allegro Hand and Control PC

In this research, PCAN-USB [68] is used for communicating between control PC and robot hand platform with 333Hz control frequency. By PCAN-USB, the robot hand is connected to PC by USB port. The PCAN-USB and the connection between Allegro Hand and PC are illustrated in fig. 2-3.

(a) PCAN-USB [68]



(b) Wire Connection

Figure 2-3 Communication equipment

(c) Framework

Allegro hand is controlled under the Robot Operating System (ROS) [69] environment. ROS is an open source framework for robot. It is including tools, libraries, and conventions that could simplify the control of various robotic platforms.

(d) User interface

The original communication interface between user and Allegro Hand is by a command-user interface (CUI) based on grasping library. User could control Allegro hand to grasp object by a few defined grasping type such as pinch grasp. RViz is used for simulating the motion of Allegro Hand (see fig. 2-4).

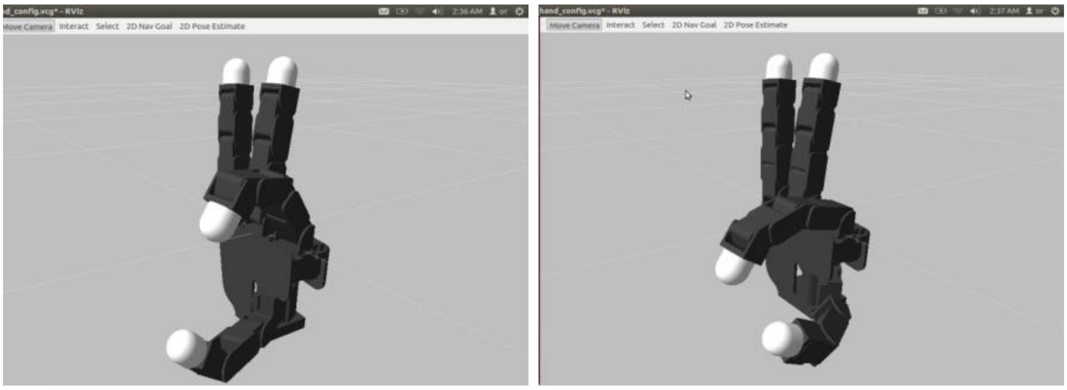


Figure 2-4 Allegro Hand simulation in RViz

(e) Kinematics of Allegro Hand

In order to generate appropriate motion of the robot hand, I considered to derive the kinematics of Allegro Hand. The following shows the derivation of Denavit-Hartenberg notation (D.H. notation) for presenting the mechanisms of Allegro hand. In here, all of the coordinate are defined by right-hand coordinate, the translation axis and rotation axis is notated by x axis and z axis.(see fig. 2-5)
The Homogeneous Transformation is given by 4X4 matrix:

$$^{A}P_{B} = \begin{bmatrix} 0 \\ 3 \\ 0 \end{bmatrix}; \quad ^{A}R_{B} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad ^{A}T_{B} = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.1}$$

where P is translation vector, R is rotation matrix, T is homogeneous transformation matrix. The superscript and subscript in $^{A}T_{B}$ present the transformation from coordinate A to coordinate B. The link parameters of Allegro hand are shown in table 2-2 to 2-5. From eq. 2.1, the transformation matrix could be derived as:

$$\begin{aligned} ^{i-1}T_{i} &= \begin{bmatrix} 1 & 0 & 0 & a_{i-1} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{\alpha(i-1)} & -S_{\alpha(i-1)} & 0 \\ 0 & S_{\alpha(i-1)} & C_{\alpha(i-1)} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_{i} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_{i} & -S_{i} & 0 & 0 \\ S_{i} & C_{i} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} C_{i} & -S_{i} & 0 & a_{i-1} \\ C_{\alpha(i-1)}S_{i} & C_{\alpha(i-1)}C_{i} & -S_{\alpha(i-1)} & -S_{\alpha(i-1)}d_{i} \\ S_{\alpha(i-1)}S_{i} & S_{\alpha(i-1)}C_{i} & C_{\alpha(i-1)} & C_{\alpha(i-1)}d_{i} \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \tag{2.2}$$

Based on eq. 2.2, when I set the origin at the root of middle finger, it is possible to calculate the position of fingertip by eq. 2.2. On the other hand, the relationship between Euler angle and the orientation could be calculated by:

$$
\begin{aligned}
{}^{A}R_{B} &= {}^{A}R_{A'}\,{}^{A'}R_{A''}\,{}^{A''}R_{B} \\
&= \begin{bmatrix} C_\phi & -S_\phi & 0 \\ S_\phi & C_\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_\theta & 0 & S_\theta \\ 0 & 1 & 0 \\ -S_\theta & 0 & C_\theta \end{bmatrix} \begin{bmatrix} C_\psi & -S_\psi & 0 \\ S_\psi & C_\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
&= \begin{bmatrix} C_\phi C_\theta C_\psi - S_\phi S_\psi & -C_\phi C_\theta S_\psi - S_\phi S_\psi & C_\phi S_\theta \\ S_\phi C_\theta C_\psi + C_\phi S_\psi & -S_\phi C_\theta S_\psi + C_\phi C_\psi & S_\phi S_\theta \\ -S_\theta C_\psi & S_\theta S_\psi & C_\theta \end{bmatrix}
\end{aligned} \tag{2.3}
$$

where $\emptyset$, θ and ψ indicate orientation of coordinate B from the view of coordinate A. Then, if we let:

$$
{}^{A}R_{B} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \tag{2.4}
$$

with the limitation $0 < \theta < \pi$, the solution could be calculated by:

$$
\begin{aligned}
\emptyset &= a\tan2(R_{23}, R_{13}) \\
\theta &= a\tan2\left(\sqrt{{R_{13}}^2 + {R_{23}}^2}\,, R_{33}\right) \\
\psi &= a\tan2(R_{32}\,, -R_{31})
\end{aligned} \tag{2.5}
$$

Considering the critical case that $\theta = 0$ and $\theta = \pi$, there are infinite solutions. I set the condition that when $\theta = 0$, the solution as the following:

$$
\begin{aligned}
\emptyset &= 0 \\
\psi &= a\tan2(R_{21}\,, R_{22})
\end{aligned} \tag{2.6}
$$

2.2 Posture interpolation control from TWendy-one Hand to Allegro Hand

Manipulation versatility is one of the problems in the conventional research about robot hand control in terms of joint trajectory generation. TWendy-one shows us an impressive result about simple position control strategy for versatile manipulation by posture interpolation control that I have mentioned above. Motivated by TWendy-one concept, I decided expanding its idea to other robot hand platform and developing an inexpensive and simple robot hand system. In TWendy-one hand, the mechanical impedance helps robot hand accomplish manipulation task successfully even though by

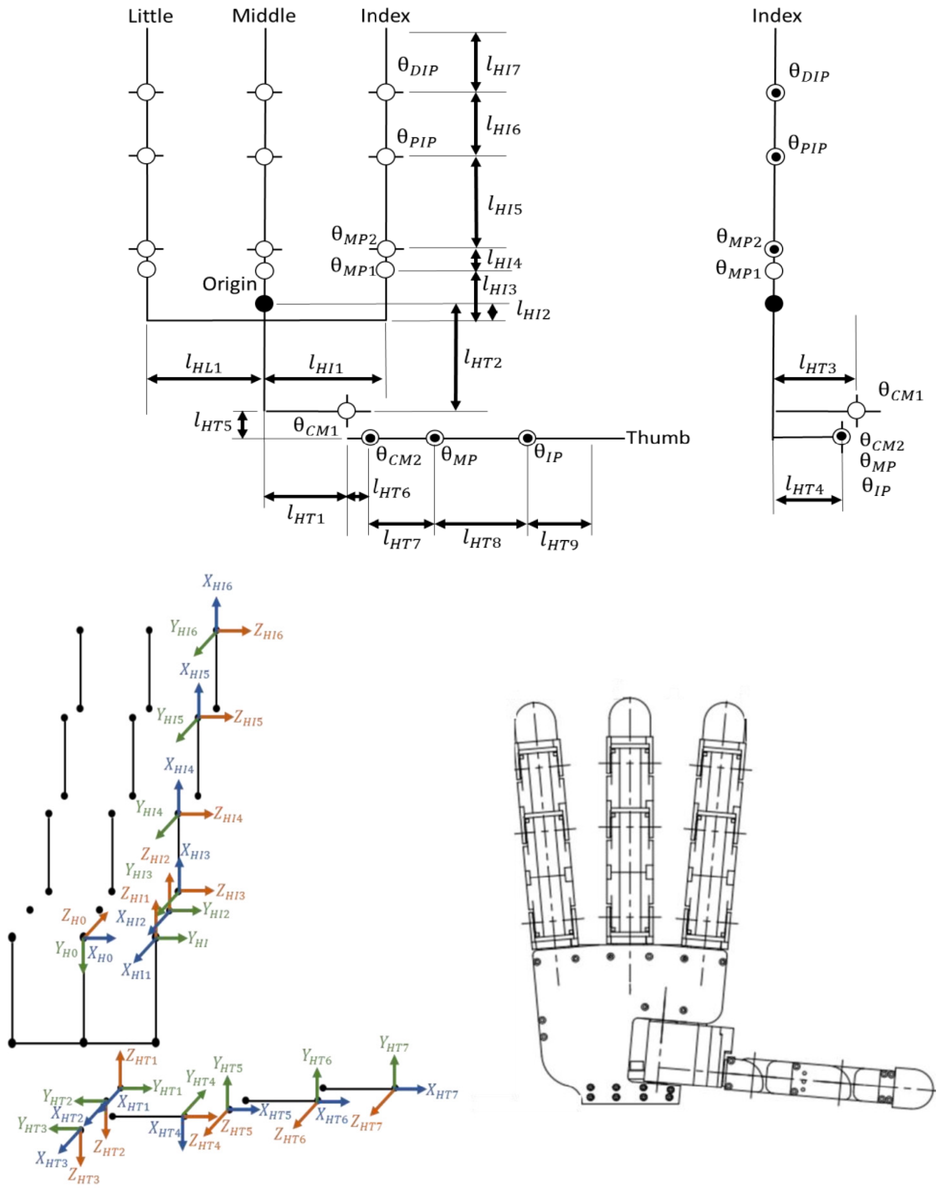


Figure 2-5 Coordinate system and D-H model of Allegro Hand

Table 2.2 Link Parameter of Thumb Model

i	a_{i-1}	α_{i-1}	d_i	θ_i
Thumb_1	l_{HT1}	$90+\theta_{BASET1}$	l_{HT2}	$-90+\theta_{BASET2}$
Thumb_2	l_{HT3}	180	0	θ_{CM1}
Thumb_3	0	0	l_{HT4}	0
Thumb_4	l_{HT5}	90	l_{HT6}	$\theta_{CM2}+90$
Thumb_5	l_{HT7}	90	0	$\theta_{MP}+90$
Thumb_6	l_{HT8}	0	0	θ_{IP}
Thumb_7	l_{HT9}	0	0	0

Table 2.3 Link Parameter of Index Model

i	a_{i-1}	α_{i-1}	d_i	θ_i
Index_1	l_{HI1}	90	l_{HI2}	-90
Index_2	l_{HI3}	θ_{BASEI}	0	θ_{MP1}
Index_3	l_{HI4}	-90	0	θ_{MP2}-90
Index_4	l_{HI5}	0	0	θ_{PIP}
Index_5	l_{HI6}	0	0	θ_{DIP}
Index_6	l_{HI7}	0	0	0

Table 2.4 Link Parameter of Middle Model

i	a_{i-1}	α_{i-1}	d_i	θ_i
Middle_1	l_{HM1}	90	l_{HM2}	-90
Middle_2	l_{HM3}	0	0	$\theta_{MP1}+\theta_{BASEM}$
Middle_3	l_{HM4}	-90	0	θ_{MP2}-90
Middle_4	l_{HM5}	0	0	θ_{PIP}
Middle_5	l_{HM6}	0	0	θ_{DIP}
Middlee_6	l_{HM7}	0	0	0

Table 2.5 Link Parameter of Little Model

i	a_{i-1}	α_{i-1}	d_i	θ_i
Little_1	l_{HL1}	90	l_{HM2}	-90
Little_2	l_{HL3}	0	0	$\theta_{MP1}+\theta_{BASEL}$
Little_3	l_{HL4}	-90	0	θ_{MP2}-90
Little_4	l_{HL5}	0	0	θ_{PIP}
Little_5	l_{HL6}	0	0	θ_{DIP}
Little_6	l_{HL7}	0	0	0

simple position control strategy. However, different robots have different joint configuration. TWendy-one is designed like human, and thus it could present the similar grasping behaviour like human easily. However, not all robot hand is designed following human's mechanism. Allegro Hand is an example which has not mechanical impedance with different joint arrangement from TWendy-one or human. It is hard to be sure that these linear trajectories would be successful for accomplishing tasks in other robot hand such as Allegro hand. It is also difficult to say all grasping postures could be realised in Allegro hand. We considered some modification should be made for fitting Allegro hand in order to implement posture interpolation control.

2.2.1 Fundamental grasping postures for Allegro Hand

The direction of joint rotation of Allegro Hand is illustrated in fig.2-6. Different from TWendy-one hand, it could be seen that there is no actuator for the abduction and adduction in the metacarpophalangeal joints (MP) of the index, middle and little finger of Allegro hand. Some fundamental postures from Kapandji's classification such as "Interdigital latero-lateral prehension" and "directional grip" are difficult to be presented.

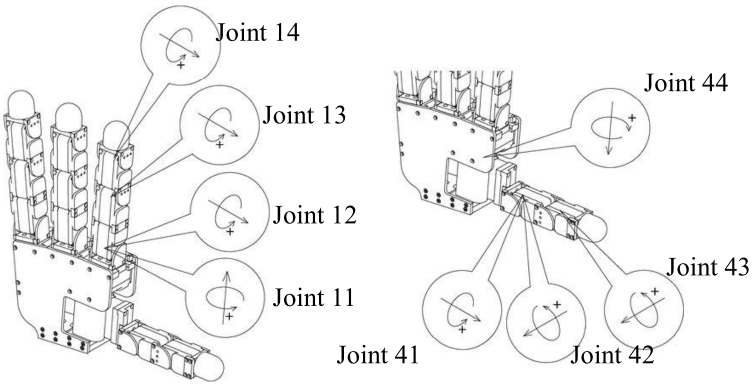


Figure 2-6 Joint directions of Allegro hand (right hand) (source from [31])

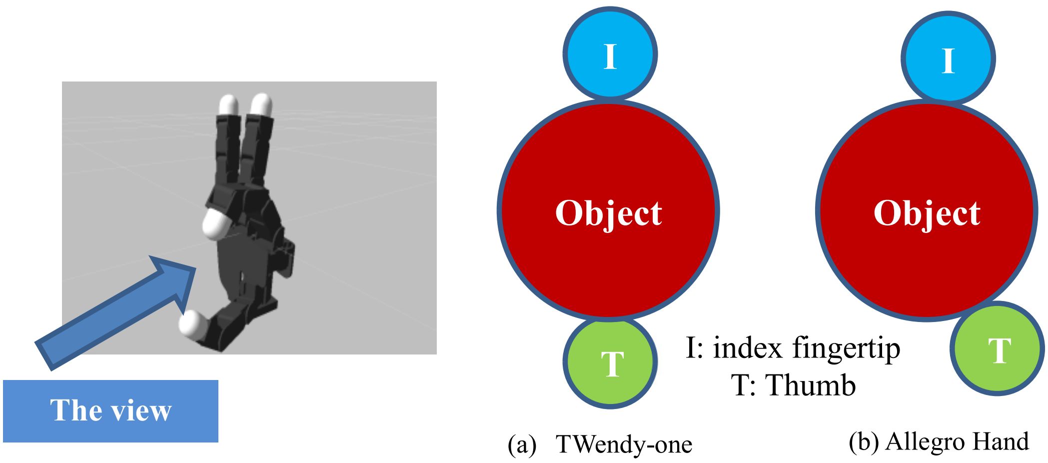


Figure 2-7 Prehension by terminal opposition in robot hand

In the order hand, the joint angle limitations of Allegro hand are also different from TWendy-one hand (one of the grasping cases is shown in fig 2-7). Therefore, some theorical posture definitions for TWendy-one hand could not be applied in Allegro Hand. Considering joint arrangement and joint limitation of Allegro Hand, I used direct teaching approach to teach Allegro hand the grasping postures (see fig. 2-8), the modified fundamental postures for Allegro Hand is shown in fig. 2-9.

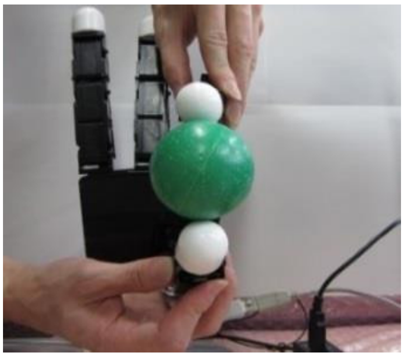


Figure 2-8 Direct teaching of static grasping posture

Spherical tridigital palmar prehension

Spherical tetradigital palmar

Prehension by terminal opposition

Prehension by subterminal opposition

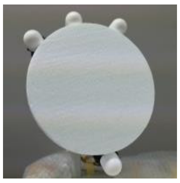
Subterminal tridigital prehension

Tetradigital grip with pulp contact

Spherical full digital palmar prehension

Digito-palmar prehension

Polici-tridigital grip



Panoramic full digital grip

Prehension by Subtermino-lateral opposition

Subtemino-lateral tridigital prehension

Cylindrical palmer prehension

Full palmer prehension

Centralized grip

Polici-cavam Interdigital nip

Figure 2-9 Fundamental postures for Allegro Hand

```
----------------------------------------------------------------
GraspingMode
----------------------------------------------------------------
      Grasping Number:        110     'N'
      Size:                   10      'S'
      Moving Time:            1000    'T'
      Action:                         'G'
      Return Normal Mode:             'R'
----------------------------------------------------------------
```

Figure 2-10 Command-user interface

In other hand, a new CUI is developed for user to control the robot hand. By simply input the posture pattern, object size and transition time of the motion, the robot hand could present the desired manipulation motion (it is shown in fig. 2-10).

2.2.2 Interpolation control algorithm

In order to accomplish versatile object manipulation by the postures transition, interpolation control strategy with a PD controller is implemented for controlling the joint to achieve my required transition in a given time. The interpolation algorithm I used in this research as:

$$q_i(t) = q_{Start} + \left[\left(q_{final} - q_{Start} \right) \times \frac{t}{\Delta T} \right] \tag{2.7}$$

where q_i , q_{Start} and q_{final} are 1×16 vectors respectively, q_i represents a set of the desired joint angles, q_{Start} is a set of joint angles at the onset of the motion. q_{final} is a set of joint angles at the end of the motion (the target posture). ΔT is the desired transition time for the motion. t is the time from the onset of the motion.

The desired joint angles q_i are computed by eq. 2.7 in each control cycle and the desired angles are sent to PD controller:

$$\tau_{des}(t) = K_p \tilde{q}(t) + K_D \dot{q}(t) \tag{2.8}$$

In eq. 2.8, K_p and K_D are the proportional and derivative control gains, respectively. And the joint position error is defined by the difference between the desired angles q_D and the current joint angle q_c:

$$\tilde{q} \triangleq q_D - q_c \tag{2.9}$$

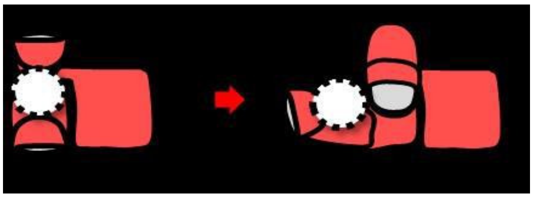
2.2.3 Pre-experiment and Result

In previous sub-section, I addressed the different between TWendy-one and Allegro hand. There is a question about the effective of these linear trajectories if they are replaced by the hand, in particular, for the case of the robot hand without mechanical impedance in its joints. Therefore, I conducted a pre-experiment for testing the performance of posture interpolation control strategy in Allegro Hand.

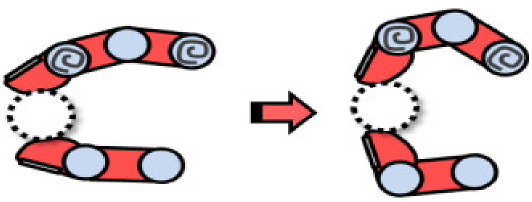
(a) Experiment setup

(i). Manipulation task definition

Two representative experiments are selected to validate the posture interpolation strategy in Allegro hand. Figure 2-11(a) shows the first task, “Rolling a sphere from the bottom of the index fingertip to its side”, which corresponds to a posture transition from “Digital grip” grasping style group to the “Palmar grip” grasping style group; fig. 2-11 (b) shows the second task, “Pull task” this task could be accomplished by posture transition from a “Prehension by subterminal opposition” posture to a “Prehension by terminal opposition” posture. (illustrated in fig. 2-12)



(a) Manipulation A: Rolling a sphere from the bottom of the index fingertip to its side



(b) Manipulation B: Pull task

Figure 2-11 Manipulation tasks of pre-experiment

Two tasks were selected because of their complexity and it is validated in TWendy-one hand. Furthermore, these two tasks could show the posture transition in different planes: manipulation in sagittal plane and manipulation in transverse plane. Because some posture transitions need intermediate postures to achieve continuous form closure, these two motions were selected in my experiments that do not require intermediate postures.

(ii). Selected object and initial grasping position setup

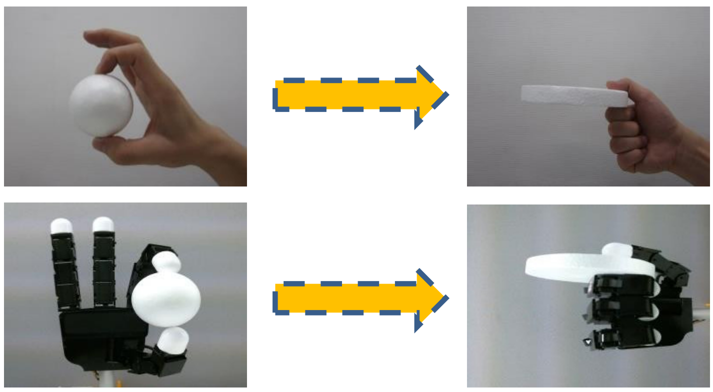
Two kinds of styropor spheres (diameter 30mm and 50mm) were used as the objects in this experiment. The size of these objects is selected to match robot hand dimension in order to facilitate object manipulation without barrier.

In this experiment, the object was fed to the place that between the fingertips of the robot hand by the experimenter, with slight variations from the centre of the fingertips, chosen randomly by the experimenter (illustrated in fig. 2-13).

(b) Experiment result

Each of the two motions, for both object sizes, was performed 40 times in my experiment. I recorded the result and counted the success rate in each case. The definition of the successful manipulation is designed as to finish the manipulation task without drop the object. As the result, in the first experiment (motion A in fig 2-12), 100% success rate in the Φ50 sphere experiment and 62.5% success rate in the Φ30 sphere experiment were obtained. For the second experiment (motion B in fig 2-12), 100% success rate for the Φ50 object and 75% success for the Φ30 object were recorded. The examples of the continuous photo in experiments are demonstrated in fig. 2-14 and fig. 2-15.

Motion A:



Motion B:

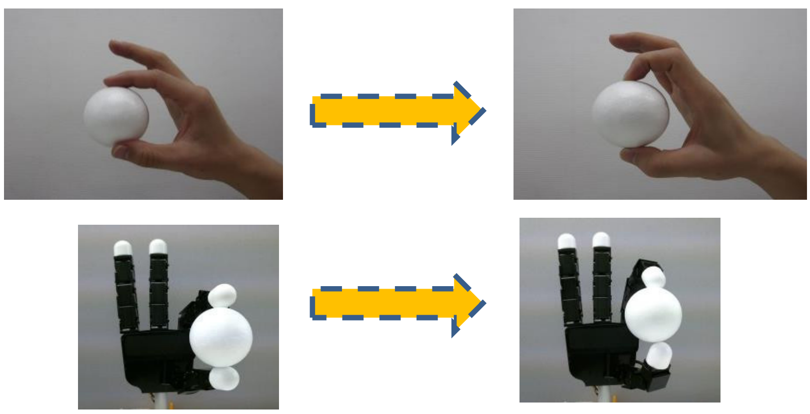


Figure 2-12 Manipulation by posture interpolation

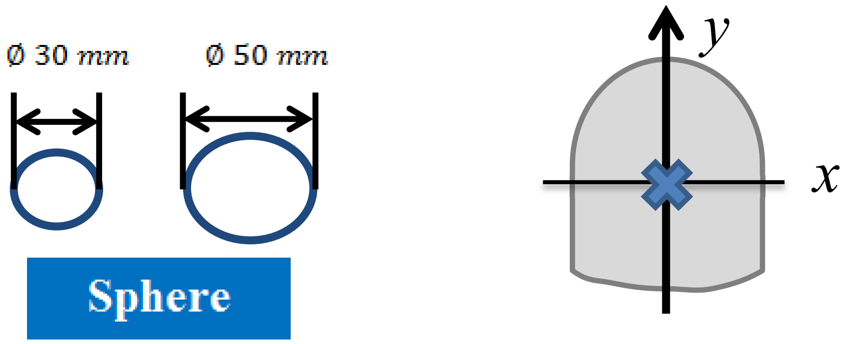


Figure 2-13 Grasping position setting

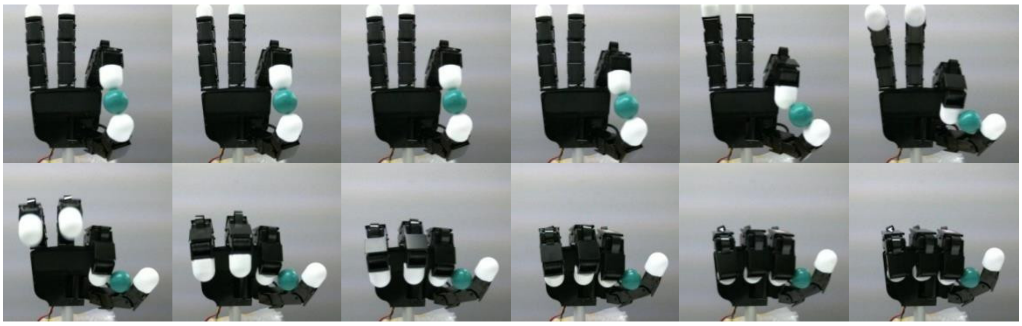


Figure 2-14 Move a sphere with the thumb and index finger from the bottom of the index finger to its side (Φ30mm sphere object)

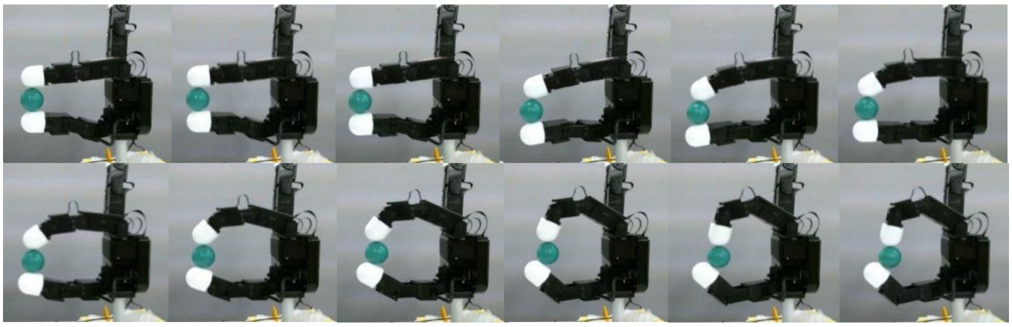


Figure 2-15 Pull task (Φ30mm sphere object)

2.2.4 Discussion and summary

(a) The problem of posture interpolation in robot hand which have not flexibility

In the pre-experiment, it could be seen the success rate of the smaller object is quite low comparing with the bigger object. I considered that it is because the control error is affecting the success rate and the influence is significate in the case of smaller object. Furthermore, I also noticed that the initial grasping position and the definition of grasping posture are two possible influences on whether the subsequent handling was successful or not. Considering the result of pre-experiment, it could be seen that the adaptability for posture interpolation control is not reliable when it is implemented in other robot hand which without impedance mechanism. Considering the case of TWendy-one, the spring in the joint helps robot hand to absorb the error in the control with initial extension (illustrated in fig 2.16). On the other hand, Shore A40 hardness of the fingertip provides too small deformation in manipulation. Therefore, when I am using the posture interpolation control in Allegro Hand, low adaptability is one of the problems to lead low success rate in object manipulation.

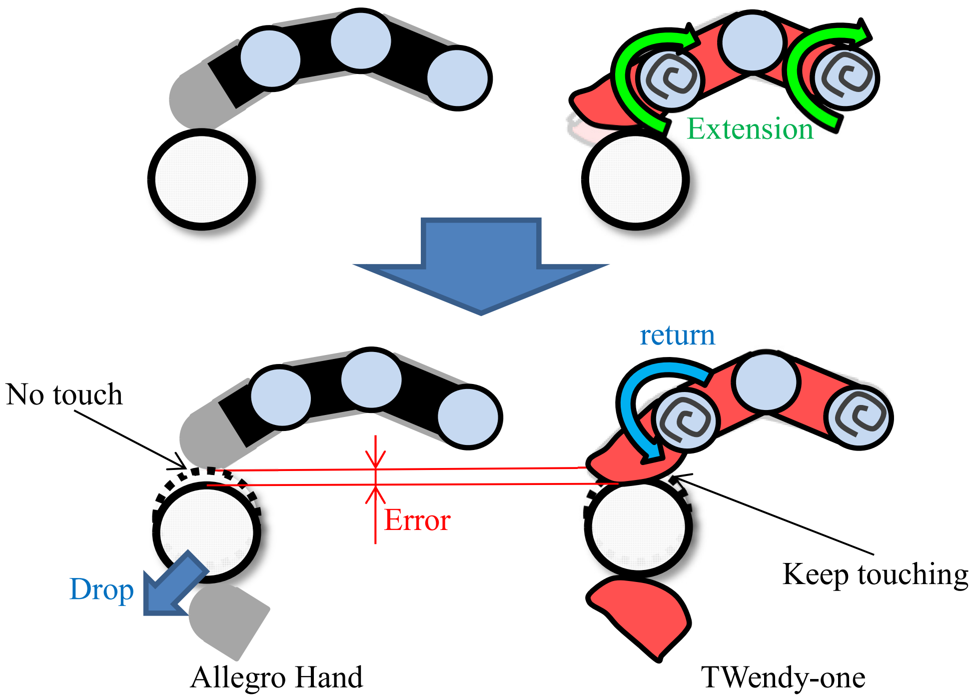


Figure 2-16 The illustration of control error in manipulation

(b) The solution throughout this research

Although the manufacturing cost of mechanical impedance joint is very high and it is difficult to be maintained, soft fingertip is one way for absorbing some degree of error by low manufacturing cost. Therefore, in this research, I considered to only use soft skin to provide certain degree of passive flexibility. On other hand, I considered that soft skin can only provide the limited flexibility. In order to cover the insufficient adaptability, I considered to improve posture interpolation by introducing the feedback from the object. Force feedback control is a possible way for recover the control error actively in terms of active flexibility. In the following chapters, an approach is proposed for improving the manipulation performance of robot hand by combining passive flexibility and "active" flexibility (the system is illustrated in fig. 2-17).

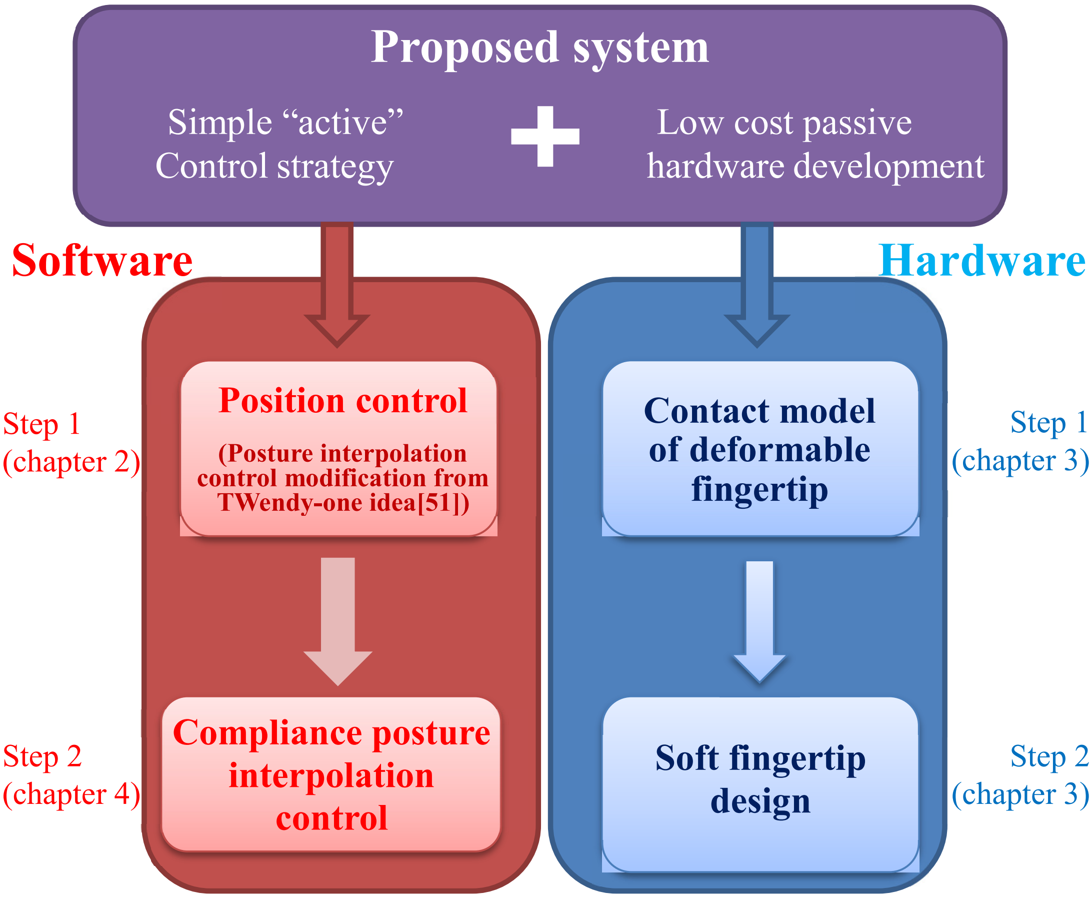


Figure 2-17 The proposed system

Chapter 3

Design of robot hand fingertip

In last chapter, I pointed out the current limitation of posture interpolation control in a robot hand with insufficient flexibility. As a possible solution, I also addressed the possibility to introduce passive flexibility and "active" flexibility in robot hand manipulation system. In the conventional robot hand development, the design of fingertip is often neglected compare to other parts such as mechanical transmission structure or sensors, despite those fingertips are crucial for object handling by in-hand manipulation. Moreover, the parameters of the fingertip are determined empirically instead of mathematically from prediction model. In particular, major error could occur if we have not a creditable prediction in design phase. Therefore, in this chapter, I introduced a new design methodology by using a new contact model. Before the design of fingertip, the studies on fingertip and a pre-experiment are conducted for investigating the probable factors that may affect the grasping performance of robot hand. It is because that a grasping is indispensable before a successful in-hand manipulation. After the consideration of the result from the pre-experiment, a new contact model is proposed which predict quantitatively the deformation of the soft robot hand fingertip when a certain given force push the fingertip at the certain location and orientation in which, I applied this model for designing the new anthropomorphic fingertip. This chapter is organized as follows. In Section 3.1, I investigated a number of past studies about various kinds of fingertips of the robot hand and also the factors which possibly affect the grasping capability are clarified by pre-experiments. Section 3.2 addressed a deviation of theoretical contact model. In Section 3.3, I morphologically designed the new fingertip on the proposed contact model. Section 3.4 demonstrated the contact area change of thickness adjustment in the fingertip design.

3.1 The fingertip of robot hand

3.1.1 Fingertip investigation

Depending on various application or purpose, robot hands have been designed with various materials and shapes to accommodate certain needs. The contact between fingertips and the target object plays a significant role for robot hand in grasping or manipulation, as the fingertips are often used to interact with the object. However, systematic analysis of fingertips is often missing. In order to understand the characteristics of various kinds of fingertip, I investigated the current available fingertips in conventional robot hand and summarized as following.

(a) Shape of fingertip

Three common robotic fingertip designs could be concluded as:

(i). Flat fingertip

The flat fingertip is widely used in robot hand with simple structure such as grippers with two or three fingers [11][70]. In this type, a relatively stable grip can be realised when the object contacts the pulp of the fingertip due to its large contact area. However, the manipulation property of flat fingertip is limited. Therefore, gripper is expected to be used to pick and place symmetric and similar objects.

Barrett Hand [11]

(ii). Hemispherical tip with cylindrical body

It is a fingertip shape which is commonly used in multi-fingers robot hands, such as [31][71]. The contact status such as grasping force can be easily analysed because of its simple geometric model. Therefore, this kind of fingertip is widely applied in traditional controlling system such as [67].

Allegro Hand [31]

(iii).Anthropomorphic fingertip

A fingertip with human-like shape is gradually gaining popularity. Some anthropomorphic robot hands were developed with this type fingertip, such as [28] [72]. However, the relationship between fingertip's curve shape and their manipulation performance is not clear in conventional researches, and the related research is very limited. As one of the reason, it is difficult to make an analytical model for this kind of fingertip because of the complex geometrics.

Shadow Hand[28]

(b) Hardness of fingertip

(i). Rigid fingertip

A robot hand with rigid fingertip is considered as a norm in traditional manipulation research [73][74], since the contact point is one of the assumptions which are needed in contact force analysis or control model. However, rigid fingers sometimes have the shortcoming of low grasp stability or adaptability in practical applications.

(ii). Soft fingertip

To overcome the shortcomings of hard fingertips, some robotic fingertips are made by soft materials [36][37]. It allows some degree of error in manipulation control such as object's size recognition error. In conventional research about soft robot hand fingertip, the focus of these researches is often located at material properties instead of robot hand application. For example, [75] analysed the desirable mechanical properties such as impact force and tested six materials for robotic fingertip designs. Therefore, the influence of the fingertip softness on the grasping and manipulation performance is not well studied.

(c) Friction of fingertip

Friction property of fingertip is often related to the stability in terms of force equilibrium in robot hand grasping. However, this factor is rarely used in robot hand control because of the difficulty in modelling. There are some researches on comparing and finding material properties similar to the human skin friction. [76] and [77] compared real human fingertip friction to the robotic fingertips made from different materials. The viewpoint of these researches are often locating at mimicking the friction properties from human's hand, the application in robotic hand such as grasping or manipulation performance is not the discussed in these researches very well.

From the investigation above, we could only have a preliminary understanding of these factors about the independent influence to robot hand performance, but the synthesis of them is still not very clear. Therefore, I considered a further study with the focus on grasping performance is needed.

3.1.2 Pre-experiment about the influence of the contact in grasping capabilities

Increasing the number of the contact for providing more constraint in order to improve force closure of an object is often considered in multi-finger robot hand studies [78][79]. Nonetheless, a stable grasping with as few as possible fingers still remains challenging in terms of few contacts. Considering the human, they often use two fingers for presenting digital grip instead of three fingers, for example, when picking up a pen from a table, a stable grasping by two fingertips is needed instead of simply increase the constraint to have better force closure. This is because a manipulation process is required after grasping the pen for changing the pen orientation in order to use it to write comfortably.

An appropriate initial grasping posture which facilitates the manipulation process is more important than just simply constraining the object to have a better force closure, therefore, not only stability, object operability is also needed to be concerned in this scenario [66]. However, the trade-off between stability and dexterity for robot hand is difficult to be evaluated. Since that there is some factors may probably affect the contact status between fingertip and object, I considered an investigation on how a digital grip can be made more robust. As the factors we may consider in robot hand design, four factors (hardness, thickness of the skin, fingertip shape and surface friction) should be experimentally investigated for their importance on grasp stability during a digital grip.

(a) Prehension experiment

Motivated by the fingertip investigation in section 3.1.1, I considered to compare the grasping performance of fingertips by developing 6 kinds of fingertips with different properties. Five kinds of them are shown in fig.3-1, and their parameters are listed in table 3.1. One 6 axis force/ torque sensor is installed into the fingertip for measuring the grasping force during prehension in the experiment. The frame of the fingertip is made out from synthetic resin material printed out from 3D printer with plastic material (AR-M2 from Keyence, which is much harder than Ecoflex® 00-30 and VytaFlex® 40 I used in this study, and approximated to be non-deformable).

Table 3-1 Various fingertips

Comparison	Factors
Hardness (Different Materials)	a). Ecoflex® 00-30 (shore00-30, 10psi 100% modulus) [80]; b). VytaFlex® 40 with (shoreA-40, 100psi 100% modulus)[81]; c). AR-M2 (shore D 85-86, Young's Modulus :26454.8psi [82])
Skin thickness	1). 0.5mm layer (Ecoflex® 00-30) 2). 2mm skin (Ecoflex® 00-30) 3). 4mm skin (Ecoflex® 00-30)
Coefficient Of Friction	i). Original Ecoflex® 00-30; ii). Ecoflex ®00-30 with MED10-6670 coating (50% friction coefficient reduced) [83][84]
Shape	I). Hemi-spherical tip with cylindrical body (same size as original Allegro Hand fingertip) II). Anthropomorphic

Two kinds of prehension were considered on this research:

(i). Prehension in vertical direction:

The position of fingertips were set to opposite against each other. The grasping force is produced by the displacement of the upper fingertip moving toward to the fixed lower fingertip (illustrated in fig. 3.2 (a));

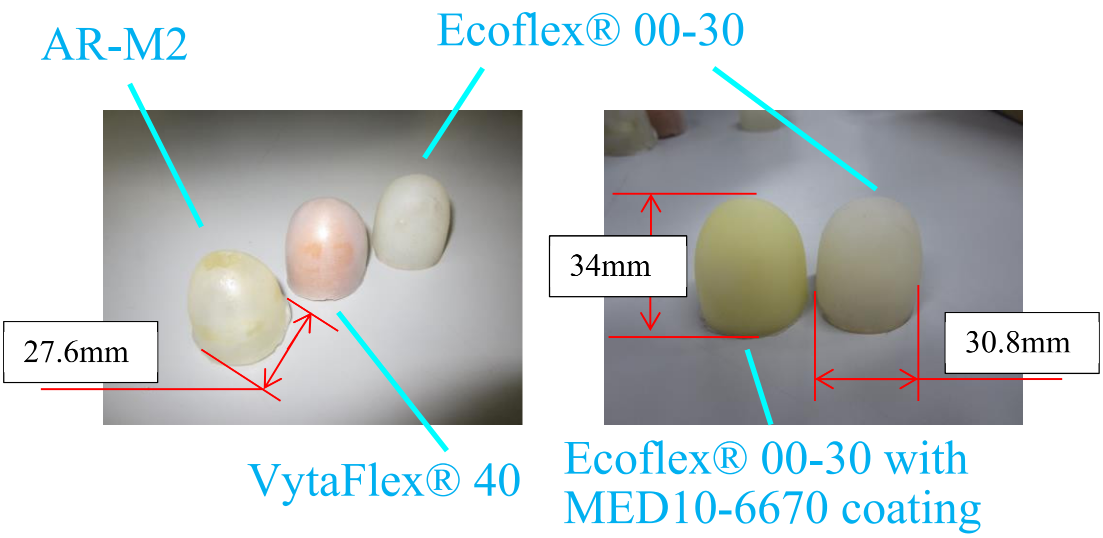
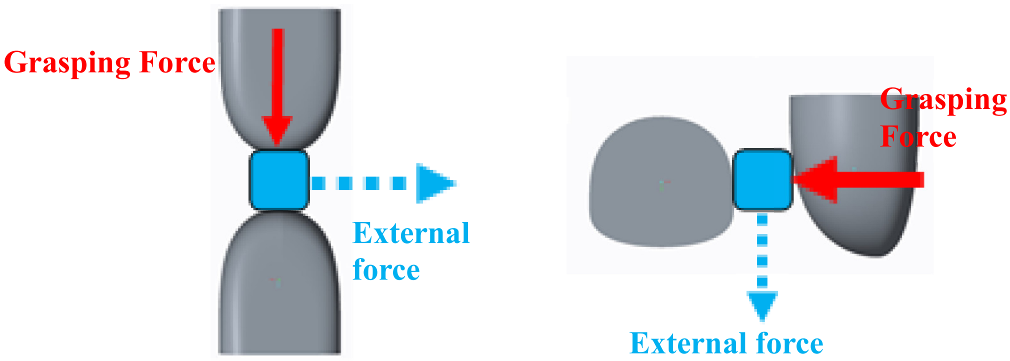


Figure 3-1 Various fingertip for comparing



(a) Prehension in vertical direction (b) Prehension in horizontal direction

Figure 3-2 Two kinds of grasping

(ii). Prehension in horizontal direction:

In order to test the prehension in different grasping direction, the fingertips are placed perpendicular to each other, the grasping force is applied horizontally and exerted onto the fixed fingertip which is pointing downwards as shown in fig. 3-2 (b). Different from the vertical direction prehension, the side of the fixed fingertip is used to contact the object instead of the tip.

Before the experiment, I defined a standard condition (Anthropomorphic shape, 4mm skin made by Ecoflex® 00-30 material (hardness: shore00-30)). Based on this standard condition, I changed fingertip parameters one by one and tested their object grasping capabilities. Considering the influence of friction may affect the grasping ability in the experiment when I am comparing between different materials and thicknesses, I produced 0.5mm Ecoflex® 00-30 layer and attached to VytaFlex® 40 fingertip and AR-M2 fingertip in order to present the same friction on different fingertip materials.

Figure 3-3 shows the overview of the experiment setup. In this experiment, I used a cubic dice as the object for grasping. Because it is made of merely deformable material with smooth surface, I considered the object deformation could be neglected in experiment. A weight tray is connected to the dice for producing tangential external force.

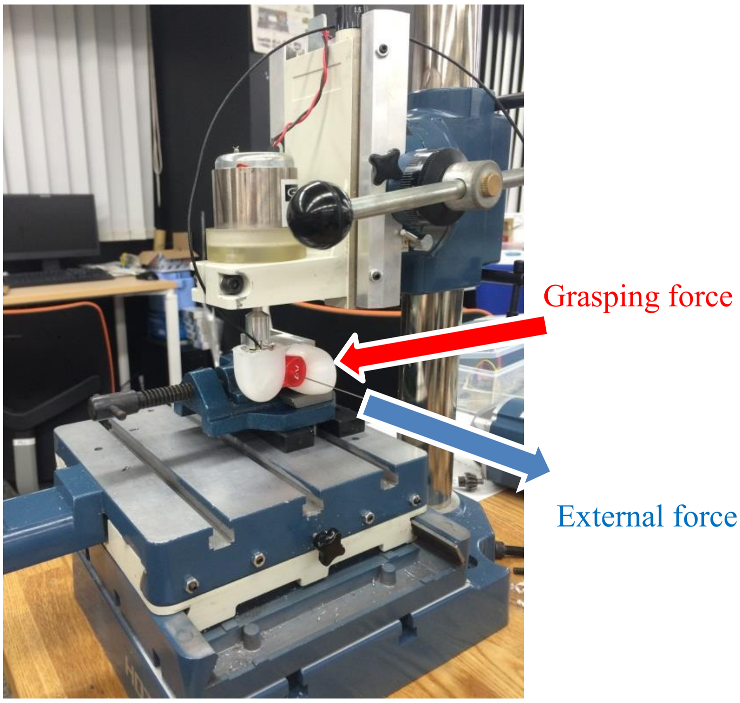
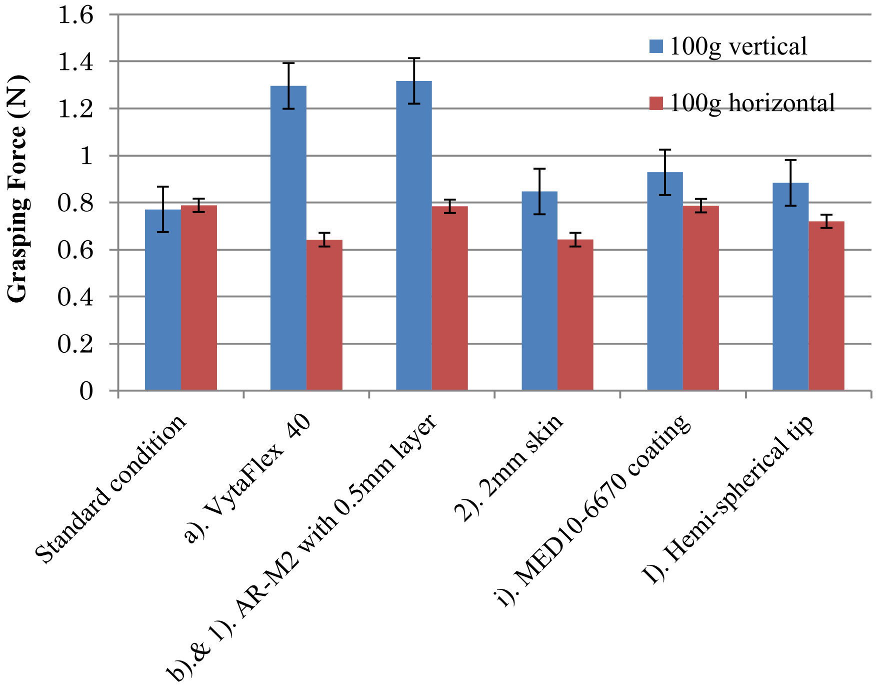


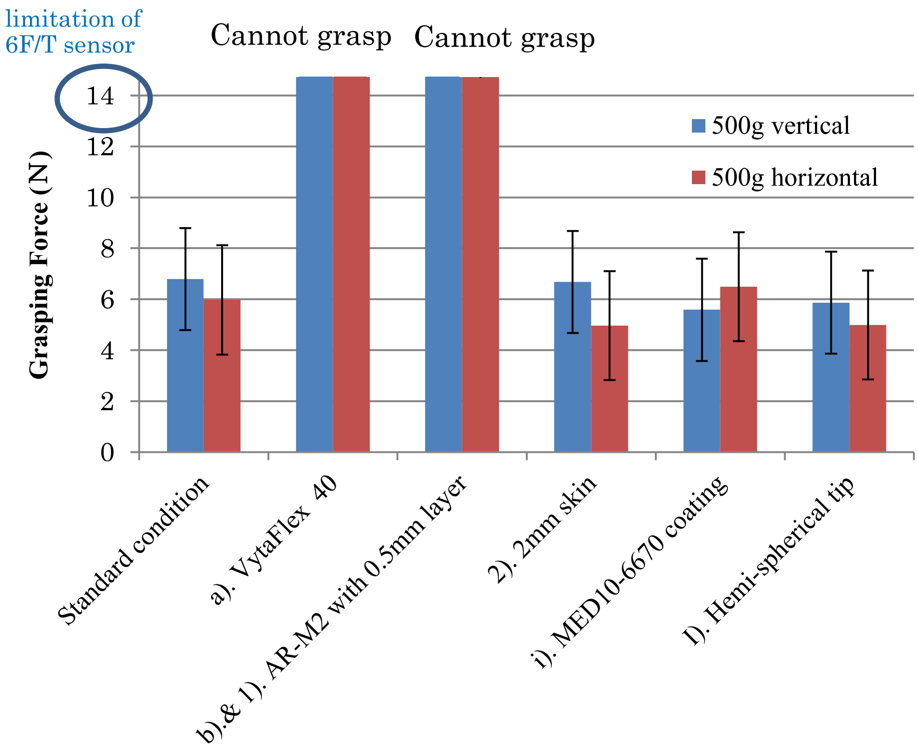
Figure 3-3 Grasping experiment setup

As the fingertips grasp the object in place with initial grasping force, there is an external force applied to the object as a disturbance, I prepared two cases in this experiment. In the first case, approximate 4.9N (500gf) is set as initial grasping force for holding 0.98N(100g) workload. In the case of 4.9N (500g) workload, the initial grasping force is set approximately to 14.7N (1500gf).

The displacement between the fingers is adjusted manually with small increment for decreasing gradually grasping force. 10 second interval is set in each grasping force reduction step in order to ensure there is sufficient time to hold the object in place till it fails. Then I recorded the grasping force at which the fingertip fails to keep holding the object. Each prehension with each fingertip condition is tested 5 times, and then average of grasping force at which it fails to keep holding the object on the fingertips is obtained.



(a) 0.98N (100g) work load



(b) 4.9N (500g) work load

Figure 3-4 The result of prehension experiment

(b) Result of prehension experiment

Figure 3-4 (a) shows the result of experiment in the case of 0.98N workload and fig 3-4 (b) presents the result of 4.9N workload experiment. It could be seen that the fingertips made of harder material (Shore A40 and AR-M2) could not hold a heavy object (4.9N workload) even by maximum grasping force (14.7N (1500gf)).

From the results of the grasping evaluation experiment I obtained, I found that even with the same shapes and material, but made with different surface friction condition, it does not come into play with a significant difference in stable grasping ability. A similar result was obtained when I change the factors such as skin thickness or fingertip shape. The result of this experiment implies that the softness is most important for the fingertip to grasp a heavy object.

(c) Discussion of prehension ability

From the results of previous experiment, I found some interesting properties:

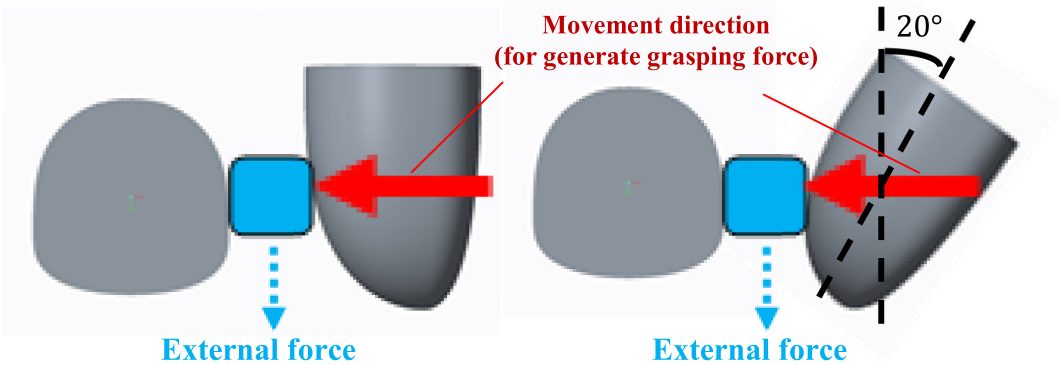
(i). Workload capability

In the higher workload grasping (4.9N external force), the fingertips made from harder material (VytaFlex40 and AR-M2) can hardly hold the object by approximate 14.7N (1500gf) grasping force, which is the maximum amount of allowed force applied to the 6 F/T sensor I used . In contrast, other fingertips with soft material cover could stably hold the object in place. Normally, the nano 6 F/T sensor used in robot hand fingertip has relatively lower loading rate compare to normal 6 F/T sensor, therefore the high grasping force could not be provided in grasping. Therefore the harder fingertip may not able to grasp the heavy object when 6 F/T sensor is installed in the fingertip.

(ii). Orientation of fingertip

Considering the shape of the fingertip could also affect the contact area, in particular, the orientation of anthropomorphic fingertip could also affect the contact area in terms of contact angle. Therefore, I tested the grasping stability by different fingertip orientation. I re-arranged the fingertip orientation from the previous experiment "Prehension in horizontal direction experiment" with an approximate 20° inclination angle (which is shown in fig. 3-5 (b)). All experiment setting is same as the standard condition in last section except the fingertip orientation and I also tested the grasping performance in the case of spherical fingertip.

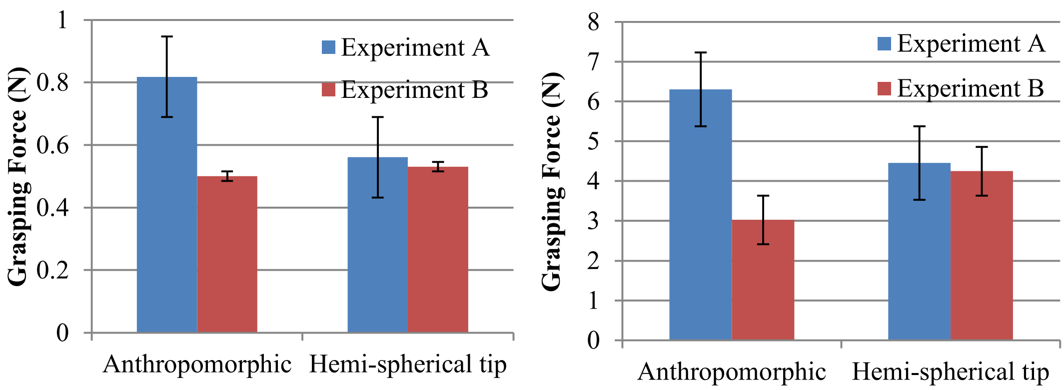
Both two fingertips were tested 5 times in both workload: 0.98N and 4.9N external tangential force. I recorded the grasping force at which it fails to keep holding the object on the fingertips and the average of them is processed. Figure 3-6 (a) shows the result of 0.98N workload experiment and fig 3-6 (b) shows the result of 4.9N workload experiment.



(a) 0° contact angle (case A) (b) 20° contact angle (case B)

Figure 3-5 Fingertip orientation experiment setup

From the result, it could be seen that the performance of spherical fingertip is quite similar both grip situations because the contact area doesn't change with different contact angle. In contrast, an impressive improvement of the grasping performance could be seen in the case of anthropomorphic fingertip, both in 0.98N and 4.9N workload, in the case B of fig.3-5. This result implies that when an appropriate contact angle is used, the



(a) 0.98N (100g) work load (b) 4.9N (500g) work load

Figure 3-6 The result of fingertip orientation experiment grasping performance of anthropomorphic fingertip could be improved in terms of effective contact area. It also means that when the robot hand with anthropomorphic fingertip, the orientation of fingertip should be considered in position control.

(iii).Friction in prehension

For the influence of the effective contact area to the grasping performance, I am considering the relationship between contact area and friction. Friction is one of factor for preventing object dropping during grasping. In [72], a preliminary idea is proposed for connecting pressure and friction theoretically by adopting friction theory [85][86]:

$$\mu = \frac{A_c(s_0 + \rho P_{re})}{P} = \frac{s_0}{P_{re}} + \gamma \tag{3.1}$$

$$\delta = \tan^{-1} \mu$$

where, A_c is contact area, P is grasping force, s_0 is shear strength at negligibly small pressure, ε, γ are coefficient which is approximately constant related to material, P_{re} is contact pressure. μ is friction coefficient and δ is acute angle of friction cone which is shown in fig. 3-7.

From the relationship in eq.3.1, it could be seen that by adjusting effective contact area, the first part of friction coefficient could be increased and the grasping ability could be improved in terms of larger friction cone angle (see fig. 3-7).

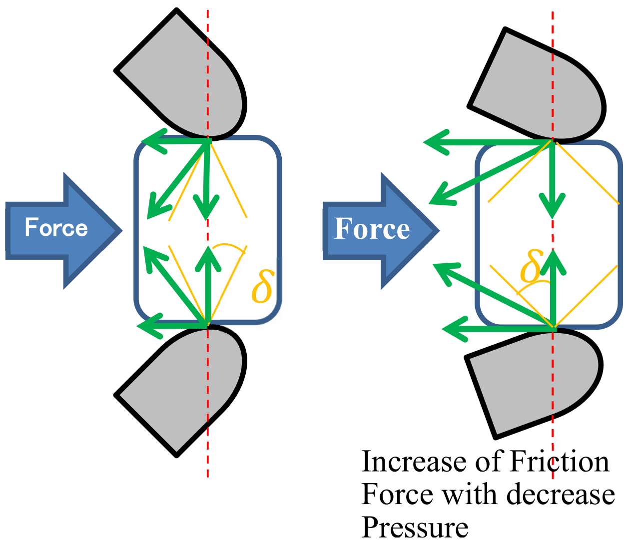


Figure 3-7 Adjustment of friction by pressure control [72]

3.2 Contact model of anthropomorphic fingertip

When an ideal robot hand fingertip with infinity hardness contacts an ideal rigid object, there is a point contact between the fingertip and the object. Compared to the deformable soft robot hand fingertip, the contact surface between soft robot hand and the object becomes complicated as the complexity of fingertip shapes.

A contact model (contact mechanics) characterises the forces that can be transmitted through the contact. And this transmission leads the ability of relative motions of the contacting bodies. These characteristics are determined by the factors which I discussed in previous section such as shape or hardness. The geometry of the contacting surfaces and their material properties could dictate friction and deformation.

Since the late 80s, [87] studied and solved the contact problem of two elastic bodies with curved surfaces. This still relevant classical solution provides a foundation for modern problems in contact mechanics (Hertzian theory). In the mid-twentieth century, [88] and [89] emphasized the importance of surface condition of bodies in contact (Microscopic state of the contact objects). The “true contact area” concept is introduced with these investigations.

Some contact models are proposed for modelling the contact situation about deformable spherical fingertip by Hertzian theory [57]. In particular, [58] proposed an empirical equation for calculating the equivalent radius of contact area by given normal force. Although this model is compatible with anthropomorphic shape, some constant coefficients in this empirical equation are obtained by experiments which are depending on curvatures and materials in contact. However, such experiential coefficient is difficult to be obtained before the fingertip is made. Besides, in these models, it is difficult to obtain the amount of deformation of anthropomorphic fingertip from equivalent radius of contact area.

Another approach for modelling the contact is proposed by [59], which used Young’s Modulus with the geometric model for presenting the contact status of fingertip instead of the empirical model. This is a good revelation for adopting contact model to robot hand design. However, only spherical shape is considered in this model. Nevertheless, a Young’s modulus based contact model with more geometric information is needed for us to design various fingertip shapes.

Therefore, in this dissertation, I introduced a two dimensions contact model derivation which could be compatible with more fingertip shapes.

3.2.1 Elastic contact model of fingertip

When the fingertip touches an ideal rigid flat object with arbitrary pitch rotation, the point contact will occur between ideal rigid fingertip and the object. In the case of soft fingertip, the deformable materials will provide deformation and affect contact area [90]. When the softness of fingertip is not used in whole fingertip, it means that a soft skin which is placed on the rigid fingertip frame. According to [59], we could assume a virtual spring inside the soft skin with virtual stiffness as K, which contribute the deformation of the soft fingertip against the rigid object.

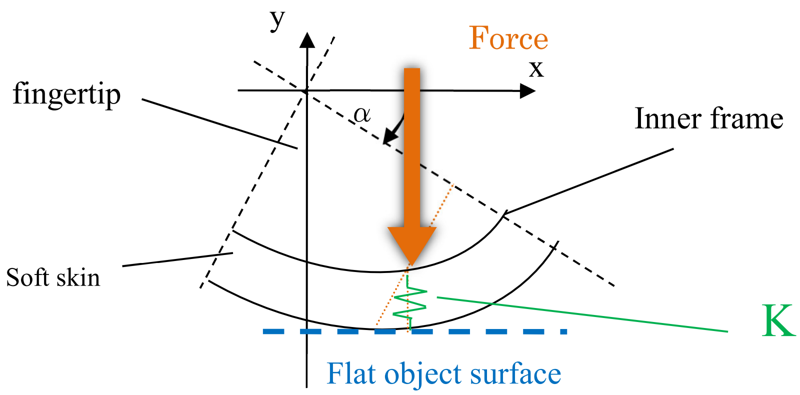


Figure 3-8 Virtual spring model of soft fingertip

In this moment, the deformation properties will be characterised by the Young's modulus of the soft material, the cross-section and the force exerted to the fingertip. From the definition of the Young's modulus:

$$E = \frac{\sigma}{\varepsilon} \tag{3.2}$$

Where E is Young's modulus, σ is stress and ε is strain, with the definition by stress and strain:

$$\sigma = \frac{P}{A} \tag{3.3}$$

$$\varepsilon = \frac{\Delta L}{L} \tag{3.4}$$

where, P is the compression force , A is the original area of soft material, ΔL is the deformation along the force direction, L is the original length of the soft material in force direction, therefore, eq 3.2 could be formed as:

$$E = \frac{P\,L}{A\,\Delta L} \tag{3.5}$$

In eq.3.5, the cross-section A is varies along the force direction and if we reform eq.3.5 to represent the relationship between deformation and pushing force, we will obtain:

$$\Delta L = \frac{P\,L}{E\,A(y)} \tag{3.6}$$

Where, y presents the force direction and following the illustration in fig.3-8.

In here, if we take an infinitesimal section from fingertip along y, with given orientation (which is shown in fig. 3-9), the corresponding deformation of such infinitely small section could be given by:

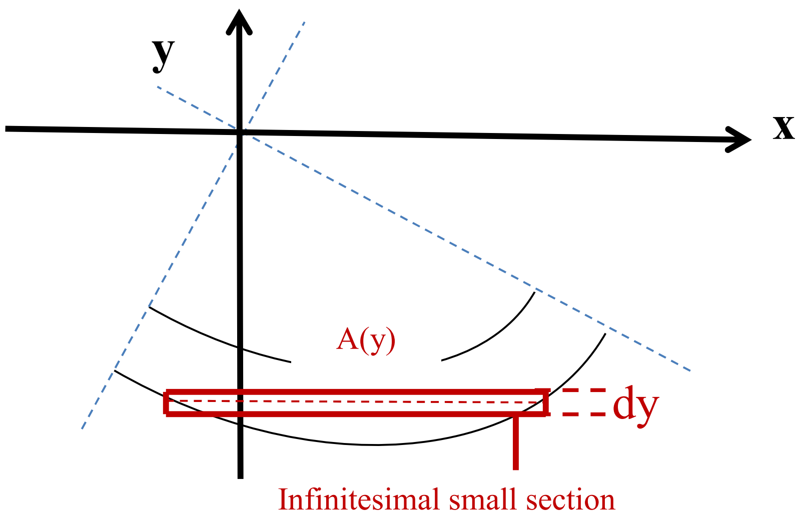


Figure 3-9 Illustration of Interpretations of the integral

$$d\ (\Delta L) = \frac{P\ dy}{E\ A(y)} \tag{3.7}$$

Therefore, the total deformation of the whole soft part of the fingertip could be deviated by the integration along the thickness of fingertip:

$$\Delta L = \frac{P}{E}\int_{L} \frac{dy}{A(y)} \tag{3.8}$$

In here, according to [59], the various cross-section could be considered by equivalent displacement in terms of current deformation. Based on this idea, I re-arrange the eq. 3.8 and collect the parameters together, the resultant deformation equation could be obtained:

$$P = \frac{E}{\int_{L} \frac{dy}{A(\Delta L)}} \Delta L \tag{3.9}$$

If we represent the eq. 3.9 as a general form:

$$P = K(\Delta L) \tag{3.10}$$

It is obvious that function K in eq. 3.10 implies the stiffness of anthropomorphic fingertip which is related to the area of cross-section, it means that the different cross-sections will produce different stiffness and outcome different deformations. In other word, it could be seem as the quantified passive flexibility of anthropomorphic fingertip.

3.2.2 Cross-section of fingertip

In eq. 3.9, the deformation equation is deviated by introducing virtual spring for presenting the elastic deformation of soft fingertip. However, as the geometric characteristics will affect the area of cross-section in eq.3.9. If the fingertip has hemi-spherical shape, the cross-section should be round and it presents round contact surface [58][59] when it is contacting rigid object with sufficient pushing force. Different from hemi-spherical fingertip, the characteristic of anthropomorphic fingertip is not clear such as geometric properties. In this section, I introduce a cross-section derivation.

(a) Contact points

Look back to the scenario in fig 3-8, in which the robotic fingertip contact an ideal rigid flat object with a given inclination angle α in pitch direction. If the geometric of fingertip is described by a set of envelope curve:

$$\begin{cases} y = f_{xy}(x) & \text{in } xy \text{ coordinate} \\ y = f_{zy}(z) & \text{in } yz \text{ coordinate} \\ z = f_{xz}(x) & \text{in } zx \text{ coordinate} \end{cases} \tag{3.11}$$

where, f_{xy}, f_{zy} and f_{xz} are the function of the curves in corresponding coordinate plane.

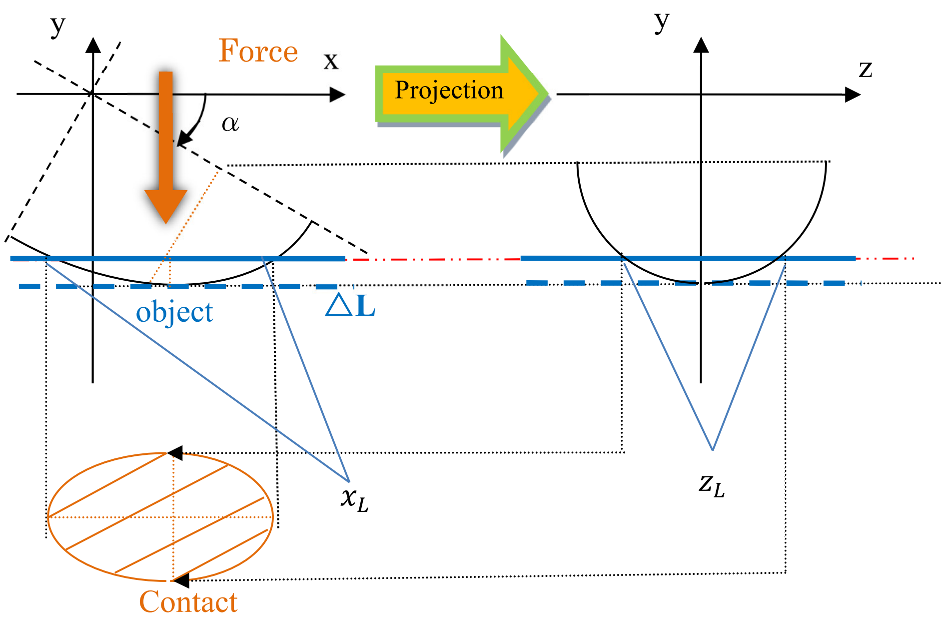


Figure 3-10 Contact mechanism

When the fingertip just touches object, we can translate this critical situation into a mathematical problem to find an intersection point of a rotated curve (fingertip envelope curve) and a horizontal line (to present the non-deformable object), as show in fig. 3-10. Therefore the intersection point could be obtained by taking differential of this curve:

$$\left.\frac{d\ {}^{r}f_{xy}(x)}{dx}\right|_{r=r_c} = 0 \tag{3.12}$$

Where ${}^{r}f_{xy}(x)$ is the rotated curve function which is obtained by rotation matrix, $r_c = [x_c, y_c]$ is the point when the differential of the curve is equate zero.

When the contact force is exerted to fingertip against the object, the force will deform the soft fingertip and increase contact area. In order to simplify the derivation process, an assumption associated with material characteristics is made:

Assumption 1: There is no shear deformation when fingertip is pushing an object.

Hence, the relative displacement could be regarded as the movement of the horizontal line. As the result, it produces two intersection points:

$$\begin{cases} x_L = {}^{r}f_{xy}{}^{-1}(y_c + \Delta L) \\ z_L = {}^{r}f_{xy}{}^{-1}(y_c + \Delta L) \end{cases} \tag{3.13}$$

where, ${}^{r}f_{xy}{}^{-1}$ is the inverse function of ${}^{r}f_{xy}(x)$. ΔL is amount of deformation corresponding to pushing force. $x_L, z_L \in \mathbb{R}^2$ are x coordinate and z coordinate of intersect points.

(b) Cross section of anthropomorphic fingertip

Because of the difficulty for determining the cross-section region of arbitrary anthropomorphic shape, an assumption is made for approximating the cross-section area:

Assumption 2: The cross-section of anthropomorphic fingertip is similar to an eccentric ellipse if the contact is at the sagittal plane of the fingertip.

Based on this assumption, the approximate area of cross-section could be estimated by the combination of each part of the ellipses as eq.3.14. Substituting eq. 3.14 into eq. 3.9, it is possible to calculate the deformation of the soft fingertip.

$$Cross\ section\ \text{area} = \frac{1}{4}\left(\sum_{i=0}^{4} area\ of\ ellipse\ i\right) \tag{3.14}$$

3.3 Fingertip design based on contact model

In last section, I introduced an elastic contact model based on two of these factors. In this research, I show possibility for applying the contact model for fingertip design in order to predict the contact area and performance in design phase.

3.3.1 Conventional research in fingertip design

(a) The current limitation of design methodology

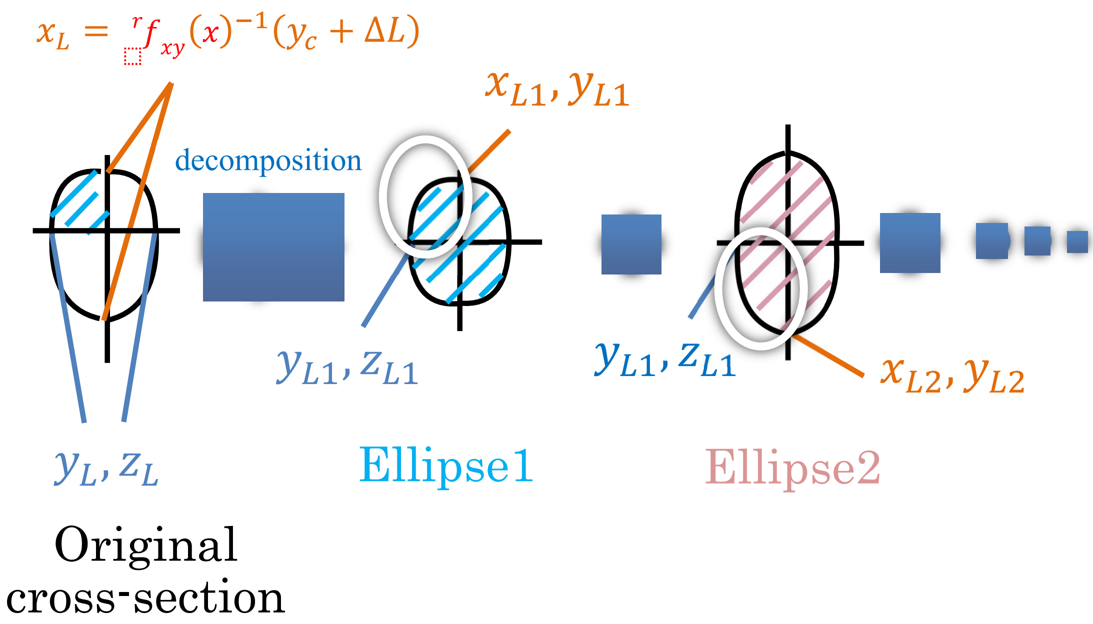


Figure 3-11 Cross-section approximation

For the robot hand development experience in our laboratory [72][90], pressure changeable fingertip could help anthropomorphic fingertip to present high skilful manipulation such as egg breaking. In section 3.1, I addressed the pressure adjustment could be performed by contact area. Therefore, the design of the shape is considered in terms of contact area. Figure 3-12 shows the contact area result of the fingertip development of TWendy-one [91]. In fig. 3-12, there is huge error between the expected performance and the measured fingertip contact area. I considered it is because that the design is done by quantitative analysis instead of quantitatively prediction in design phase.

Therefore, I proposed to apply the contact model for fingertip design in order to improve the design predictability and reduce the design error.

(b) Contact model preparing

In the viewpoint of designer, we always hope to obtain the contact area by given pushing force. In section 3.2, I introduced the elastic model and cross-section approximation of anthropomorphic fingertip. In practical robot hand design, some of the fingertip shapes are designed with complex geometric properties, which make the result

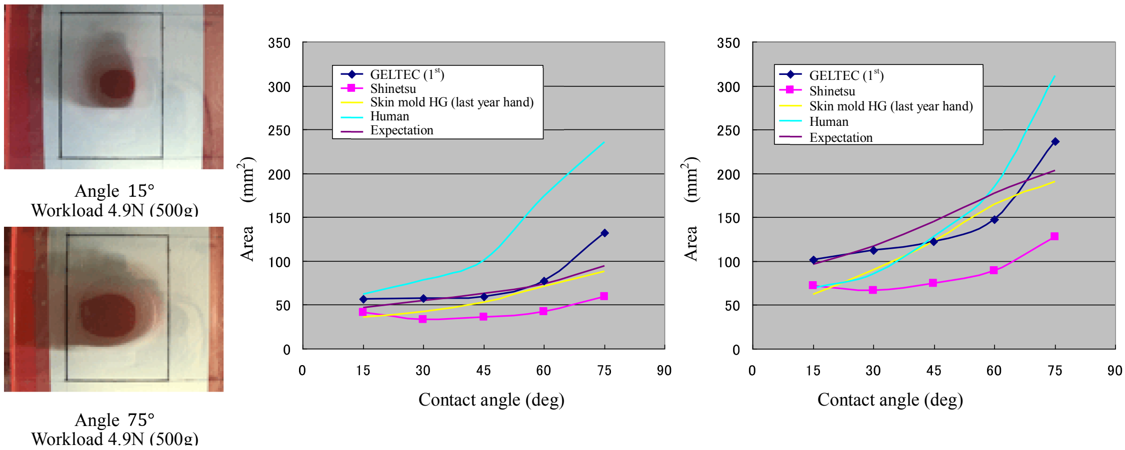


Figure 3-12 The result of fingertip design in conventional research[91]

from eq. 3.10 to become non-linear. It leads a fact that the inverse function of eq. 3.10 becomes difficult to be obtained. Therefore, I proposed to use least squares method (LSQ.) to generate a lookup table in order to find the inverse function of eq.3.10 ($\Delta L = K^{-1}(P)$).

$$\sum_i \left(\Delta L_0 - a_1 P_i - a_2 {P_i}^2 - a_3 {P_i}^3 - a_4 {P_i}^4 - a_0\right)^2 \qquad (3.15)$$

Where, P_i is a set of force expectation data generated by the eq.3.10 from deformation 0 to the maximum deformation (thickness is assumed as maximum in this research) in given inclination angle, i indicate the number of the data. ΔL_0 means the initial deformation when force is 0. a_0, a_1, a_2, a_3, a_4 are coefficients of the target formula we need to find.

By LSQ, it is possible to determine the coefficients by a set of input data (force and deformation). After the inverse function of eq.3.10. is determined, if we substituting $\Delta L = K^{-1}(P)$ into eq.3.14, the area equation of cross-section could be generally represented as:

$$\mathit{Cross\ section}\ \text{area} = \text{A}^*(\mathit{shape}, \alpha, \text{P}) \qquad (3.16)$$

Where function $A^*(\,)$ presents the relationship obtained by eq.3.14 and the result of LSQ. Based on eq. 3.16, it is possible to calculate the area of cross-section by given pushing force, contact angle and shape which is represented by a set of enveloped curve. According to the first assumption, I considered using cross-section area to approximate the contact area.

(c) Fingertip shape determination

For the flat type of fingertip, it has highest grasping stability when the contact at the pulp comparing to the other two types that I mentioned above. However, the transition from the pulp to the side of fingertip is not smooth. It leads the difficulty when the object is manipulated from the pulp to the side (red circle in fig 3-13 b). On other hand, in the TWendy-one development, [91] proposed to use a gradually reduction of inclination angle of fingertip to design the TWendy-one fingertip, as the definition of incline:

$$s = \tan(\alpha) \tag{3.17}$$

s means the slope of the curve and α is the incline.

With these concepts, I also consider an additional factor to improve the shape design by analysing curvature change.

The curvature of a fingertip curve in xy coordinate (the fingertip curve is presented in eq. 3.11) is obtained by:

$$\kappa = \frac{f_{xy}''(x)}{\left(1 + f_{xy}'^{2}\right)^{\frac{3}{2}}} \tag{3.18}$$

Considering tip and pulp of fingertip are two of the main areas for grasping the object in posture interpolation control. Therefore, we considered:

(i). In the case of the pulp, it should be designed similar to a flat fingertip because this type has relative higher stability for pulp contacts.

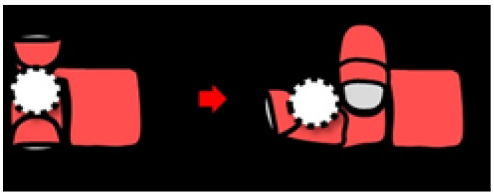
(ii). The inclination angle change should be smoothly decreasing from the tip to the pulp [91].

(iii). Finally, a monotonically increasing of curvature change is preferred for gradually decreasing the contact area from the pulp to the tip of fingertip.

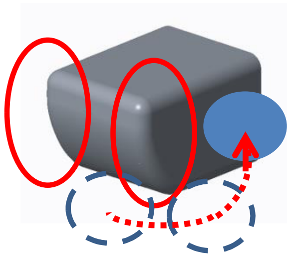
After the targets are determined, the envelope curve function of fingertip shape should be selected. In order to simplify my design, I selected a curve function which is used in TWendy-one fingertip design, it is presented by several parameters, such as length, width.

$$\begin{cases} x = length\ of\ fingertip \times (1 - w^m)^{\frac{1}{n}} \\ y = width \times w \end{cases} \quad w \epsilon [0,1] \tag{3.19}$$

In here, w means the normalized length. m, n are parameters of the curve function.



(a) Manipulation by using the side of the fingertip



(b) An example of flat type fingertip

Figure 3-13 The analysis of flat fingertip

In order to fitting the dimension of Allegro hand, we decided the width depending on the size of Allegro Hand finger at the first. After that, by iteratively adjusting the parameters, we found the suitable parameters to fulfil my requirement. An example about the iteration for determining the length of fingertip is demonstrated in fig. 3-14. After the iteration of all of parameters, I determined a prototype shape and show in fig.3-15.

3.3.2 Pressure experiment and discussion

The theoretical requirement of the current design was described in the previous sub-section. In order to test the performance of the fingertip, a fingertip prototype is made and a contact area experiment is conducted for measuring the performance of the prototype. In this experiment, the contact area of the fingertip was measured under different condition such as contact angles and workloads.

(a) Experiment setup

Considering the fingertip should be covered by soft material, the soft fingertip prototype consists of two parts:

- Inner frame: Hard inner frame is made by 3D printer with plastic material (AR-M2 from Keyence[82], hardness: Shore D 85-86).

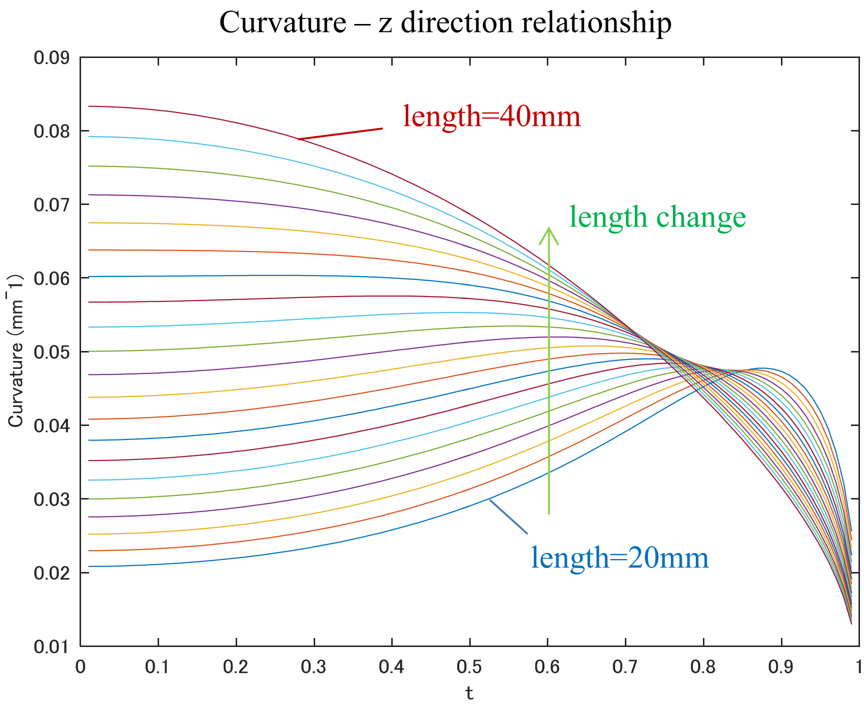


Figure 3-14 The result of length iteration affects curvature

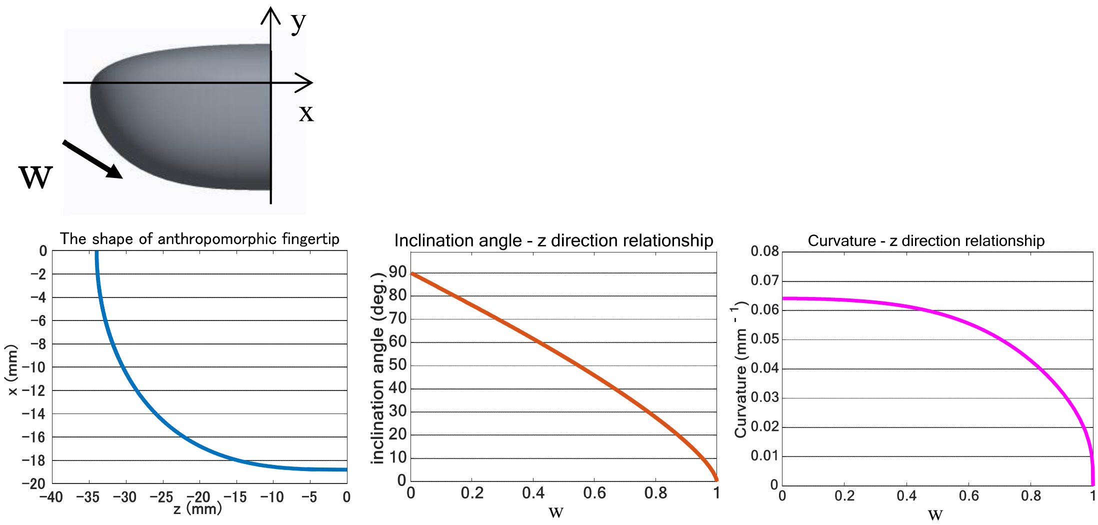


Figure 3-15 The characteristics of prototype fingertip

- Soft skin: The softness of fingertip is produced by silicon rubber (Ecoflex® 00-30 from smooth-on, hardness: Shore 00-30, 10 psi of 100% Modulus[80]). Without loss of generality, the soft skin is designed as uniform thickness (4mm thickness).

Comparing with the soft skin, the inner frame is much harder (Shore D 85-86 vs Shore

00-30), therefore the inner frame is possible to be assumed as non-deformable in this experiment. Besides, the surface of each fingertip is generated by boundary blend in Cero Parametric[101] with the corresponding envelope curves as eq. 3.19. For the soft skin, the liquid Silicon rubber was poured into the mould cast. In order to show the contact area clearly, Silc Pig® [92] is used for colouring the silicon rubber. The fingertip parameter and experiment condition are listed in table 3-2.

Figure 3.16 shows the overview of experiment setup. The instruments consist of height adjustable aluminium shaft adapter for providing pushing force for fingertip, electronic scaler for monitoring pushing force, digital camera for capturing contact area of fingertip, acrylic box act as rigid object, a rotatable mount for holding the fingertip simples. The rotatable mount could be adjusted for providing contact angles.

At the beginning of the experiment, the fingertip was installed to the rotatable mount, then it was set to the required inclination angle, the inclination angle is fixed by the screws for guaranteeing the contact angle is not changed during experiment. The height of the adapter is adjusted manually for moving the fingertip toward to the acrylic box. When the fingertip barely contacts the surface of acrylic box, the contact

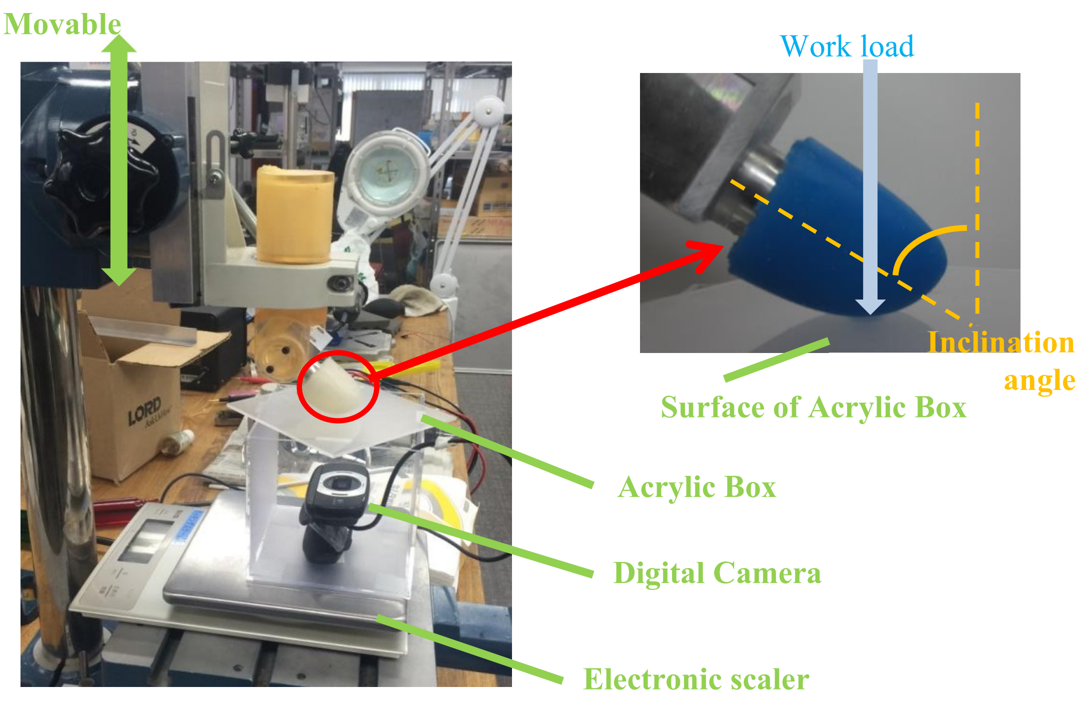


Figure 3-16 Pressure experiment setup

Table 3-2 The experiment setup of fingertip testing

Parameter	Condition
Shape (Size)	Parameter m=2; n=3, length =34, width =15.4
hardness	Shore 00-30 (100% Modulus: *10psi)
thickness	4mm (uniform)
Contact angle	15°, 30°, 45°, 60°
Work load	100g, 200g, 300g, 400g, 500g

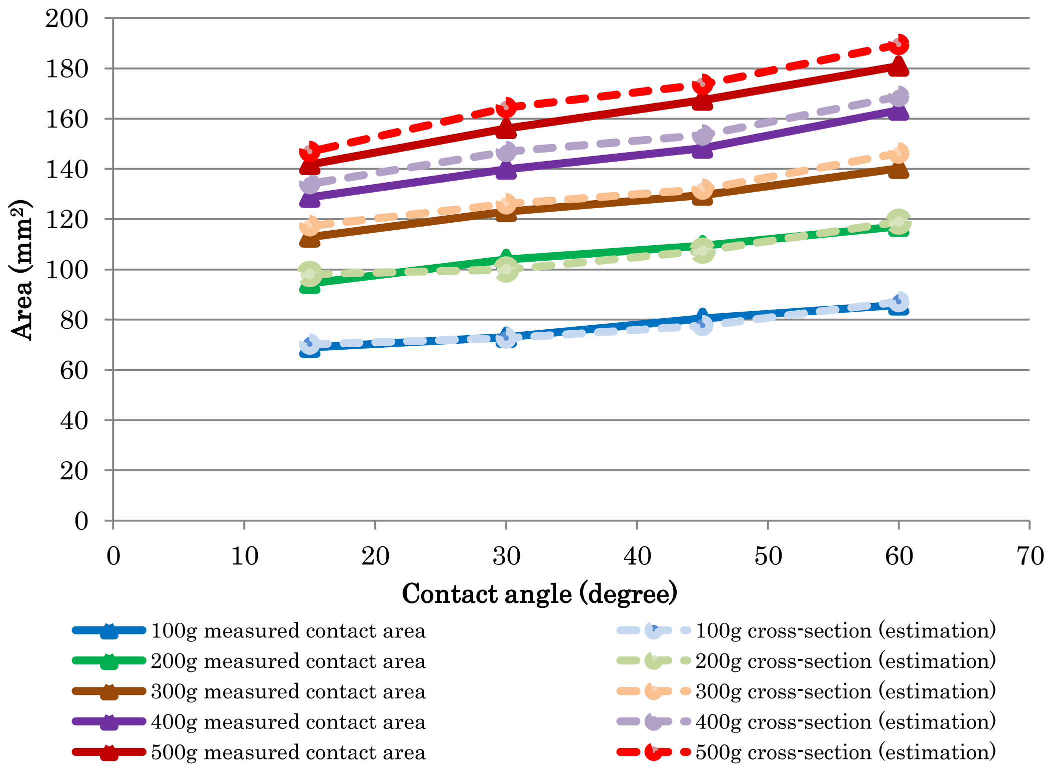


Figure 3-17 Contact area of prototype fingertip

force and displacement of the fingertip was recorded. The pushing force was increased gradually by manually adjusting the height of the adapter to the target work load (approximate 100g interval, which is shown in table 3-2). The contact status was captured by the digital camera and the displacement of the fingertip was recorded. Each of the condition is performed 3 times.

The contact area and deformation of each condition is recorded in the experiment. ImageJ [93] is used to measure the contact area from the captured photos. The average of the measured contact areas and the corresponding contact angle are shown in fig. 3-17.

(b) Result of experiment

The result in fig. 3-17 shows that the contact area is monotonically increased as contact angle increase. The largest contact area (within 15°-60° contact angle domain) occurs at the maximum contact angle (60° in this experiment). It means that the contact area change could satisfy my desire. Furthermore, the tendency of the measured contact area change is matching the calculated estimation very well. Although the error is increasing with the work load increasing, the average error in this experiment is smaller than 10%, and the maximum error is smaller than $10mm^2$.

As the influence of the curvature, fig. 3-19 illustrates the relationship between the tendency of contact area change and the curvature of fingertip. In fig. 3-19, the contact positions and the corresponding curvatures are pointed out, the yellow point shows the 15° contact angle, blue point shows 30°, red point shows 45° and the green one shows 60 ° contact angle. Considering the relationship between curvature and radius of curvature:

$$\kappa = \frac{1}{R} \tag{3.20}$$

Where, κ is curvature which is obtained by eq. 3.18, R is radius of curvature.
Since the radius of curvature is inversely proportional to curvature, the smaller curvature will come out the bigger radius of curvature. It means that if the contact point located at the position with smaller curvature, there is the larger radius of curvature.

In there, if we look back to the cross-section derivation (eq. 3.13), when we fix the amount of deformation ΔL, the distance between two intersection points will depend on the size of radius of curvature (see fig. 3.18). For more analysis, I re-produced TWendy-one fingertip [38] with uniform thickness of soft skin which is same as the prototype I used in current experiment. I show the testing result in the same figure (fig. 3.19) and compare it with the prototype. I found that the contact area change of TWendy-one fingertip is not obvious along contact angle change. Furthermore, the contact area of TWendy-one fingertip is not monotonically decreasing or increasing when contact angle is increasing. Considering the curvature of TWendy-one fingertip, the increment of curvature makes contact area decreasing around the tip of fingertip (yellow point to blue point), and the decline of curvature makes contact area increasing slightly when the contact point close to the pulp (from red point to green point). From this

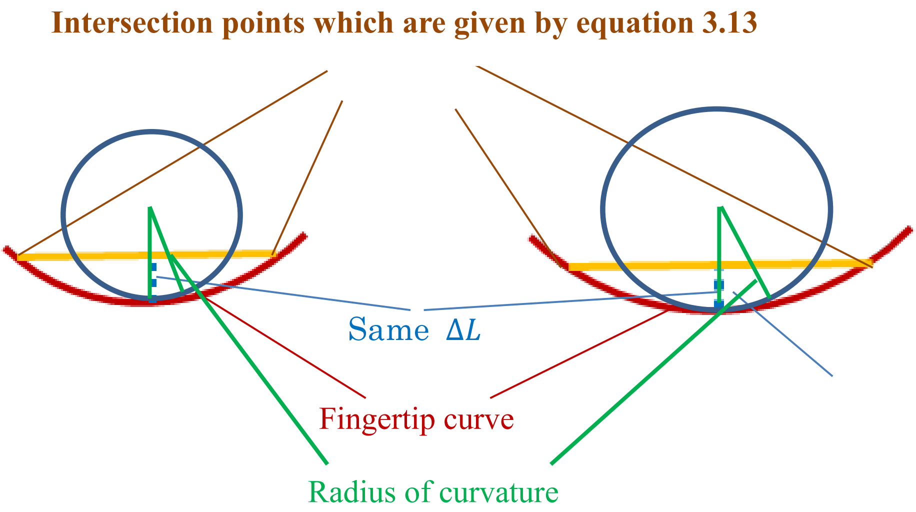


Figure 3-18 Curvature comparison

analysis, there is possibility to improve the shape design by a reasonable curvature.

(c) The consideration of other fingertip design propose

In (b), I show a fingertip design for achieving the requirement that the contact area could be gradually increased by increasing the contact angle. In practical robot hand development, there are many other fingertip requirements which is depending on the purposes of the robot hand. In order to verify that my model could be also used for other fingertip shapes, I produced another fingertip by change the parameter of fingertip shape function. The parameters in eq. 3.19 are changed to m=2; n=6, which is corresponding to the nonlinear contact area change.

I tested the performance of two fingertips and compared the measured data with the calculation result from the proposed model. Figure 3-20 and fig. 3-21 show the result of the comparison. In here, two properties are considered to be verified:

(i). Contact area- Deformation relationship (fig. 3-20)

(ii). Force – Deformation relationship (fig. 3-21)

In fig. 3-20, the estimation results by my proposed model are closed to the measured data of both fingertips. Although the errors increased as the work load increase, the errors are still small and the maximum error in this experiment is approximate 10mm2. It means that my two assumptions are appropiate. Since that the calculated areas of

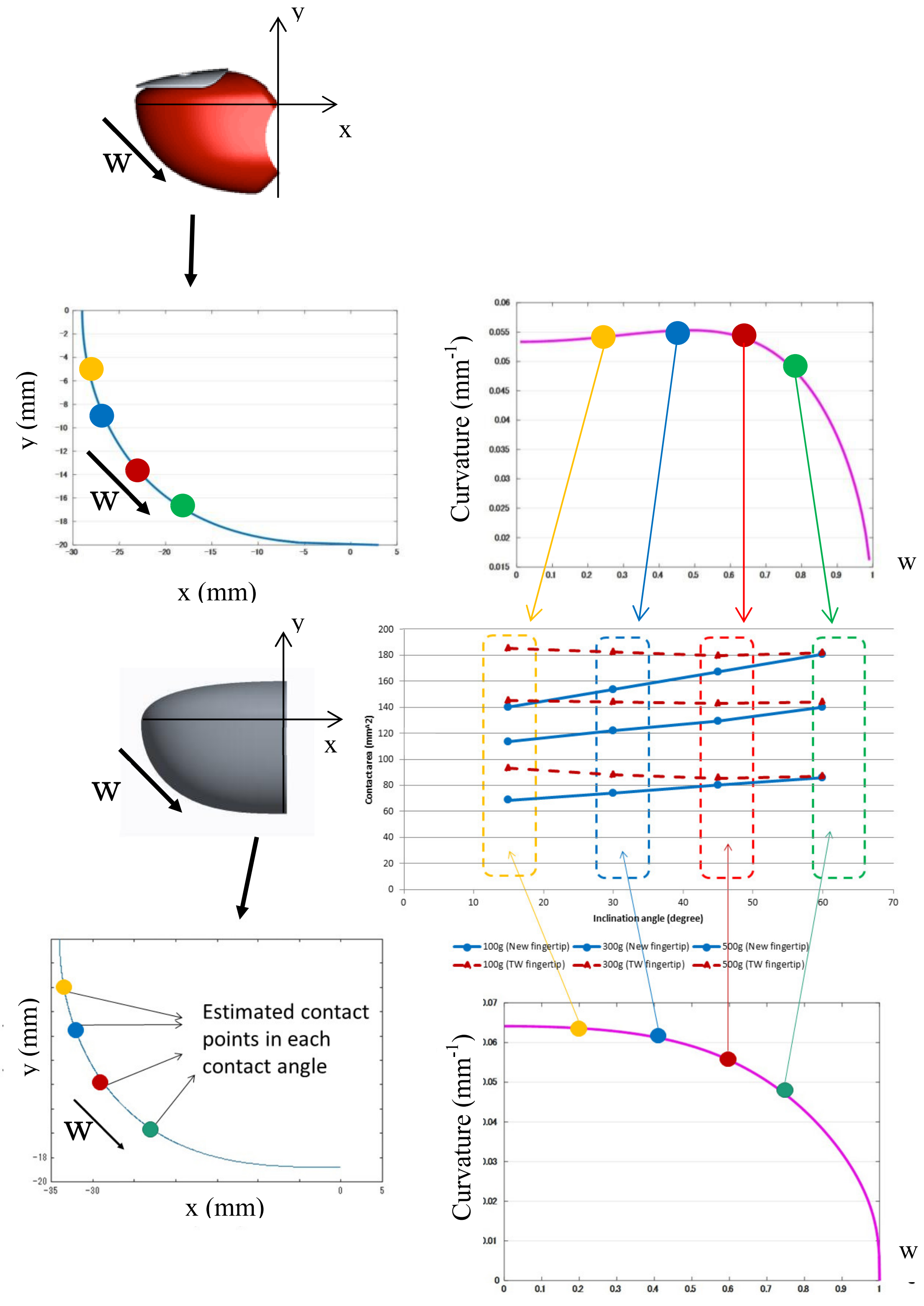


Figure 3-19 The analysis of the influence about curvature

cross-section are close to the measured contact areas, it means that it is possiblilty to use the area of cross-section to approxiate the contact area with given deformation. Moreover, the results implies that using the sum of the areas of four quarter ellipses to approximate the cross-section of anthopromophic fingertip is reasonable.

There are the similar results when I compared the estimated force with the measured force by given deformation (it is shown in fig. 3-21). In here, the force – deformation relationship (equation 3.10) is obtained by cross-section area of fingertip instead of practical contact area, therefore the validation in fig. 3-21 verified my elastic model and cross-section calculation (equation 3.14).

From the viewpoint of robotic hand designer, the performance of contact area change with various contact angles is often concerned. Figure 3-22 shows the tendency of contact area change respect to contact angles. In here, the result shows us that the contact area trend of the measurement is also close to my expectation. Comparing two kinds of fingertip, the first fingertip (result in fig. 3-17) presents a property that the contact area increases with increasing contact angle. The second fingertip (result in fig. 3-22) presents the property that the contact area decreases with increasing contact angle (within 15°-60° contact angle domain). From these two results, I conclude that my model is effective and it is possible to be used for robotic fingertip design in terms of performance prediction.

Considering the curvature influence in the design phase, fig. 3-23 shows the curvature comparison of these two fingertips. For the fingertip with parameter m=2, n=6, the contact points is very close within 30 ° to 60 ° contact angle, therefore their corresponding curvature very close, it leads that the contact area change is not obvious. Nonetheless, contact area is slightly decreasing when the contact angle is increasing (within 30°to 60° contact angle domain). When the contact angle achieved 60degree, the curvature is achieving the peak, it come out a result that contact area decreasing with contact area increasing until 60degree. After the peak, we expected that the contact area will start to increase because of curvature decrement nearby the pulp.

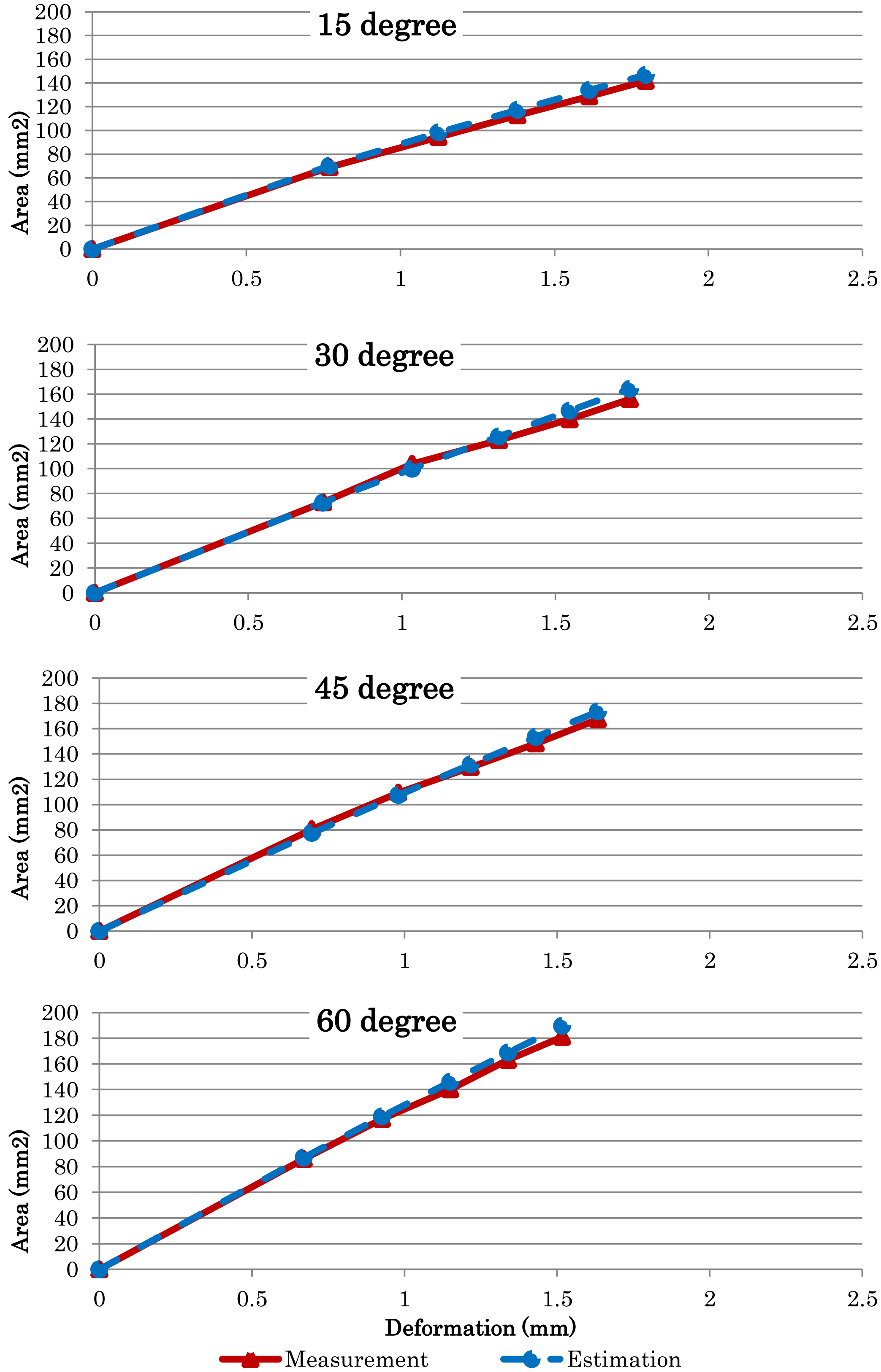


Figure 3-20 (a) The experiment about contact area vs cross-section
(Parameter:m=2; n=3 in eq. 3.19)

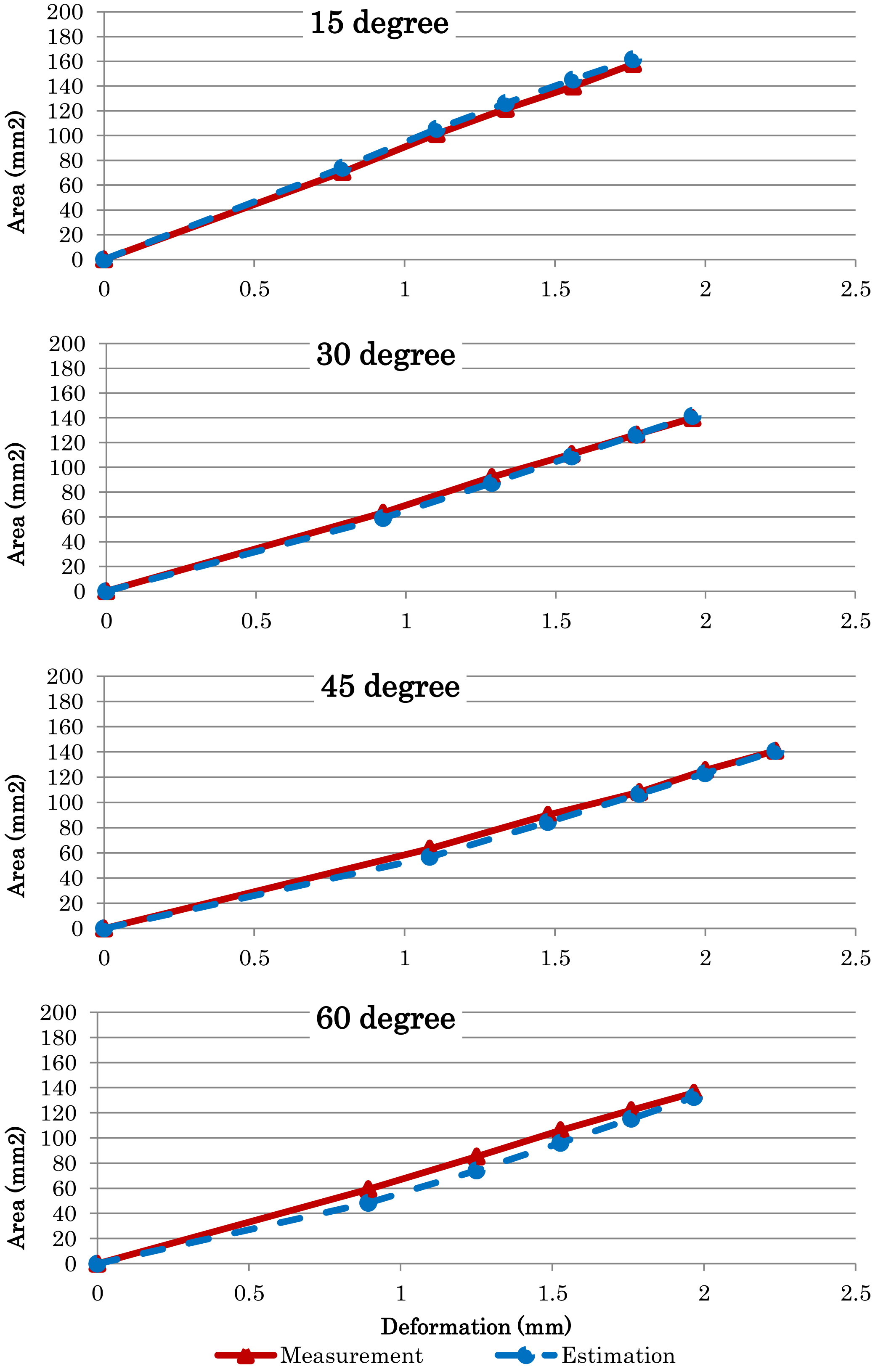


Figure 3-20 (b) The experiment about contact area vs cross-section
(Parameter:m=2; n=6 in eq. 3.19)

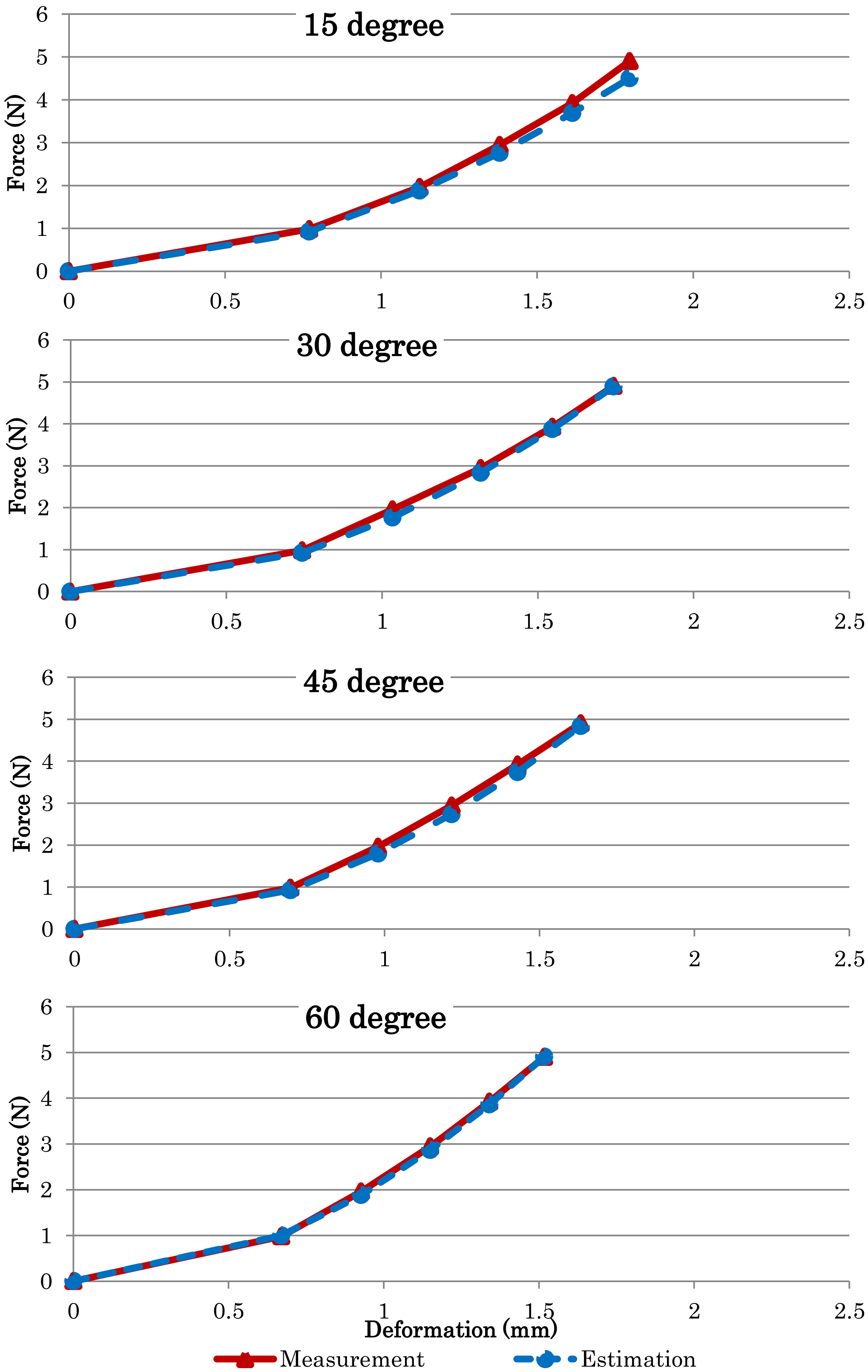


Figure 3-21 (a) The experiment about force-deformation relationship
(Parameter:m=2; n=3 in eq. 3.19)

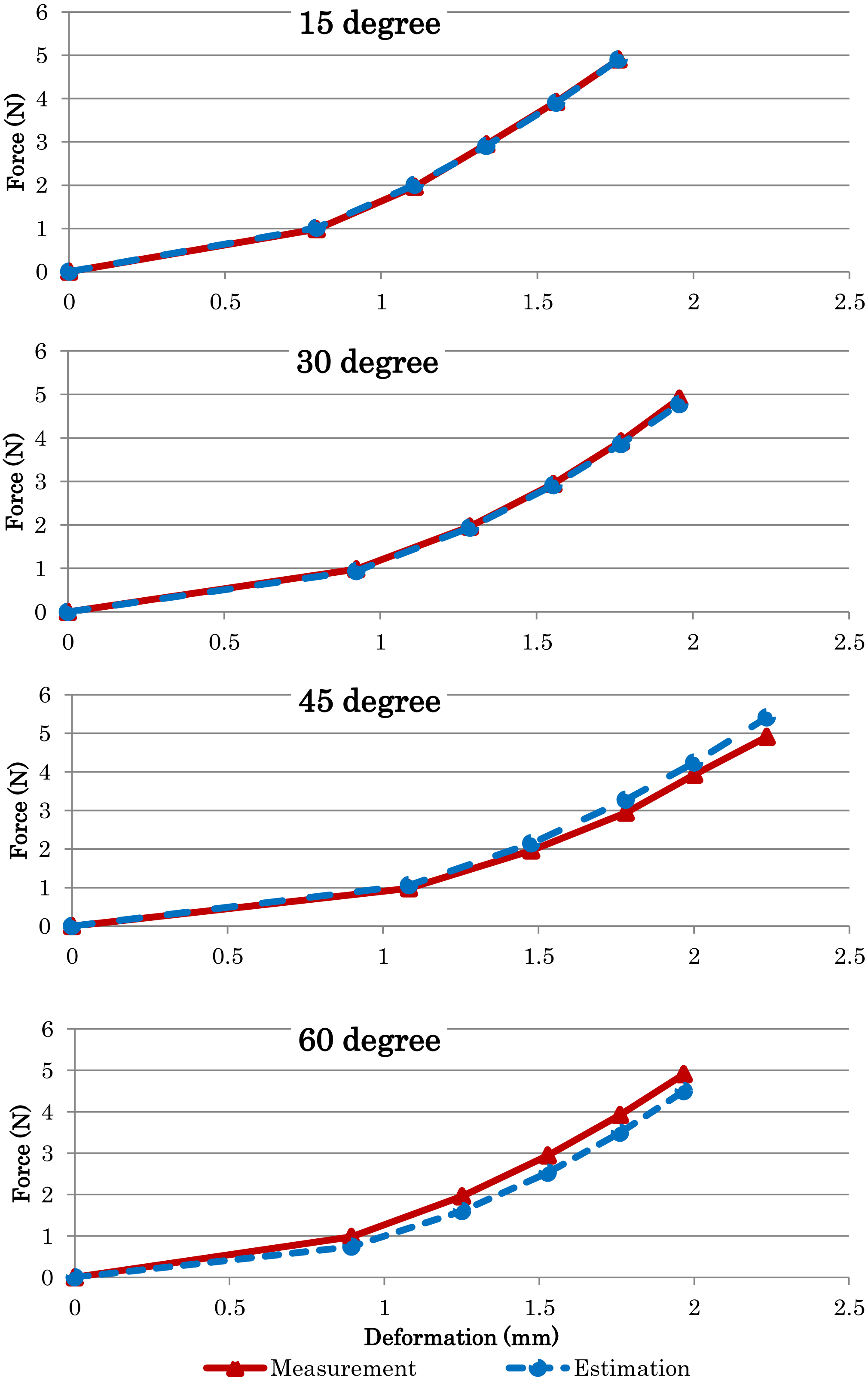


Figure 3-21 (b) The experiment about force-deformation relationship (Parameter:m=2; n=6 in eq. 3.19)

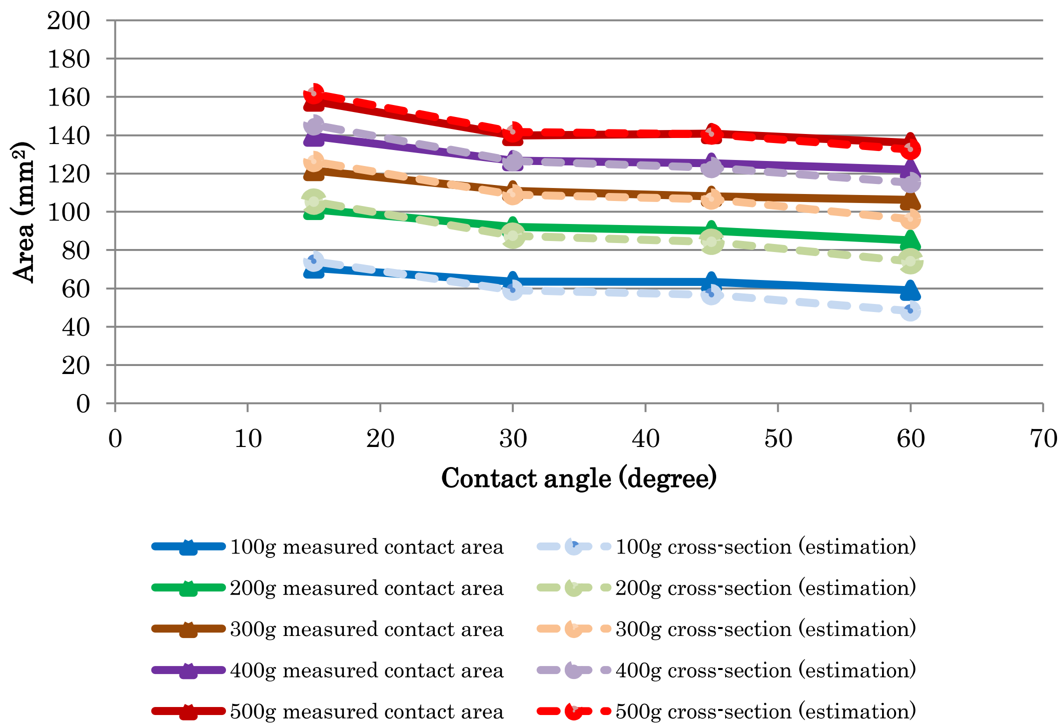


Figure 3-22 The comparison of estimation and measured contact area (another type fingertip)

3.4 The contact area properties adjustment

In last section, the fingertip shape design is addressed for producing pressure adjustment function in the case of uniform skin thickness. In the TWendy-one hand development [91], in order to produce more contact area change, non-uniform skin thickness is also considered in fingertip design. Therefore, I consider producing a fingertip with non-uniform soft skin thickness by proposed design approach with adjusting the thickness parameter ΔL in the deformation model. I used the same fingertip parameters as the previous experiment but change the thickness to non-uniform (which is illustrated in fig.3-24). In here, in order to verify the pressure property, I also show the contact area change of original TWendy-one fingertip. In order to guarantee the contact area is just affected by shape and thickness, I used shore 00-20 hardness material which is similar to TWendy-one hand soft skin (shore 00-17). And I preliminarily tested the fingertip in 45°,60°,75° contact angles. The results are shown in the fig. 3-25.

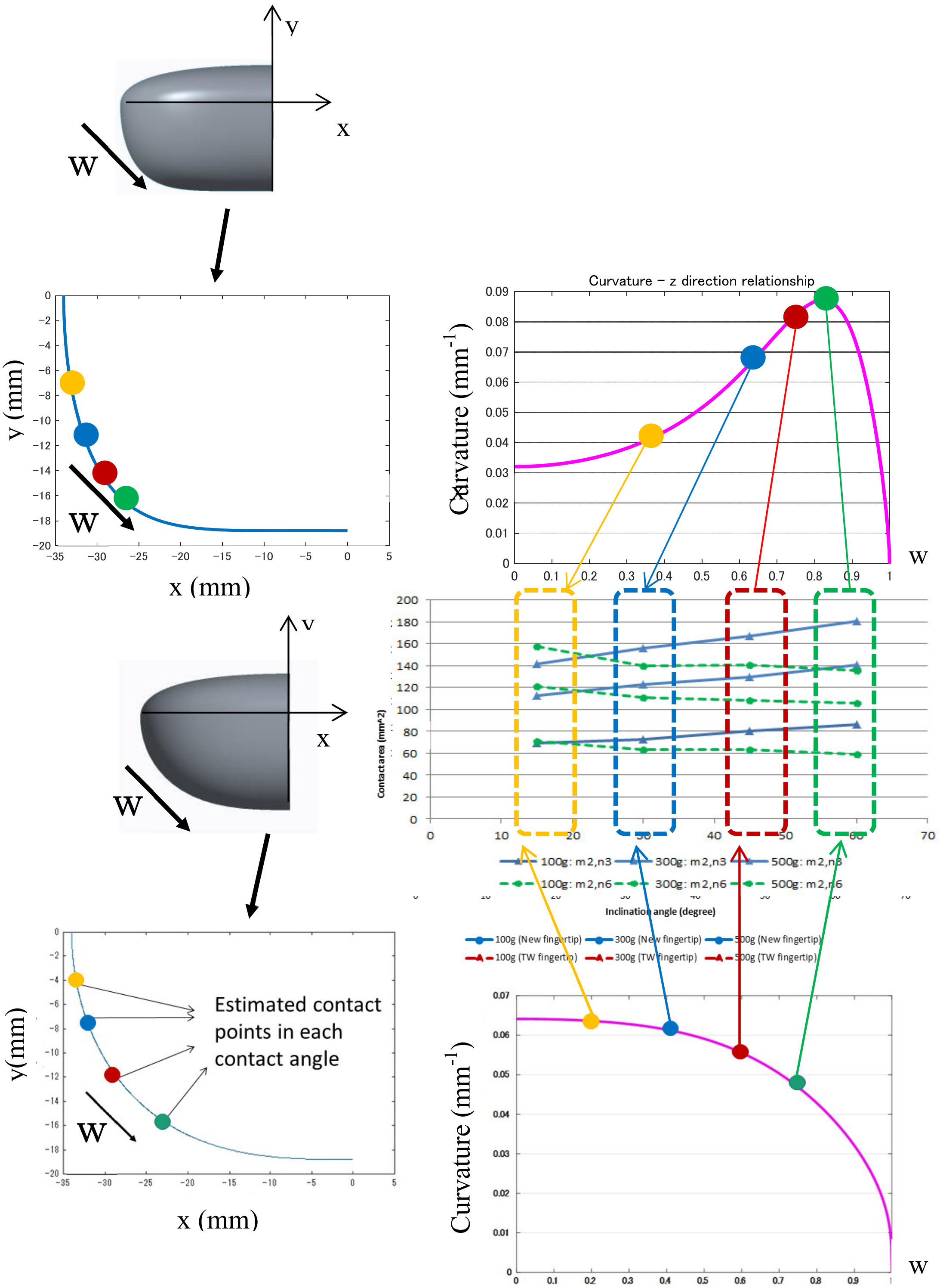


Figure 3-23 Comparison of two kinds of fingertip

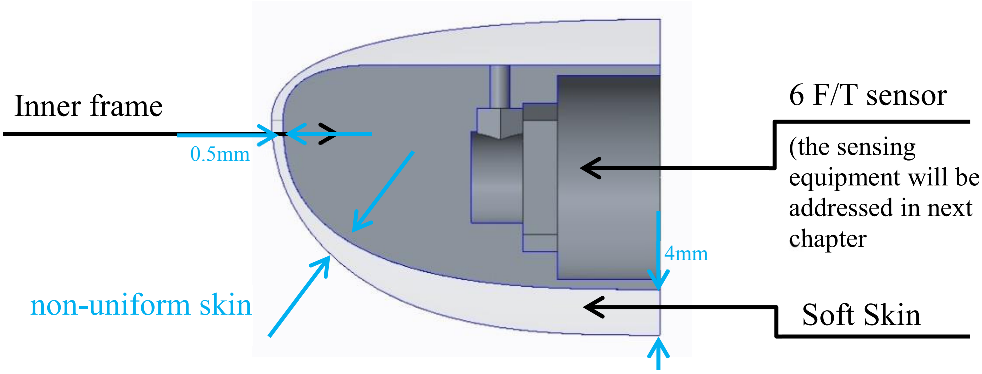
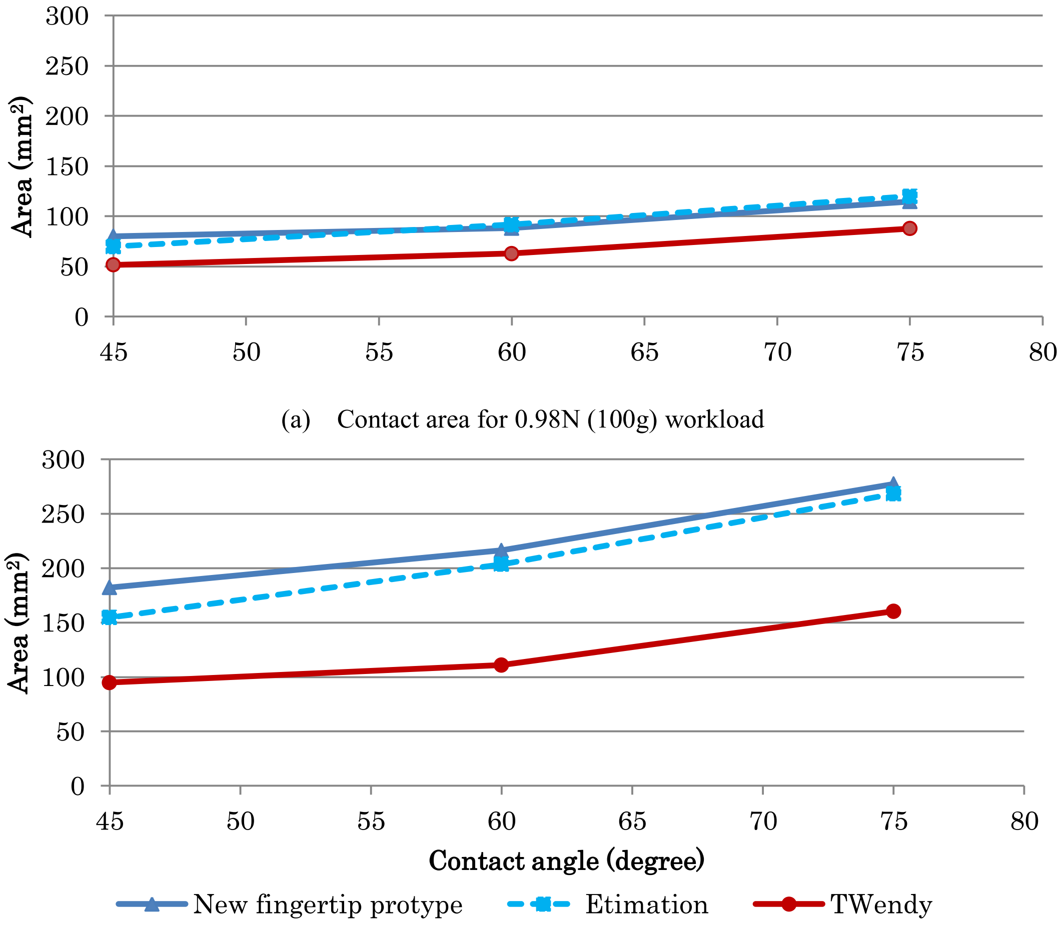


Figure 3-24 The structure of non-uniform thickness skin fingertip



(b) Contact area for 4.9N (500g) workload

Figure 3-25 Contact area of Pressure experiment

From the result, comparing with TWendy-one fingertip, it could be seen that by appropriately adjust the thickness in fingertip design, it could provide wider contact area change.

3.5 Summary

Before the development, in order to clarify the influence of hardware on grasping performance, a study about grasping capability of various fingertips is conducted. After clarified the importance of these factors, I introduced a new contact model by using elastic deformation model and cross-section estimation of anthropomorphic fingertip. Based on these two models, I deviated the relationship between fingertip shape, pushing force, contact angle and hardness and thickness of soft skin on fingertip. This model could enable us to quantitatively analyse and predict the contact performance of fingertip. Only changing the parameters in the model, such as Young's modulus or thickness, we could estimate the contact status before we made the fingertip. Besides this model, I also discussed the curvature influence in fingertip design.

The verification experiments are conducted in this chapter by measuring the deformation, contact area and contact force of the fingertip. The result shows that the measurement data for real fingertip is matching my estimation very well, and the performance of the fingertip also fulfils my requirement. Comparing to conventional research, my new methodology could improve the predictability in design phase and reduce the design error. Furthermore, comparing to the conventional research about elastic contact model, the theoretical contact model is limited in spherical fingertip. In my research, I show that my model could be effective with anthropomorphic shape.

In this chapter, I quantified passive flexibility of soft skin by stiffness K in deformation model. As a whole robot hand manipulation system, I also consider the active flexibility in robot hand control system. In the next chapter, I will introduce new controller enable robot hand to present robust manipulation.

Chapter 4

Flexibility and task versatility of in-hand manipulation

Passive flexibility could improve manipulation performance by allowing small error in position control. However, high manufacturing cost obstructs robot hands with passive flexibility to be adopted widely in our daily life. Force control is one of the other solutions which could improve manipulation performance instead of hardware impedance. Traditional force control strategies need complex mathematical models with numerous information for trajectory planning. These strategies are often difficult to be realised in daily environment if there has not sufficient information such as the case that too dark to recognise the object by vision sensor. In this research, a manipulation system is proposed by introducing both software and hardware flexibility into general robot hand. In the third chapter, I proposed an approach to design robot hand fingertip with passive flexibility quantitatively. In this chapter, I addressed an improvement of posture interpolation controller by introducing compliance into it in order to provide "active flexibility" for in-hand manipulation. Two experiments were conducted for verifying the versatility and adaptability of our manipulation system. At the end of this chapter, a discussion is addressed about the performance and limitation of myproposed system.

4.1 Introduction

The support from robots in human daily activities is a greatly anticipated solution for labour shortages in aging societies. Considering there are many practical tools/objects in our daily environment with complex shapes, the recognition error, object deformation, or low accuracy of kinematics calculation of these objects will lead error in the control of manipulation. Therefore, insufficient control adaptability often causes in-hand manipulation failure in traditional position control with rigid fingertips.

To overcome the shortcomings of rigid fingertips, force control is considered as a way to improve stability and adaptability in robot hand. Two major force control strategies in conventional researches are: hybrid position/force control and impedance control.

For the traditional hybrid position/force controller, an example of force control task with a 3DOF arm is shown in fig 4-1. A representative hybrid position/force controller is shown in fig 4-2.

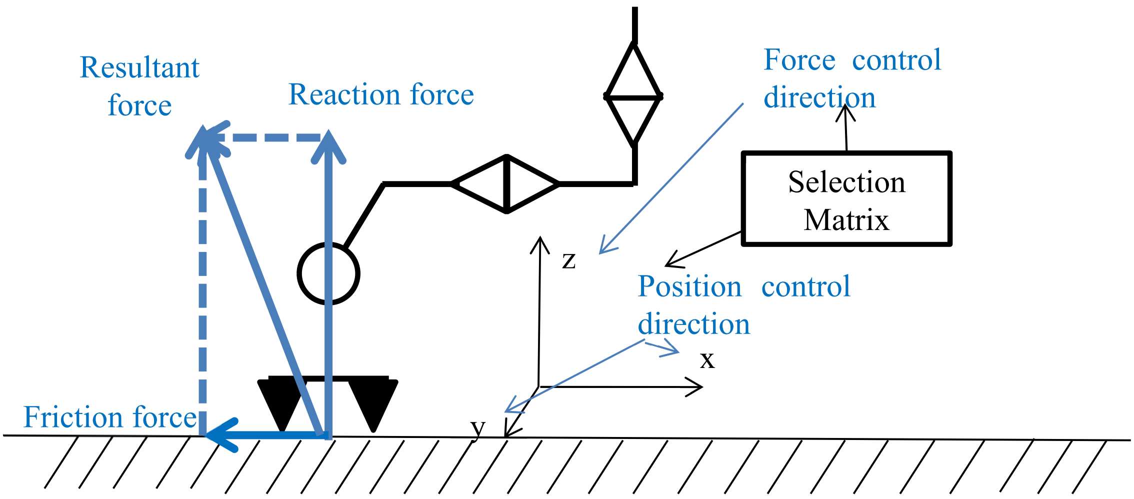


Figure 4-1 The control situation of 3 DOF arm

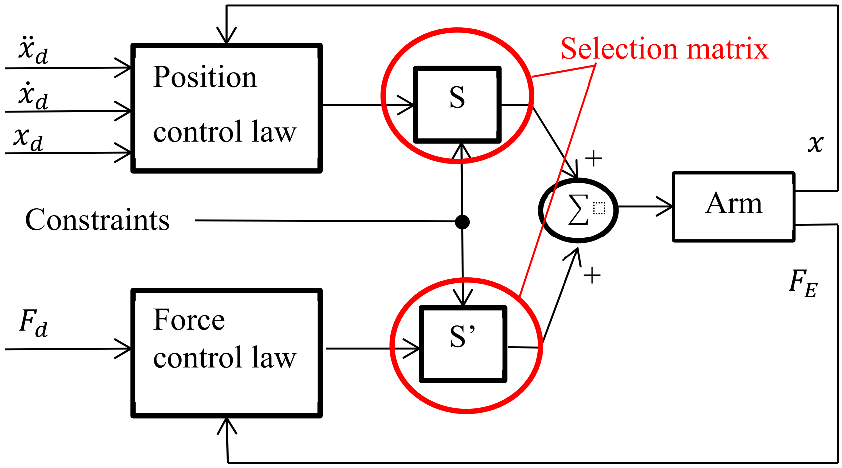
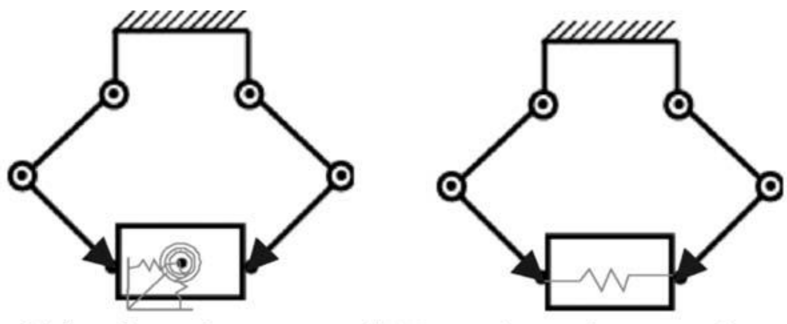


Figure 4-2 The hybrid Cartesian controller for a 3-DOF arm[94]

In this hybrid controller, by introducing a selection matrix, separation was made explicitly between position and force control loops through projections of feedback signals onto admissible motion space and constraint space [93]. Therefore, the position and force control target should be separated into different direction. As an example, in fig.4-1, the positon control is considered in x-y plane and the force control will be used to control the contact force in z-direction. Considering a manipulation task of robot hand, the movement of finger should be in three-dimension, the desired positon of fingertip is related both desired object position and desired contact force. Therefore, it is difficult to decouple them during in-hand manipulation.

As another force control approach, impedance control is one way that aims at realizing the following desired object impedance property.

$$M_D\ddot{r}_O + D_D(\dot{r}_O - \dot{r}_{Or}) + K_D(r_O - r_{Or}) = t_E \tag{4.1}$$



(a) Object impedance (b) Impedance between fingers

Figure 4-3 Impedance control concept [95] where M_D, D, and K_D are, respectively, the desired inertia, damping-coefficient, and stiffness matrix. all of which are symmetric and positive definite. r_{Or} is the position of the reference frame to which the desired impedance is attached. r is position and orientation of the object. t_E is the other possible external force working on the object. If we assume the movement of the object is similar to a mass-spring-damper model, by appropriately designing the impedance parameter M_D, D, and K_D, it is possible to calculate the actuation force t_E in eq.4.1, for presenting the required object impedance properties. Therefore, impedance control is often used to present grasping behaviour instead of in-hand manipulation.

4.2 Compliance posture interpolation control strategy

As I introduced in chapter 2, a simple posture interpolation control strategy is proposed in the convention research on TWendy-one hand. By the transitions of pre-defined postures, versatile manipulations could be generated without any additional trajectory generator. However, in the same chapter, I also clarified that insufficient adaptability is the shortcoming of this control strategy when it is implemented in other robot hand which have not installed any impedance mechanism. Therefore, I considered an improvement by introducing force feedback information into this controller.

4.2.1 Control scheme of compliance posture interpolation control

(a) Force Control strategy

Grasping force is often considered as the feedback from the object for improving the grasping performance. In order to perform stable manipulation, I considered to introduce force information into posture interpolation controller. Since the posture interpolation controller is designed in joint space instead of operational space, the relationship between force magnitude/direction and joint angle is given by inverse kinematics.

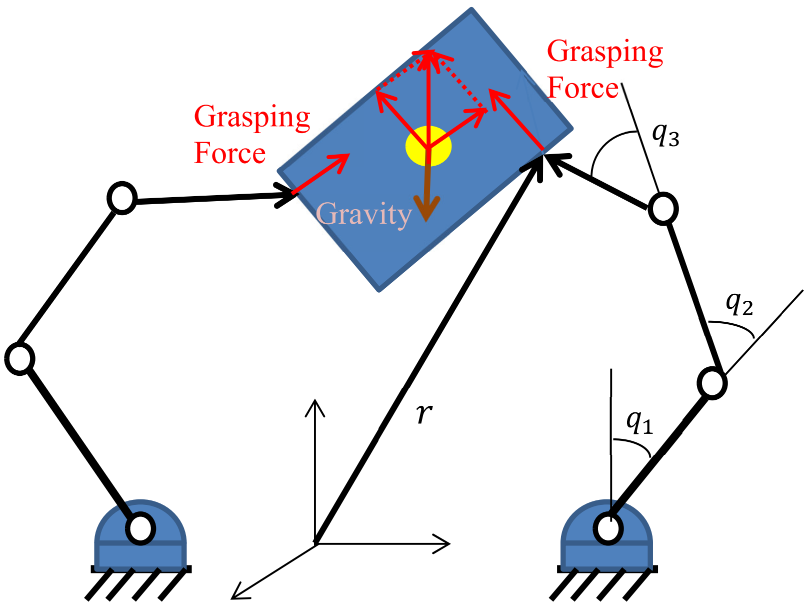


Figure 4-4 Manipulator model

At the first, the relationship between joint vector and position vector of fingertip is obtained by the kinematic relationship:

$$r = f(q) \tag{4.2}$$

where $r \in \mathbb{R}^{12}$ presents position vector of fingertips with respect to inertial coordinate, $q \in \mathbb{R}^{16}$ is joint angle vector of robot hand. $f(q)$ is kinematics relationship of robot hand with the parameters addressed in section 2.1.

Therefore the relationship between the joint velocity and fingertip velocity could be derived by:

$$\dot{r} = J\dot{q} \tag{4.3}$$

Where J is the Jacobian.

In each controlling cycle, with the small time interval $\Delta t = t_i - t_{i-1}$, the corresponding joint displacement and the displacement of fingertip as:

$$\Delta r = J\Delta q \tag{4.4}$$

Thus the inverse kinematic relationship could be obtained as:

$$q_f = q_c + J^{-1}(r_f - r_c) \tag{4.5}$$

Where r_f, r_c are target and current fingertip position vector. As the redundancy of Allegro hand fingers, in order to get a single solution from inverse kinematics, I introduced the following constraint: the joint angle of distal interphalangeal joint equals the joint angle of proximal interphalangeal joint. Therefore the desired joint position q_f of the force control could be obtained with the inverse kinematics solution.

And then, a force could be controlled by the displacement of the contacting fingertips with a proportional gain:

$$\Delta r \triangleq K_s \bigtriangleup F \qquad (4.6)$$

where the proportional gain K_s is decided empirically in negative value (I set $K_s = 1e - 4$ in current experiment). From the viewpoint of geometrics, it means that the target force magnitude is controlled by the opposite displacement of the fingertip.

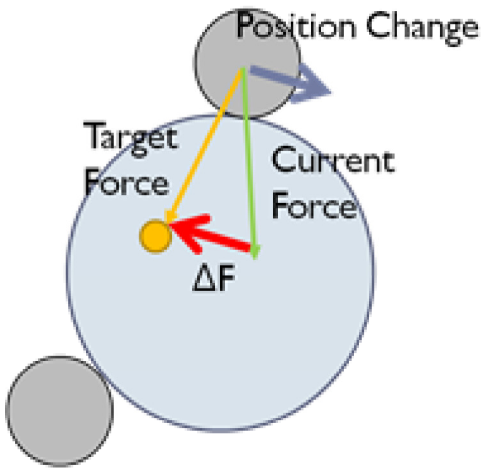


Figure 4-5 Force control strategy

(b) Compliance posture interpolation control (combined control)

With the posture interpolation position control (in chapter 2) and force control I introduced above, I combined the desired angle from both control schemes, and the control block diagram is shown in fig. 4-6.

In this control scheme, two proportional gains K_f, K_i were introduced and I experimentally determined it as $K_f = 0.8$, $K_i = 0.2$ in current experiment. Therefore the control law is presented as:

$$q_{des} = K_f q_f + K_i q_i \qquad (4.7)$$

q_i and q_f were calculated in each control cycle using eq. 2.7 and eq.4.5.

(c) Gravity compensation in PD controller

Since the inertia properties of actual robot hand will affect the movement of the fingers, a modified PD controller acting on the error between the desired and current position of the joints is used:

$$\tau_d(t) = K_p[\tilde{q}(t) - G(t)] - K_d\dot{q}(t) \quad (4.8)$$

where $\tilde{q} \triangleq q_{des} - q_c$ is the joint position error which is defined as the difference between the desired angles q_{des} and the current joint angles q_c, $G(t)$ is gravity compensation term respects to robot hand joints. K_p and K_d are the proportional and derivative control gains, respectively.

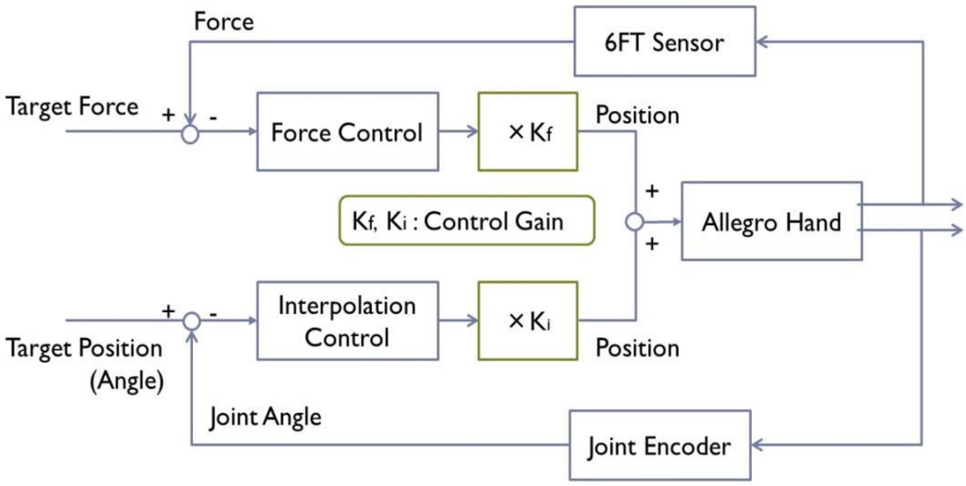


Figure 4-6 Control block diagram

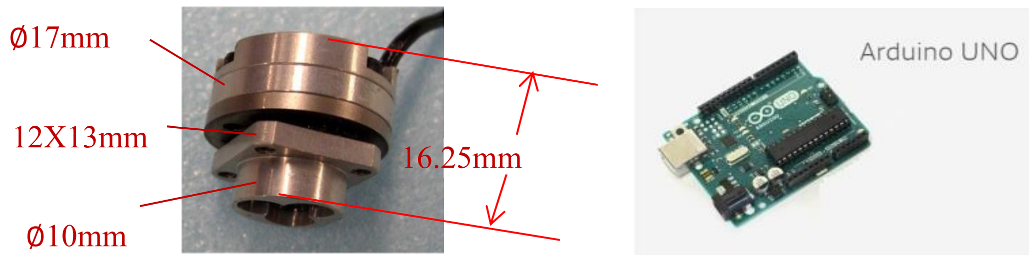
4.2.2 The control of system

(a) Sensing element

In this research, in order to obtain force information for controlling grasping force, I used 6 axis force/ torque sensor in each fingertip. The overlook of the selected 6-axis force/torque sensor is illustrated in fig. 4-7(a) and the specification is shown is table 4-1.

Table 4-1 Specification of 6 axis F/T sensor

Location	Inside each of the fingertip	
Maker	BL AUTOTEC, Ltd. (customized product)	
Type	Strain gauge type 6 axis (F_x, F_y, F_z, M_x, M_y, M_z)	
Dimension (mm)	φ17×16.25	
Driving voltage (V)	5	
Output (V)	1～4	
Loading rate	Force F_x, F_y, F_z (gf)	1500
	Torque M_x, M_y, M_z (gf･cm)	1500
Resolution	F_x, F_y, F_z, M_x, M_y, M_z	1/256 of the rate
Accuracy	F_x, F_y, F_z, M_x, M_y, M_z	1.5%FS



(a) 6 axis F/T sensor (b) Arduino UNO[89]

Figure 4-7 Sensing instrument of fingertip

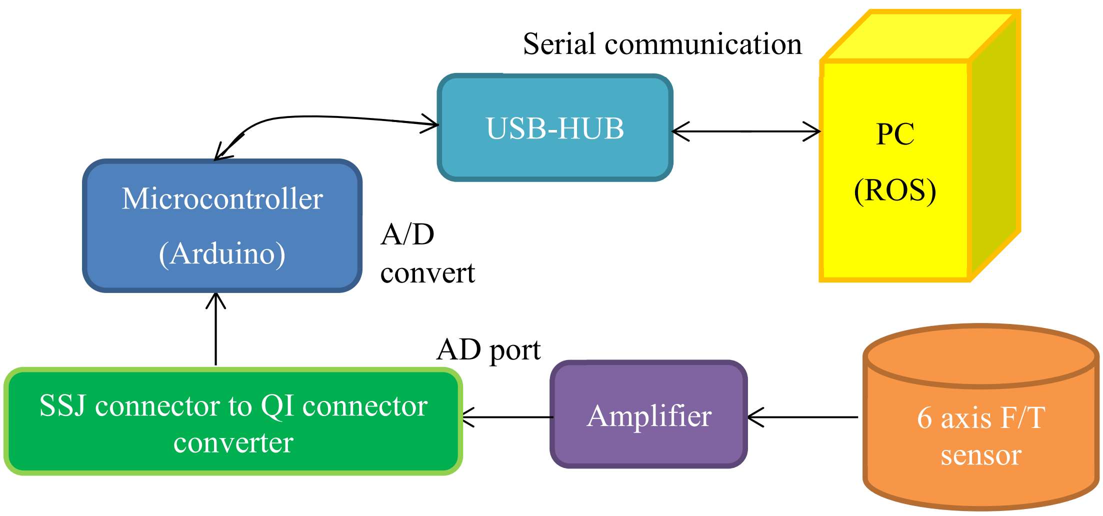


Figure 4-8 Sensor communication

The force/torque information from the sensor will be passed through Arduino uno micro-controller [96] and it is connected to PC via USB. Figure 4-7(b) shows the micro-controller I used and fig 4-8 show the sensing communication setting.

(b) The overall of system

In the chapter 2, I have introduced the Allegro Hand system with posture interpolation control platform. With the fingertip development in last chapter and compliance posture interpolation controller in this chapter, I upgraded the CUI for communicating with user and modified the simulator with the new fingertip CAD. The CUI is capable the posture input, size input, control mode selection, transition time input, with force/ joint information indication. The overall of system is shown in fig. 4-9 and the new CUI is shown in fig. 4-10.

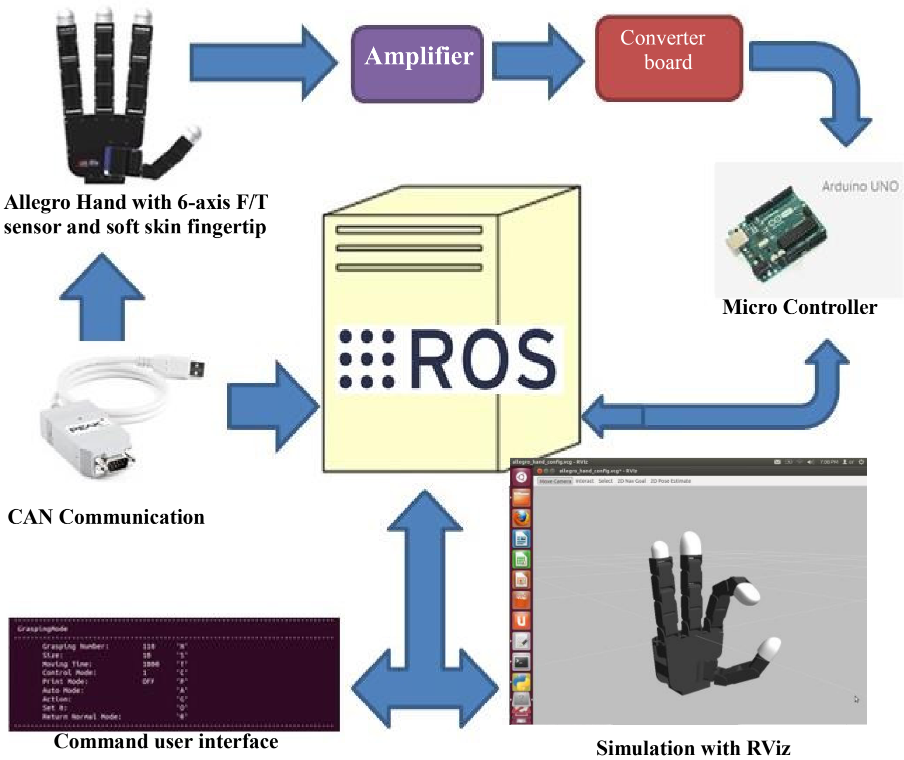


Figure 4-9 Robot hand system overview

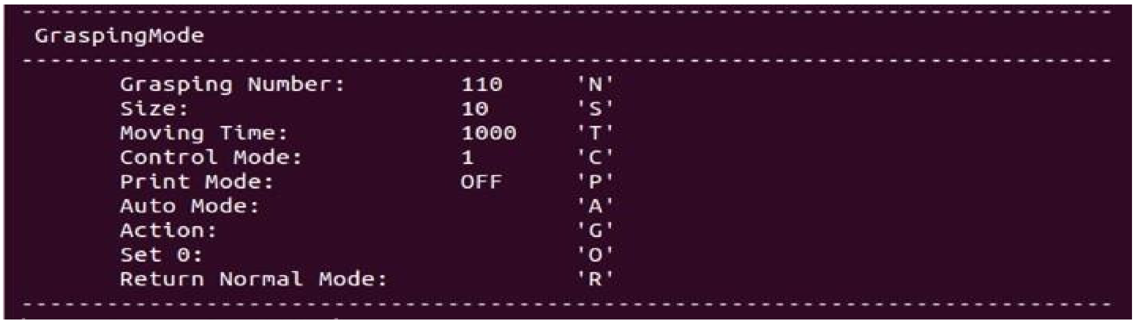


Figure 4-10 The CUI of new system

4.3 Experiments and result

In order to verify my proposed system, in this section, two kinds of experiments are presented for validating task versatility and adaptability to inappropriate posture.

4.3.1 Evaluation of Versatility

Task versatility is one of an important advantage of posture interpolation control. In order to verify the versatility of my proposed system, I tested my system with various task parameters. Before the experiment, I introduced a standard condition (listed in table 4-2). Based on this standard condition, I changed task parameter one by one and tested the robustness of object manipulation. The definition of successful manipulation was to set to accomplish a manipulation without dropping the object. Each of the task parameter settings was tested 10 times. The various task parameters I used in this experiment were defined as the following:

(i). Motion
(ii). Object shape
(iii). Object size
(iv). Object material
(v). Initial grasping position

Table 4-2 The standard condition for experiment

Task Parameter	Condition
Motion	Rolling a sphere from the bottom of the index fingertip to its side (Motion A in fig. 4-11)
Initial Position	At the centre of the fingertip
Object Size	φ60 [mm]
Object Shape	Sphere
Object Material	Polystyrene foam

Each task was tested in the following ways:

① Compliance Posture interpolation control with soft skin
② Compliance Posture interpolation control without soft skin (rigid fingertip)
③ Interpolation control with soft skin
④ Interpolation control without soft skin (rigid fingertip)

When the skin was not used, the 3D printed material (AR-M2) was in contact with the objects, which is much harder than the Ecoflex 00-30, and was considered approximately to be rigid for my experiments. Allegro Hand was located at an XYZ stage. XYZ stage is an instrument which could provide a movement in three directions. The movement of X and Y directions could controlled in 0.1 mm; the movement of Z direction could be controlled in 1 mm. This XYZ stage was used to place the objects in controlling the locations in order to provide initial grasping position.

(a) Motion experiment setting

Three kinds of manipulation which I have chosen for testing the versatility of the motion. These motions are designed by the transition between the fundamental

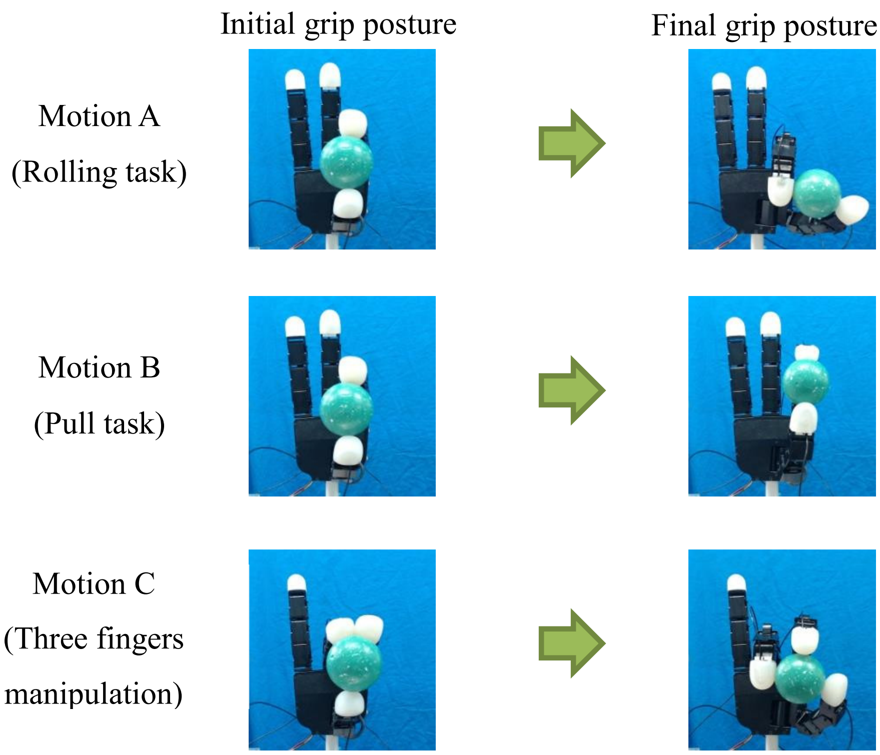


Figure 4-11 Manipulation Motion definition

postures which is defined in chapter 2. Without loss of generality, two fingers motions and three fingers motion are also tested in this experiment. Two types of two fingers motions are selected: rolling task and pull task.

Comparing two kinds of two fingers motion, the push task (the Motion B of fig. 4-11) was chosen in my experiment because this is a posture transition in sagittal plane. Another experiment “rolling a sphere from the bottom of the index fingertip to its side” (the Motion A of fig. 4-11) was conducted in this experiment in order to verify the manipulation property in the transverse plane.

(b) Object setting

In other hand, about the object simple, three shapes are selected in this experiment: sphere, cylinder and egg. Three sizes spheres (Ø30, Ø60, Ø80) were chosen for verifying the object size adaptability of my proposed system. In additional to polystyrene foam sphere, different material objects were also selected in this experiment: Plastic cup and real egg. The selected object description is shown in fig. 4-12.

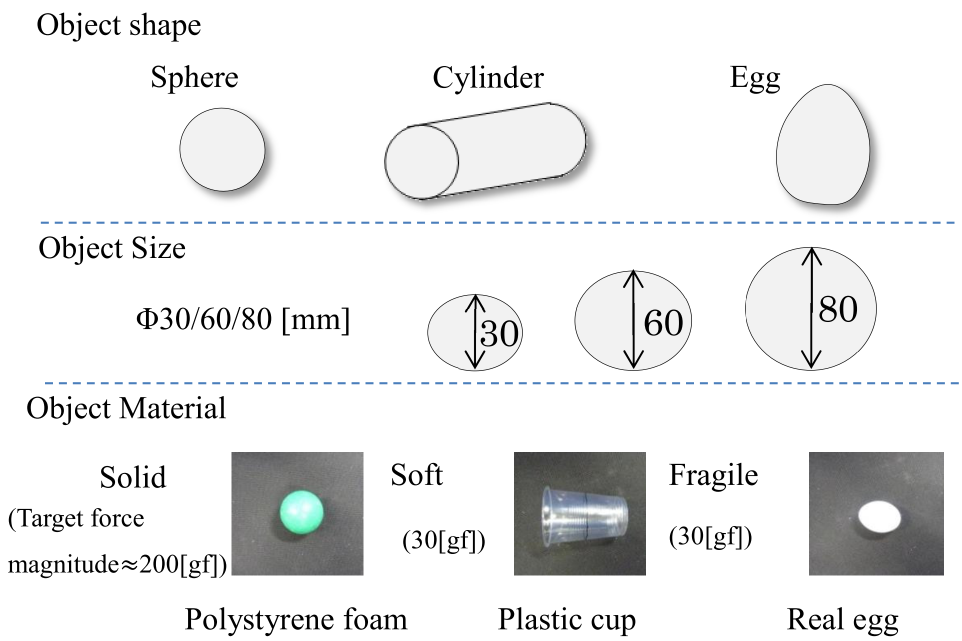


Figure 4-12 Object definition

(c) Initial Grasping Position

In the evaluation experiment, the initial grasping status is also verified in this research. In this experiment, the object is fed by human with various positions. The grasping position was controlled by XYZ stage. The contact position and the XYZ stage were defined and illustrated in fig 4-13 and fig.4-14.

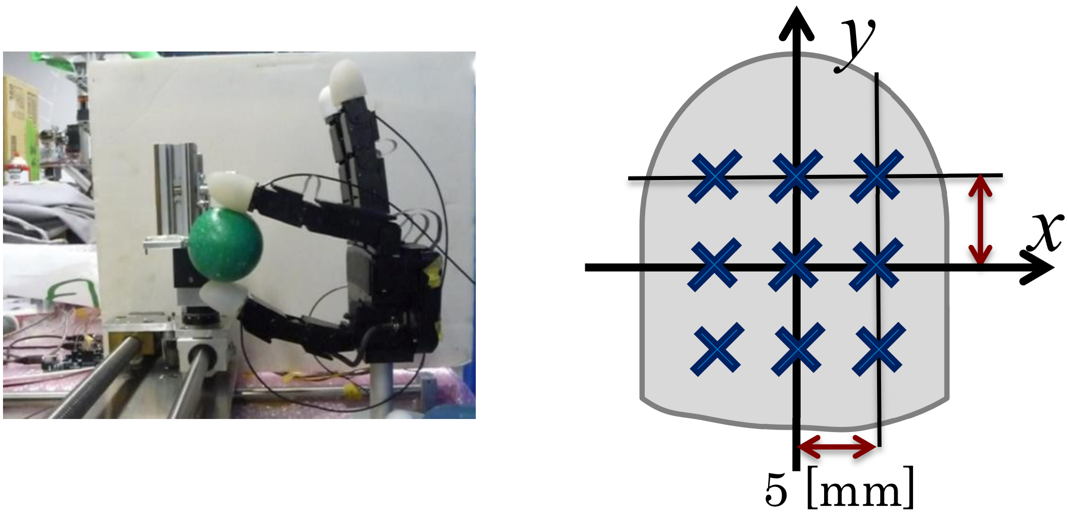


Figure 4-13 Grasping position definition

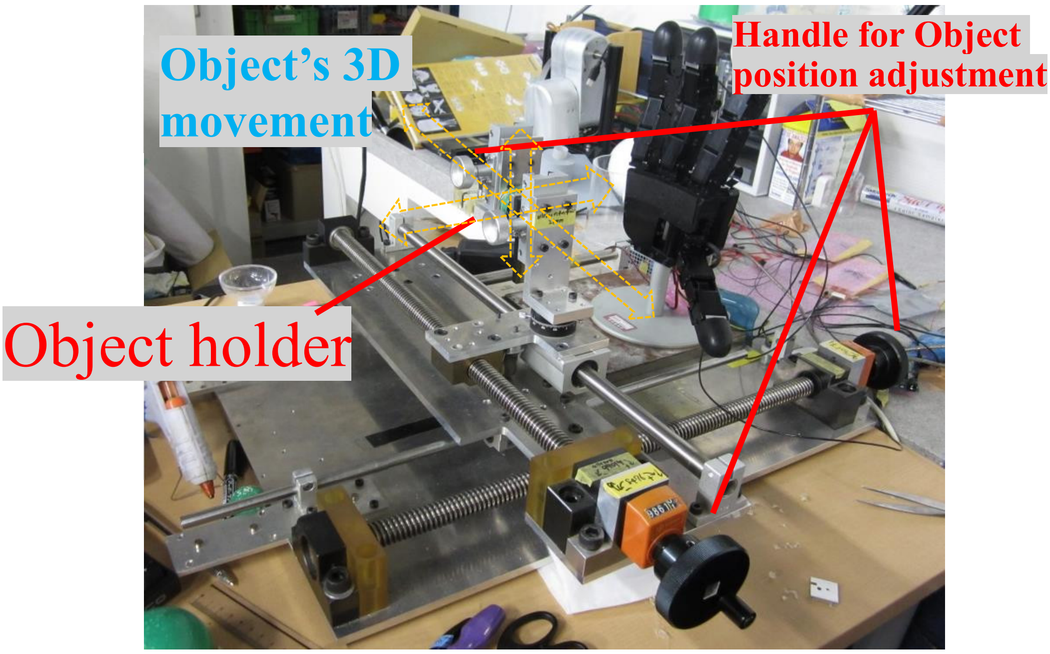


Figure 4-14 XYZ stage

(d) Result of motion versatility and object versatility

Some representative continuous manipulation photos are shown in appendix. The results about manipulation testing are recorded in table 4-3. The soft skin showed an impressive effectiveness compared to the rigid fingertip, even with the simple posture interpolation control strategy. This illustrates the importance of passive compliance and material properties for effective manipulation, which is often neglected compared to the control strategy. The real egg and plastic cup experiments were also successful without breaking either object, with both the new controller and the posture interpolation control. Yet, as we will see in the next section, this result can be only obtained when the correct object size is provided (appropriate posture).

(e) Result of initial grasping position

The results regarding the initial grasping position are shown in fig. 4-15. The red circles show the success rate over 80% and the grey triangles show the success rate over 30%. I used a lower success criterion for the rigid fingertip (without the soft skin) as it never achieved a success rate of 80%. Moreover, this result shows that the adaptability for the offset in the initial grasping position was greatly extended when

Table 4-3 Result of versatility experiment

		1 Skin/ Combined	2 Skin/ Combined	3 No Skin/ Combined	4 No Skin/ Interpolation
Standard (motion A/60/Sphere/Solid)		10	10	2	0
Motion	Motion B	10	10	4	0
	Motion C	10	10	0	0
Size	30 mm	10	10	1	0
	80 mm	10	10	1	2
Shape	Cylinder	10	10	0	0
	Egg	10	10	0	0
Material	Soft	10	10	0(Can't Grasp)	0(Can't Grasp)
	Fragile (real egg)	10	10	0(0/3)	0(0/3)

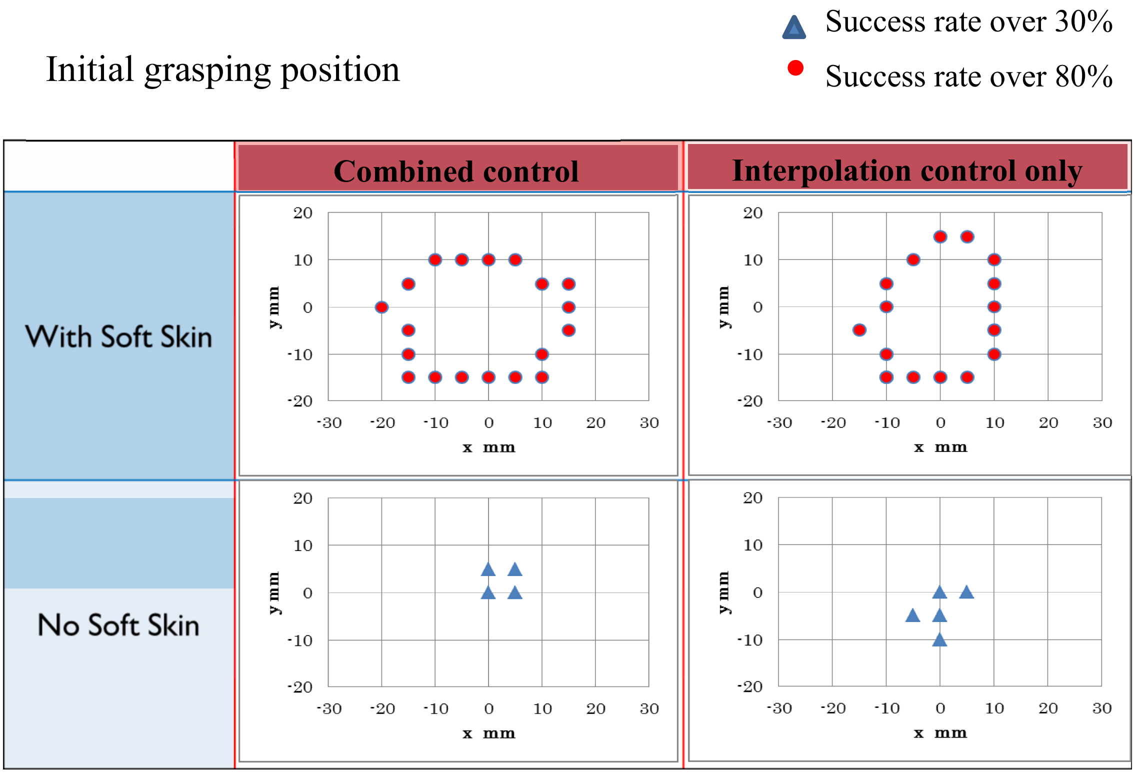


Figure 4-15 The result of initial grasping position

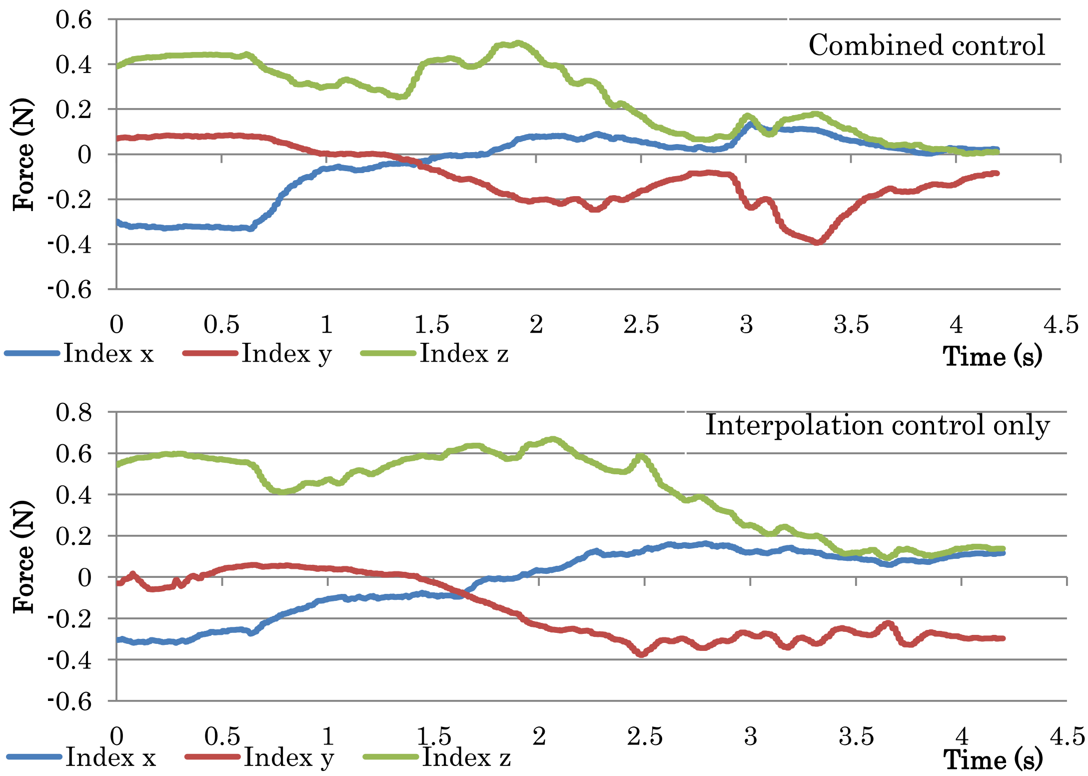
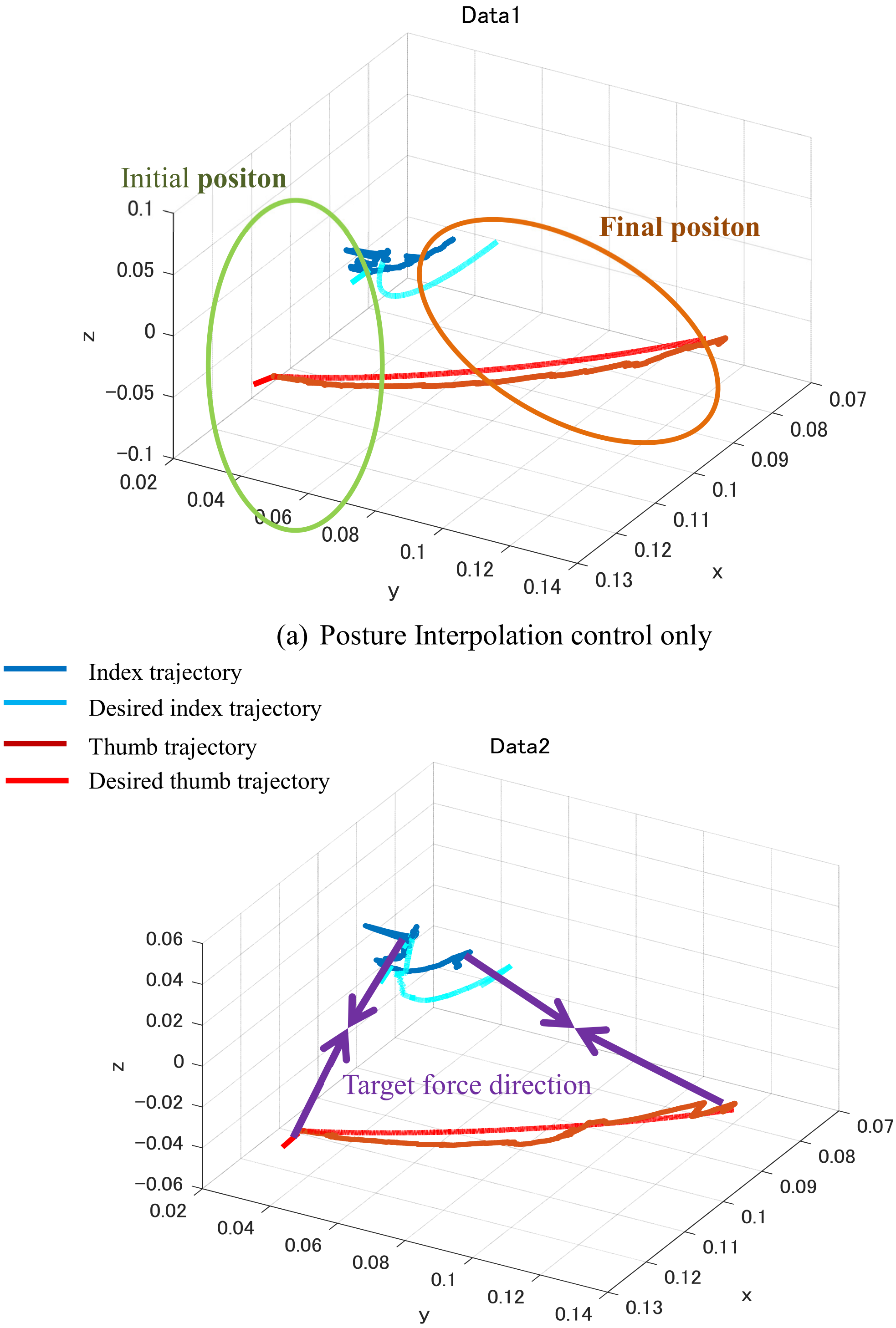


Figure 4-16 Grasping force in initial grasping position



(a) Posture Interpolation control only

(b) Compliance Posture Interpolation control

Figure 4-17 fingertip trajectory of initial grasping position using the soft skin. This result demonstrated again the effectiveness of the soft skin. Nevertheless, the stable initial grasping range of the combined control is slightly larger than for the interpolation control. It means that the new control strategy allows larger initial position range for manipulation without dropping object compared to the posture interpolation control only.

Moreover, fig.4-17 shows one of representative result about fingertip trajectory in the initial grasping position experiment and 4-16 shows its grasping force of combined control and interpolation control only. In here, the arrow in fig. 4-17(b) indicate the force control direction which toward to centre of fingertips. As the selected manipulation postures, the working plane of target force direction gradually change to sagittal plane in terms of y direction grasping force. It is obvious that from the comparison of new controller and interpolation control only, the grasping force in y direction is reduced significantly. Therefore, the stable initial grasping range in x direction is larger than y direction in the case of new controller (fingertip coordinate).

(f) Discussion about manipulation with three fingers

Different from conventional force control in grasping, target force direction is often difficult to be determined in in-hand manipulation. In here, I introduced virtual object position from [90] for determining the centre of fingertips and controlled the force direction toward to the centre of the fingertips (see fig. 4-5 and eq. 4.14):

$$r_0 = \frac{1}{3}\sum_{i=1}^{3} r_i \tag{4.9}$$

Where $r_i \epsilon \mathbb{R}^3 (i = 1,2,3)$ denotes the position of the centre of each fingertip. Namely, the virtual object position r_0 signifies the centroid of the triangle made by the position of centre of each fingertip. Furthermore, the subscript $i(= 1,2,3)$ in each equation indicates finger's number. Figure 4-14 shows the data of the force and distance between fingertips and the centre of fingertips. In fig.4-17, it could be seen that the distance between fingertips and the centre of fingertips were getting far away for adjusting the magnitude of force during manipulation. Furthermore, considering the force equilibrium:

$$r_o \triangleq \frac{\sum_{i=1}^{3}(F_{di} r_i)}{\sum_{i=1}^{3} f_{di}} \quad (4.10)$$

Where $F_{di} \geq 0$ denotes a nominal desired grasping force that is not necessarily satisfied when stable grasping is established. Equation 4.10 with fig.4.15 indicates that the index and middle fingertip move toward each other automatically according to the

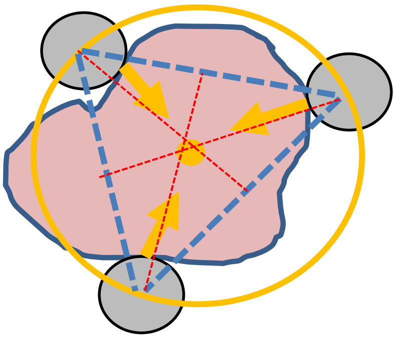


Figure 4-18 Force direction with virtual object position

magnitude of each finger's desired nominal force so as to satisfy the force equilibrium condition at the centre of fingertips.

4.3.2 Evaluation of Adaptability to Inappropriate Posture

The performance of the posture interpolation control relies and depends on the appropriate posture definition and correct object size information. If an inaccurate object size is used, the posture interpolation control will fail, because there is no feedback from the interaction with the object. In order to avoid dropping or breaking the object, information about the contact state should be utilized for in-hand manipulation. Two cases were considered in here: "target fingertip distance too close" and "target fingertip distance too far". Here, target fingertip distance refers to the target distance between the thumb and index fingertip for the final posture. Two experiments were conducted for evaluating our proposed system in these two cases and each case is tested 10 times.

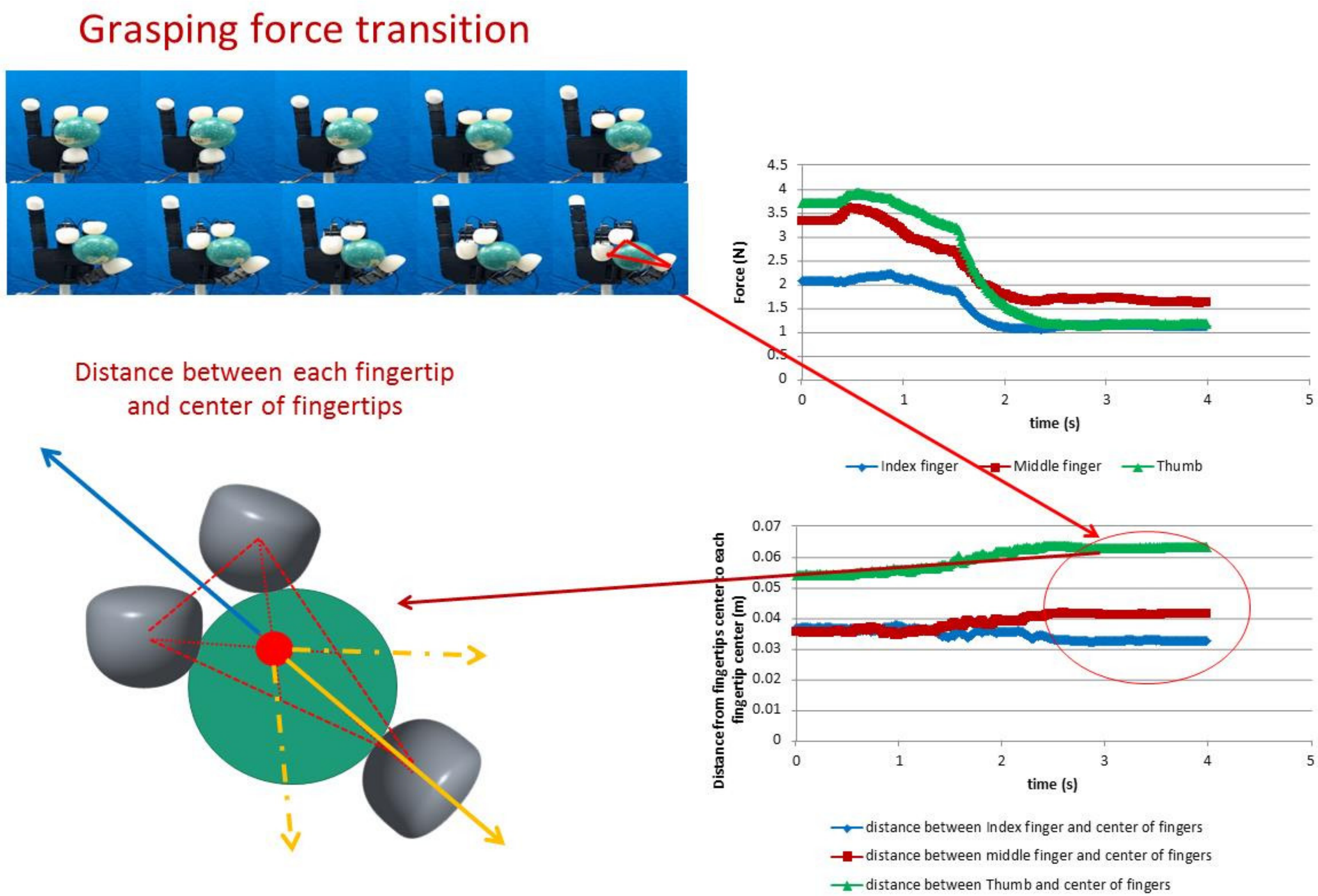


Figure 4-19 Combined control performance in 3 fingers in-hand manipulation

(a) Target fingertip distance too far

This experiment was conducted with motion B (pull task, shown in middle of fig. 4-11) which was mentioned in the previous experiment. The experiment setup has shown in the following:

Table 4-4 The experiment setup of Target fingertip distance too far

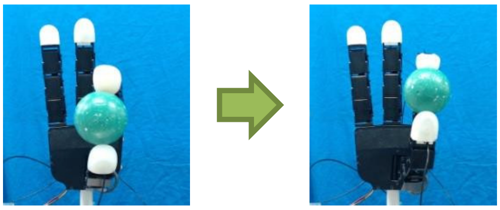
Parameter	Value
Motion	
Real object size [mm]	Φ60
Command object size [mm]	Φ70
The shape of object	Sphere
The material of object	Polystyrene foam
Initial grasping position	Centre of fingertip

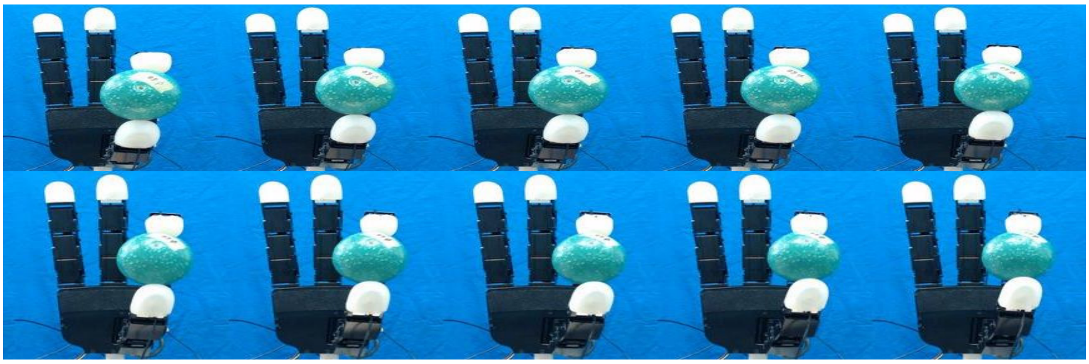
Fig. 4-20 and 4-21 show the results of "Target fingertip distance too far" experiment. It could be seen that the object was dropped in the case of the interpolation control only because the distance between the fingertips is longer than the object diameter. It is because that there is not object feedback in manipulation control. On the contrary, the manipulation was successful with the compliance posture interpolation control.

(b) Target fingertip distance too close

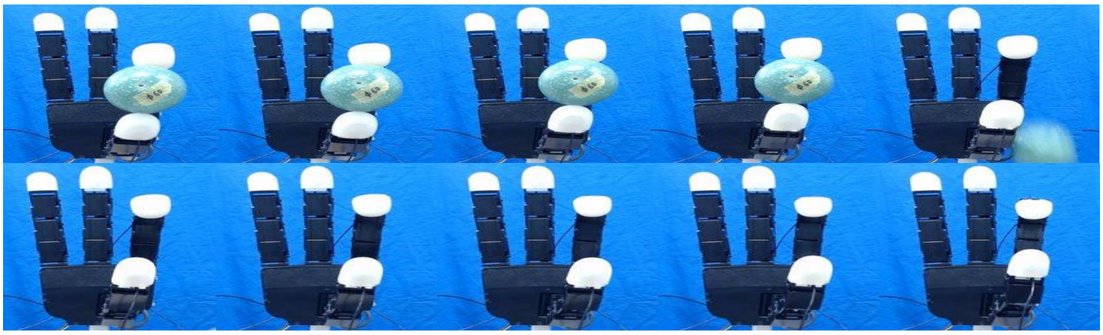
Excessive grasping force will break the object, especially in the case of objects made from fragile material. In this experiment, a purposefully incorrect input command with too close fingertips was sent to the controller. A plastic cup was used as the manipulation object, and the condition of this experiment has been shown in following:

Table 4-5 The condition of "Target fingertip distance too close" experiment

No.	Soft skin	Control	Category
1	Yes	Combined	Proposed method
2	No	Interpolation only	Only passive impedance



(a) combined control



(b) Interpolation control only

Figure 4-20 The continuous photo of "Target fingertip distance too far" experiment

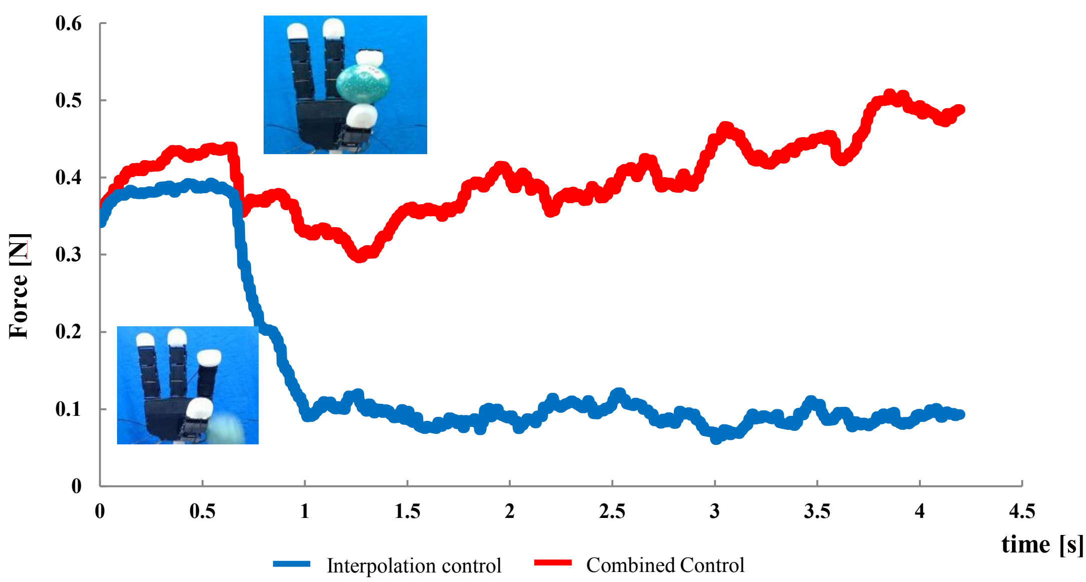
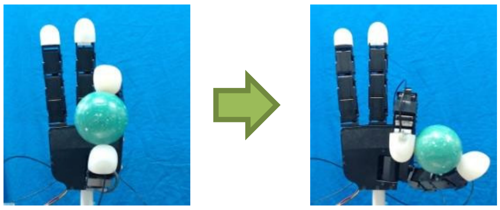


Figure 4-21 The grasping force in "Target fingertip distance too far" experiment

Table 4-6 The experiment setup of Target fingertip distance too close

Parameter	Value
Motion	
Real object size [mm]	Φ55
Command object size [mm]	Φ-30
The shape of object	Cup
The material of object	Plastic
Initial grasping position	Approximate at the centre of fingertip

The sequence of photos of the experiment is shown in fig. 4-22 to 4-25. Figure 4.22 shows the grasping force which measured in 6 axis force-torque sensor both in compliance posture interpolation control and posture interpolation control only. Figure 4-25 shows the average error of grasping force in 10 times. From the grasping force data, it indicates that the posture interpolation control could achieve the desired final position well, but high resultant force is produced by this position, and the plastic cup was

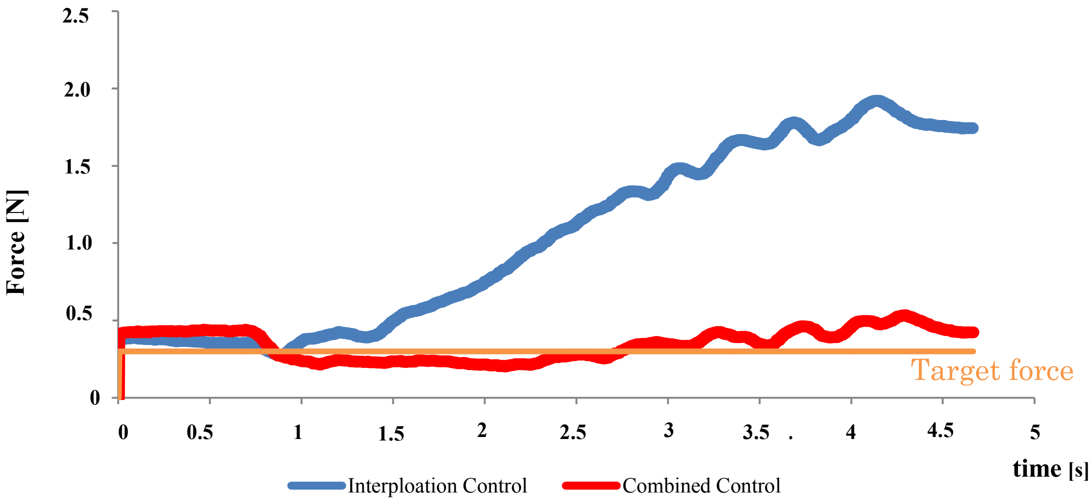


Figure 4-22 The grasping force in "Target fingertip distance too close" experiment

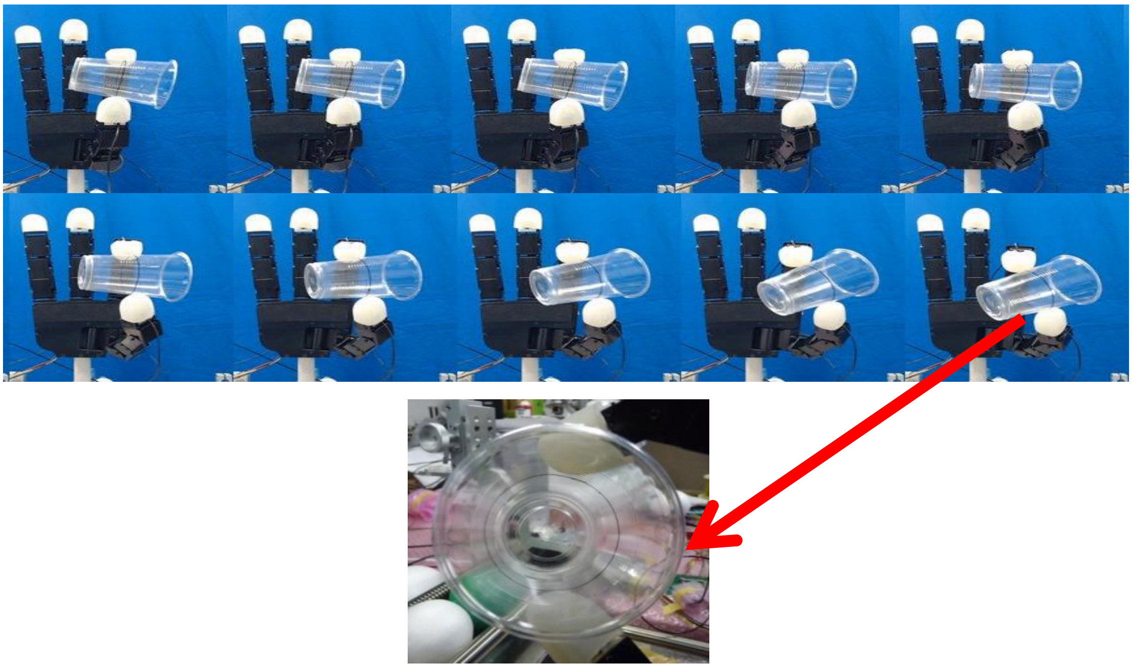


Figure 4-23 The continuous photo of "Target fingertip distance too Close " experiment (combined control)

Figure 4-24 The continuous photo of "Target fingertip distance too close " experiment (interpolation control only)

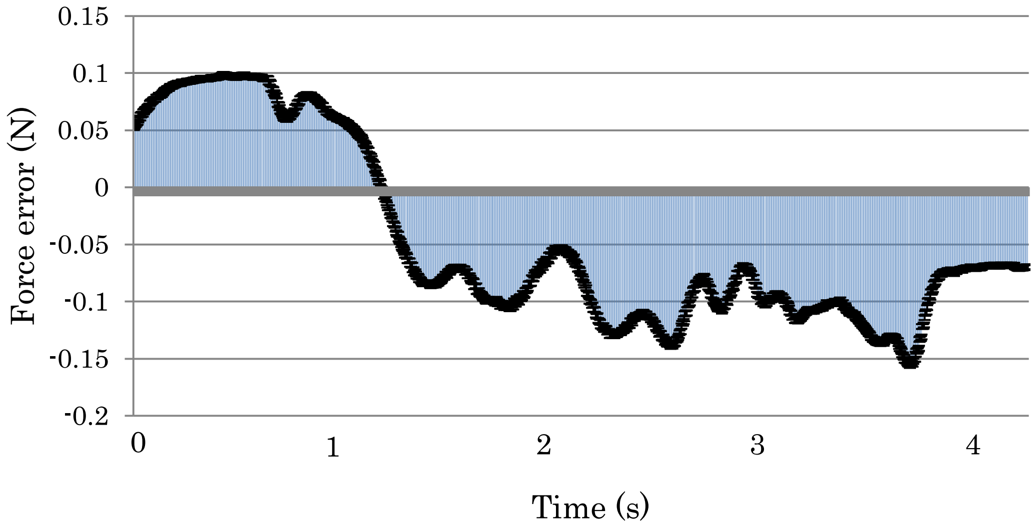


Figure 4-25 The average force error of 10 times trial in combined control

deformed as a result (On the contrary, a stable resultant force could be achieved in the case of new controller and the plastic cup was not deformed (see fig 4-23). However, the desired posture was not achieved at the end of the motion. Therefore, a trade-off has to be considered when setting the proportion gains K_f and K_i in eq. 4.7.

4.4 Object size estimation with deformation compensation

(a) Introduction of objection size estimation

In the convention grasping research [98], they proposed an object size estimation approach by kinematics calculation. However, the deformation of soft skin is not considered in this approach and the result shows some error in estimation. Since that there is not commercial deformation sensor available in current market. The measurement of deformation of anthropomorphic fingertip is still impossible in conventional research. As the application of the proposed deformation model in chapter 3, I considered a possibility to apply the deformation model to this grasping application. Therefore, I also conducted a preliminary experiment for testing the performance about it.

(b) The idea of deformation compensation in objection size estimation

In previous research, the contact point is measured by tactile sensor, since there is not three dimension sensing ability, the contact is considered on the surface of fingertip without deformation (see fig. 4-23). Therefore, the error occurs when the fingertip made by soft material, and the error is related to the softness of the soft material, and thickness of soft skin.

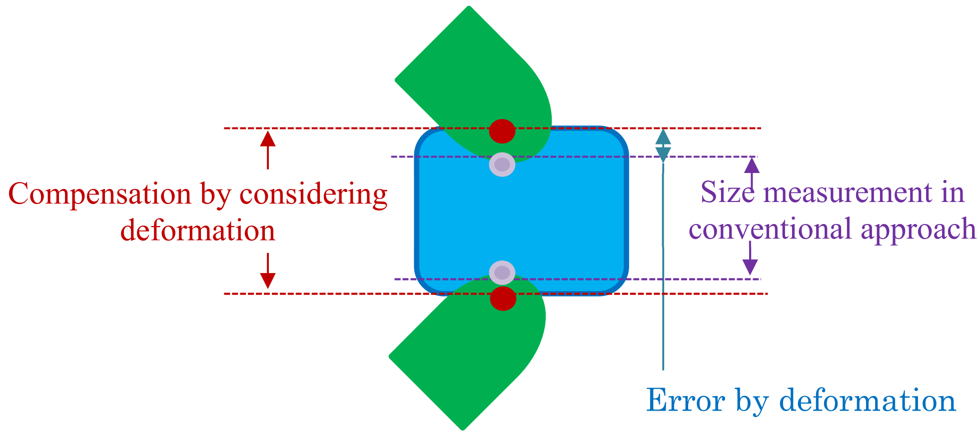


Figure 4-26 The idea of the compensation in object size estimation

I considered compensation by the addition of the estimated deformation from the resultant of kinematic calculation by:

$$object\ size = r_I - r_T + (\Delta G_I + \Delta G_T) \tag{4.11}$$

Where, r_I and $r_T \in \mathbb{R}^3$ are contact position of index and thumb fingertip which could be calculated by forward kinematics, ΔG_I and ΔG_T are the deformation of index and thumb fingertip along grasping force direction which calculated by eq. 3.15.

(c) Evaluation experiment

In order to test my hypothesis, I conducted the experiment for testing the performance of proposed approach about object size estimation. In this experiment, I used the same Allegro Hand which is mentioned in section 4.3. The inclination angle of index fingertip is controlled to keep approximately constant. In the same time, the fingertip is controlled to move toward to object until the grasping force achieved the target range I set (within 2.5-3N). Three sizes of cube objects is used for size estimation, which is shown in fig. 4-24.

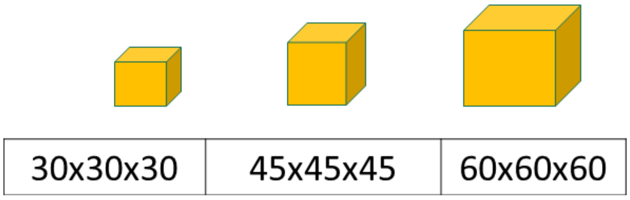


Figure 4-27 Object sample in evaluation experiment

In practical implementation, there is error accumulation in kinematics calculation of actual robot hand. Therefore, I used rigid fingertips for normalizing the result of kinematics calculation. Then I compared it with the soft fingertip and applied the proposed compensation. The absolute average error of 5 times trial is shown in fig. 4-25. It could be seen that the proposed compensation is very effective for improving the accuracy of object size estimation. Considering the case of smaller object, the influence of the error caused by deformation is quite obvious (over 10% error for 30mm object). Therefore the compensation is significantly helps the object size estimation in the case of smaller object. For the case of bigger object, because the deformation of the 4mm soft skin has relative less influence, the benefit of compensation is not very clear, but it is still able to improve the accuracy in object size estimation by comparing with the conventional approach.

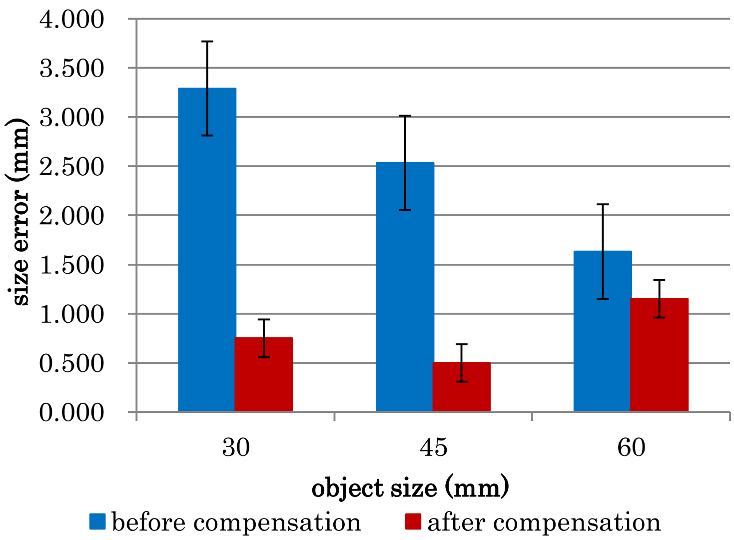


Figure 4-28 The result of object size estimation experiment

4.5 Discussion and limitation

4.5.1 Current limitation of proposed controller

In this research, for simplifying the force control, the reachable region of fingertip is not considered yet. It means that when the fingertip is required to move beyond its joint limit, the controller will fail. However, considering the investigation in [51], human is rarely manipulate the oversize object (for example, from Panoramic pentadigital grip to Spherical palmar prehension). Therefore, I considered the controller in this research is appropriate, but, for the best performance, reachable region could be considered in the future.

Furthermore, the control target of force direction is set to the centre of fingertips, therefore, it is useful for the object which has approximate spherical cross-section because the centre of the object is close to the centre of fingertips. For more object shapes, more research about the determination of target force direction need to be considered in the future.

4.5.2 Summary

In the result of first experiment, the pre-defined postures are produced very well, therefore the error of the posture is limited. The effectiveness of force control is not obvious, and the deformation of fingertip helps manipulation significantly with “small error” because of the indirection deformation, providing some degree robust manipulation capability for Allegro Hand.

For the second experiment, because I provided incorrect posture command in order to show the large error case, the performance of soft fingertip is not obvious because the error larger than what it could absorb. In this case, the force control significantly helps to improve the manipulation performance. In the case of “Target fingertip distance too close” the force control provided stiffness by the appropriate parameter in eq. 4.7 and kept the continuous contact force in manipulation. As the result, Allegro Hand could manipulate plastic cup without any deformation. In the case of “Target fingertip distance too far”, the force feedback helps Allegro Hand to keep force closure and lead a successful manipulation even though incorrect postures command.

Comparing to conventional research, the traditional force control such as impedance control need more object information such as grasping matrix and pre-defined trajectory. In particular, different from spherical fingertip, the anthropomorphic fingertip need tactile sensor for understanding the contact information for these controller. It will increase the manufactory cost of the robot hand and make the control complex. TWendy-one shows us impressive result by simple posture interpolation control strategy, in which the trajectory could be automatically generated by just input initial posture and final posture with few manipulation information such as object size and transition time. In this research, by introduce compliance into simple posture interpolation controller, it is possible to improve the performance of such linear trajectory generator, especially for the case that the robot hand have not passive impedance joint. For determining the target force direction, I introduced the virtual object position idea from [97]. As the result, the various in-hand manipulation could be achieved with less information and in simply way. This controller could take the benefit about the stability of traditional force controller and the simplicity of posture interpolation control simultaneously. Comparing with conventional research, the trajectory could be automatically generated by initial posture and final posture.

Besides the in-hand manipulation, at the end of this chapter, I also demonstrated an application of the proposed contact model (which is proposed in chapter 3) in grasping purpose – object size estimation compensation. As the result, my approach shows the improvement by comparing with conventional estimation approach. It means that my approach could improve the accuracy of object size estimation.

Chapter 5

Concluding Remarks

Throughout this dissertation I have presented a methodology to develop a simple and low-cost robot hand manipulation system framework for implementing robust in-hand manipulation in an inexpensive commercial available robot hand – the Allegro Hand. Based on this system, the Allegro Hand could perform various object manipulations in a simple way. I discussed the effectiveness of flexibility for grasping and versatile manipulation. In this final chapter, I will summarize some of the key points of this work. After that, some possible future works will be discussed.

5.1 Summary and Contributions

Flexibility and versatility are two of important evaluations for robot hand manipulation. Previously, posture interpolation control has shown good results with the TWendy-one hand. TWendy-one is a rather expensive robot, and a high manufacturing cost makes it difficult for a system to be adapted widely into our daily life. A simple and reliable integrated system is missing in the market. The development of a simple/ low cost robot hand system could extend the application of the robot hand.

5.1.1 From TWendy-one to Allegro hand

Unlike TWendy-one, a mechanical impedance mechanism is often not implemented in a low-cost multi-fingered robot hand. A robust and versatile manipulation is difficult to be implemented in such robot hands, because there is no flexibility for absorbing errors in manipulation. Although TWendy-one shows us a simple but effective manipulation strategy by interpolating postures, it is still a question whether such linear trajectories can be successfully implemented in other general robot hands. Indeed, it is interesting to understand the boundaries of such a simple control strategy in other robot hands without mechanical impedance mechanisms in the joints.

Furthermore, not every robot hand is designed with a human-like joint arrangement. Modifications about the pre-defined static grasping postures that form the basis for the interpolation control should be made for fitting to the Allegro hand. In Chapter 2, the differences between TWendy-one and the Allegro hand are addressed. The modification of the postures in conventional posture interpolation control strategy is also described in this chapter. At the end of this chapter, a pre-experiment is conducted for showing the performance of conventional posture interpolation control with the Allegro Hand. The limitations and the problems of the implementation of posture interpolation control in the Allegro hand are discussed. Based on a trade-off between manufacturing costs of hardware impedance and the complexity of the control system, a simple and low-cost approach for improving the manipulation performance with a general robot hand is proposed throughout this dissertation by the combination of low cost passive flexibility and simple "active" flexibility.

5.1.2 Deformable anthropomorphic fingertip with elastic contact

For the hardware development, an investigation about various kinds of fingertips is conducted, because fingertips are often used for contacting the object in posture interpolation control. However, systematic study about fingertip design is very limited in conventional research. In this research, by developing different kinds of fingertips, I compared the grasping and contact properties of the fingertips. From the results of these experiments, the influence of various factors on the grasping capability can be understood.

The passive flexibility of a robot hand characterises the deformation properties of a soft robot hand. After I clarified the factors which possibly affect the grasping capability of a robot hand, I developed a novel contact model which can be used for different kinds of fingertip shapes. This model quantitatively shows the relationship between the fingertip deformation and fingertip conditions such as the shape of the fingertip, the hardness and thickness of the soft material on the fingertip and the contact angle. Compared to a conventional robot hand design methodology, I enable a quantitative analysis before the construction of any physical prototype, and thereby improve the design quality by predicting the contact performance. In an evaluation experiment I verified that the model can be used for robot hand design.

5.1.3 Compliance posture interpolation control

In Chapter 4, force feedback is considered for improving the flexibility of posture interpolation control in a robot hand without mechanical impedance joints. In this chapter, a force-posture combined interpolation control scheme is proposed by introducing simple compliance control into the posture interpolation control. By controlling the contact force, force closure could be achieved and the robot hand could accomplish in-hand manipulation with "active" flexibility.

Two evaluation experiments are conducted for evaluating my proposed system in terms of task versatility and adaptability to inappropriate posture. As a result, the Allegro Hand could achieve robust in-hand manipulation with various motions, objects sizes, object shapes and object hardness.

5.2 Discussion of importance of robot hand system

5.2.1 The importance of hardware design of robot hand

As the result of chapter 3 and chapter 4, "softness" showed an impressive effectiveness for the grasping ability of heavy objects and object manipulation success rate compared to hard fingertips. Moreover, a reasonable fingertip shape, hardness and skin thickness design could improve the robot hand design in terms of contact properties. By applying my proposed model, a reasonable fingertip design could be made by designing appropriate a passive flexibility in terms of fingertip stiffness.

5.2.2 The importance of robot hand control with flexibility

Compared to position control only, the control with force feedback could improve the manipulation performance of the robot hand in the following cases:

(a) Target fingertip distance too far

The compliance posture interpolation control could keep the contact continuously between the fingertip and object by introducing contact force feedback into the control loop. Thanks to the force feedback, the posture interpolation control becomes successful under a certain degree of object size recognition error.

(b) Target fingertip distance too close

When manipulating a soft object, a flexible manipulation performance should be achieved in order to avoid deforming the soft object. In this dissertation, I show that such flexible manipulation could be achieved in a low cost robot hand platform by my proposed system. Thanks to the force feedback, the contact force magnitude could approximately follow the target force. The robot hand could manipulate a soft object without deforming it.

5.3 Future works

5.3.1 The relationship between hardware and control

In this dissertation, the relationship between the fingertip properties and grasping capability is addressed. The relationship between fingertip properties and manipulation capability should be further investigated in the future. In particular, as the over grasping stability may prevent dexterous manipulation, there is a possibility that a harder material / lower friction coefficient could be better for manipulation. The resulting trade-off between stability and dexterity should be studied.

Furthermore, regarding the contact model I proposed in this dissertation, I consider extending it to three dimensions model in the future. Different from a rigid robot hand, for a soft robot hand, the softness improves the manipulation stability, but at the same time the accuracy of object positioning is decreased because of unexpected deformations (detail discussion in chapter 4). Because there is no deformation sensor available in the current market, I believe that a creditable deformation model could improve the accuracy of manipulation by correcting the fingertip trajectories corresponding to the deformation. By considering the stiffness of the fingertip, some conventional position control could be extended, such as [97]. Furthermore, because the friction will be affected by the pressure condition, as qualitatively analysed in chapter 3, the combination between eq. 3.1 and the contact model could be useful for manipulation control as future work.

5.3.2 Software improvement – the use of machine learning

As I mentioned in Chapter 4, the trade-off between position accuracy and force accuracy should be discussed in the future.

Moreover, although there are many objects with simple shapes in our daily life, there are still many objects with complex geometries. For traditional control strategies, it is difficult to generate analytic solutions to manipulate such complex geometries. For the proposed control strategy in this research, the controlled force direction is also difficult to be determined in the case of the object with complex geometrics. In our laboratory, machine learning was proposed to be used in manipulation [98]-[100]. It is a robust control strategy with high adaptability to complex object shapes. Therefore it is a possible solution to overcome such difficulties since the detail of the controller is depending on the training data. However, generating training data with a data glove is not suitable for some robot hand platforms because the joint arrangement is different from humans. Therefore, if the training data could be collected by the control strategy proposed in this research, it is possible to extend the boundary of current research.

Appendix

APPENDICES CONTENTS

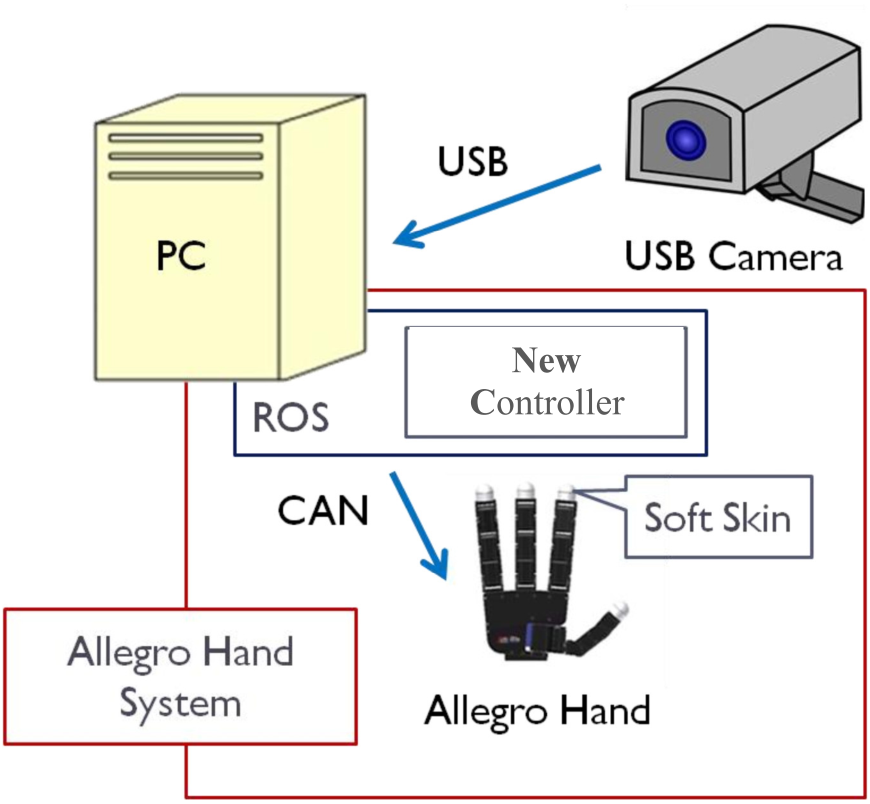
A.

The grasping posture classification of TWendy-one hand

Reproduction of 18 kinds of hand grasping styles as static fundamental posture required for realizing a variety of grasping and handling[38]

B.
The illustration of versatility experiment setup

The versatility experiment setting has shown as following:

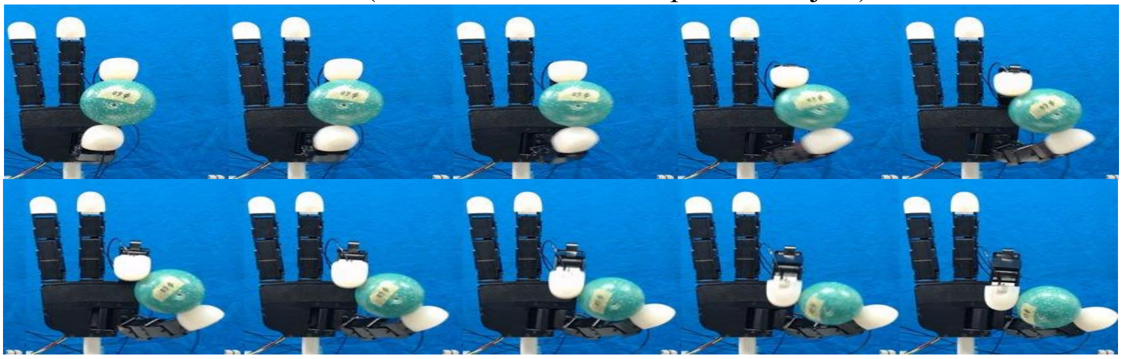


The experiment setting of Chapter 4

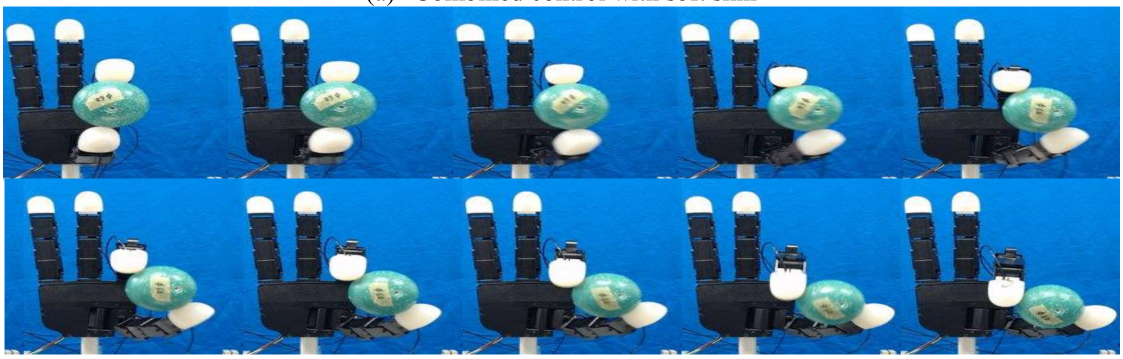
C.

The continuous photo of experiment in section 4.3.1:

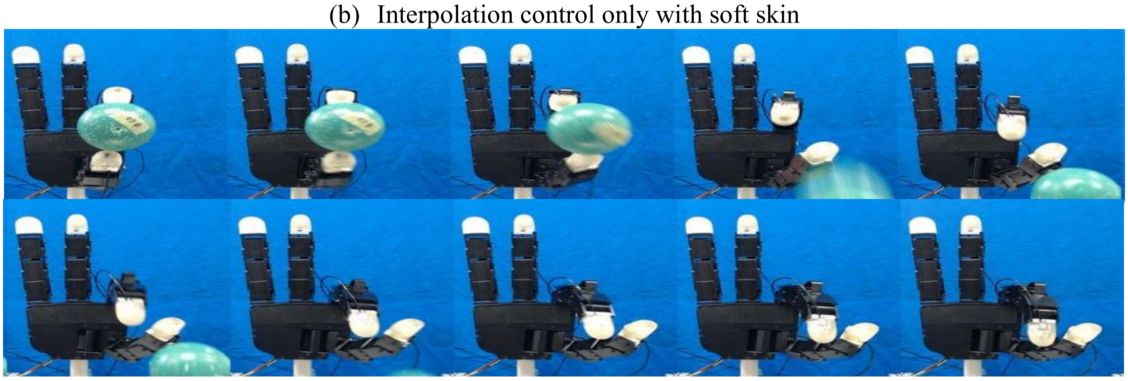
Standard(motion A/Φ60 Solid Spherical object)



(a) Combined control with soft skin



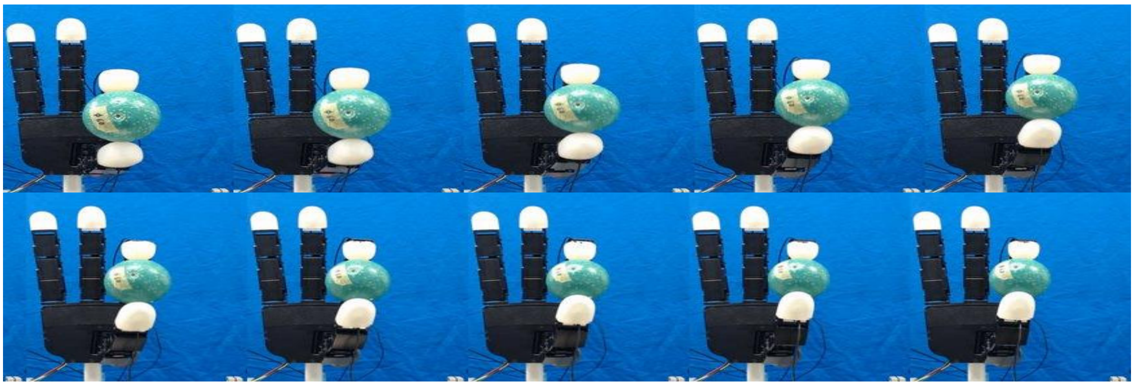
(b) Interpolation control only with soft skin



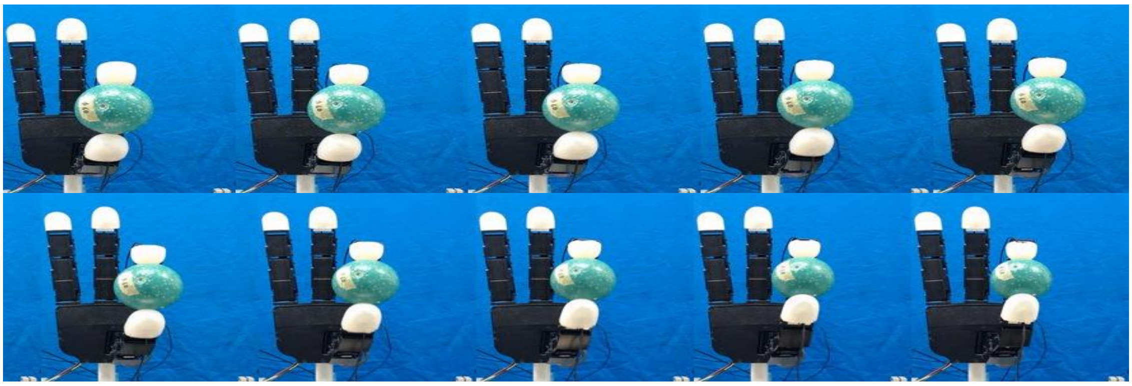
(c) Combined control without soft skin

(d) Interpolation control only without soft skin

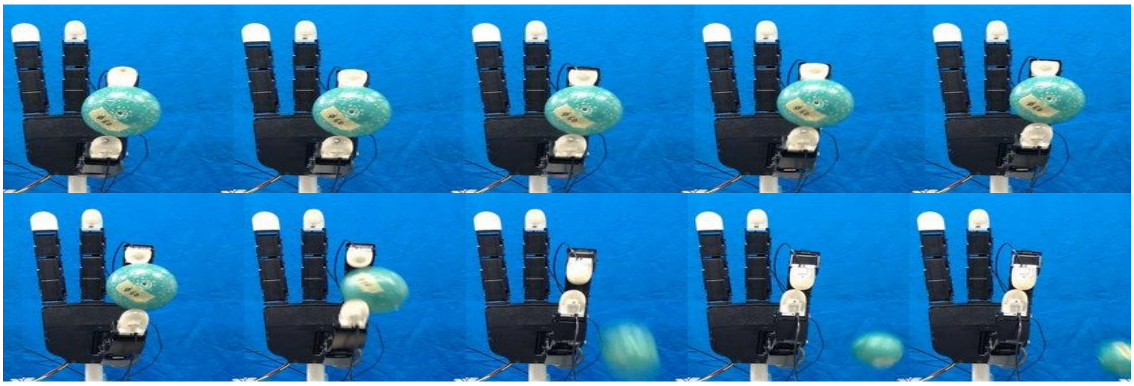
Motion B/ Φ 60 Solid Spherical object



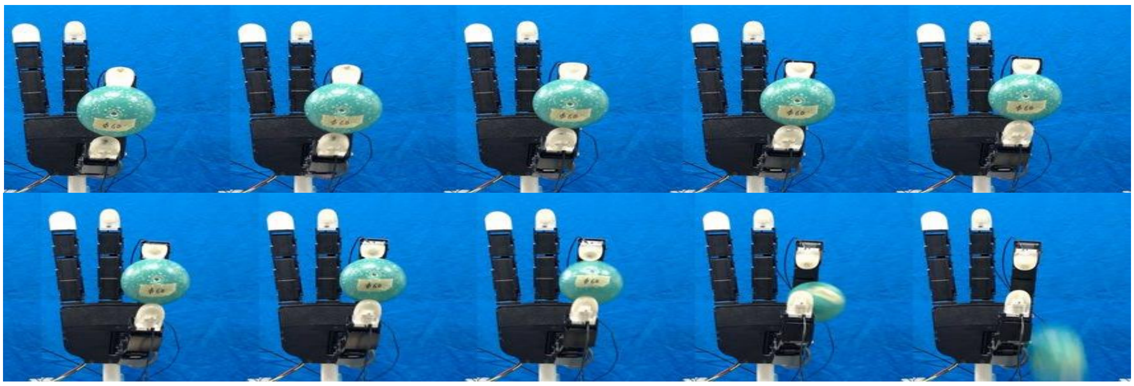
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

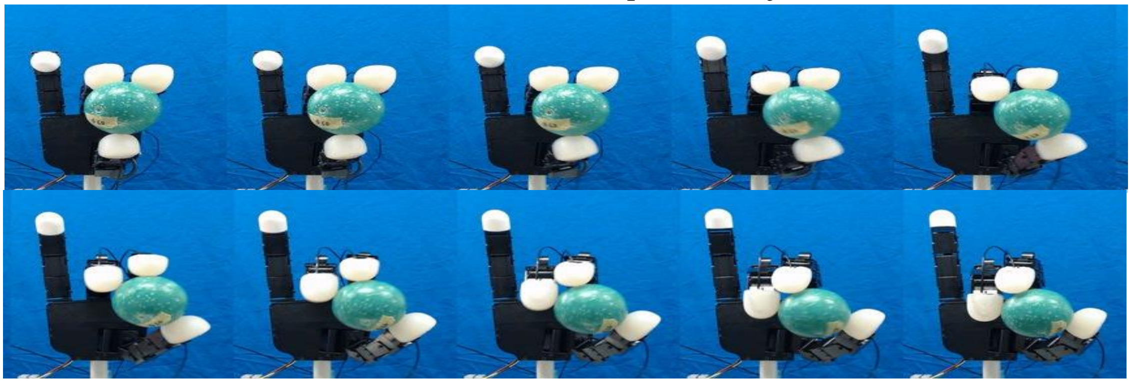


(c) Combined control without soft skin

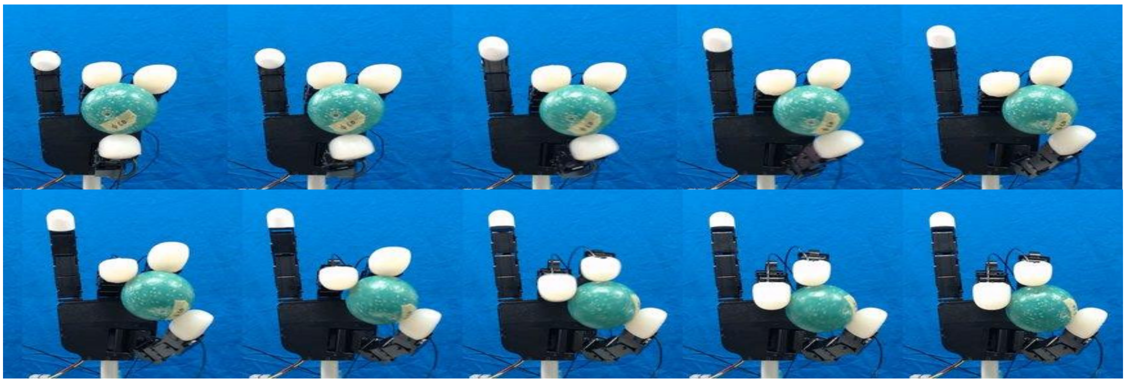


(d) Interpolation control only without soft skin

Motion C/ Φ60 Solid Spherical object



(a) Combined control with soft skin



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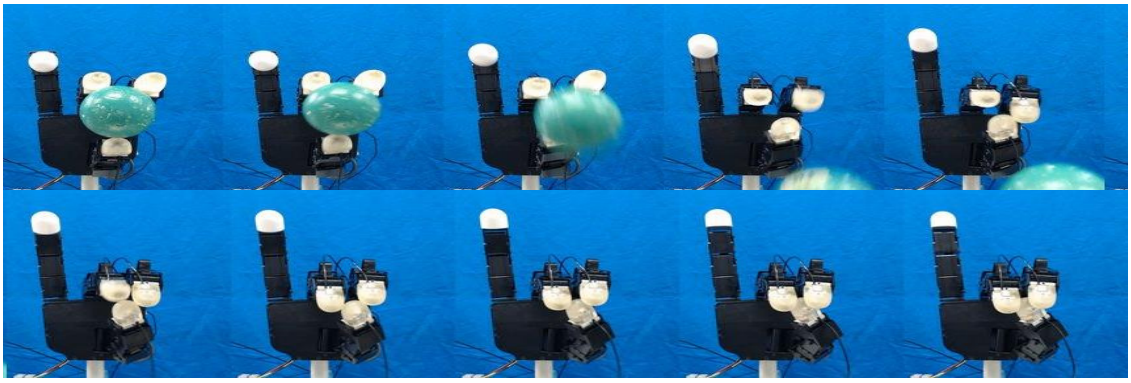
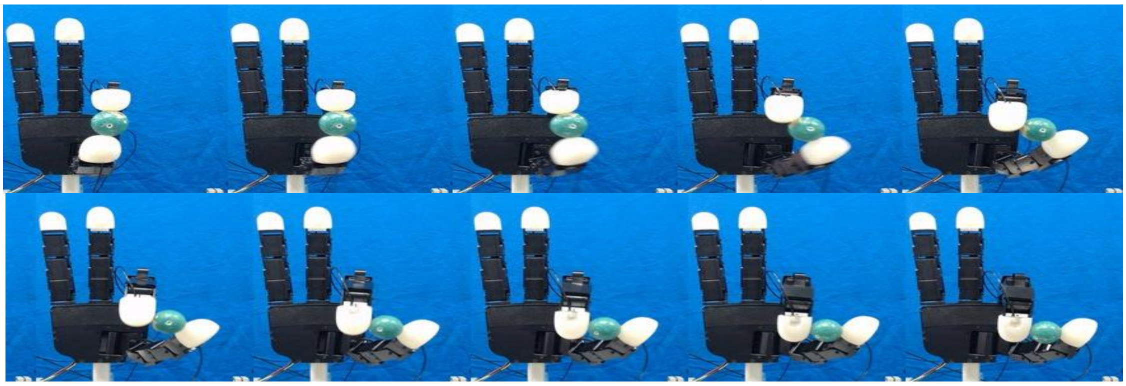


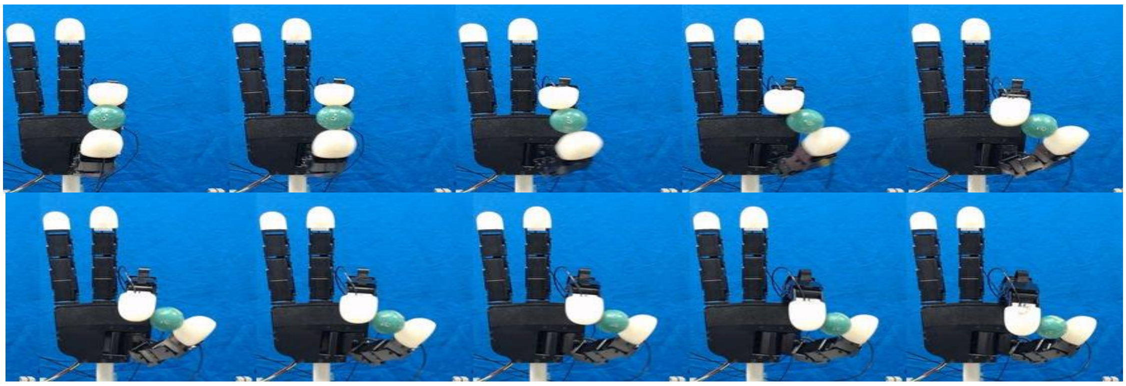
(c) Combined control without soft skin

(d) Interpolation control only without soft skin

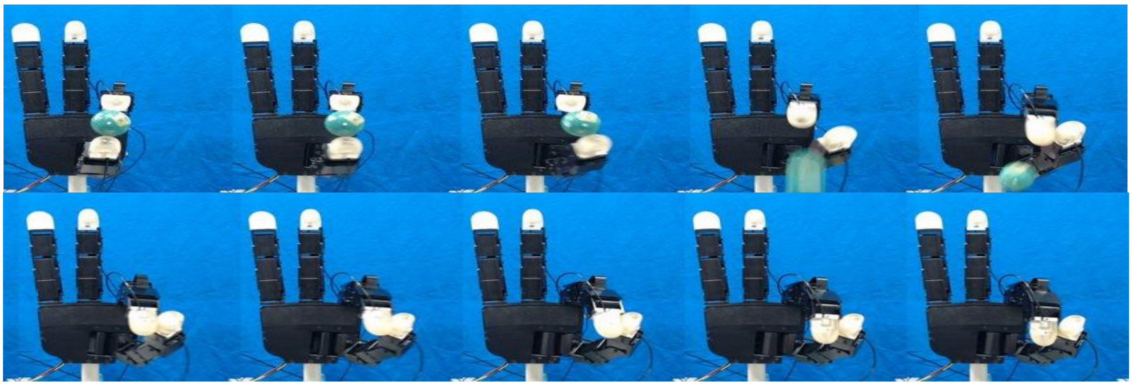
Motion A/ Φ 30 Solid Spherical object



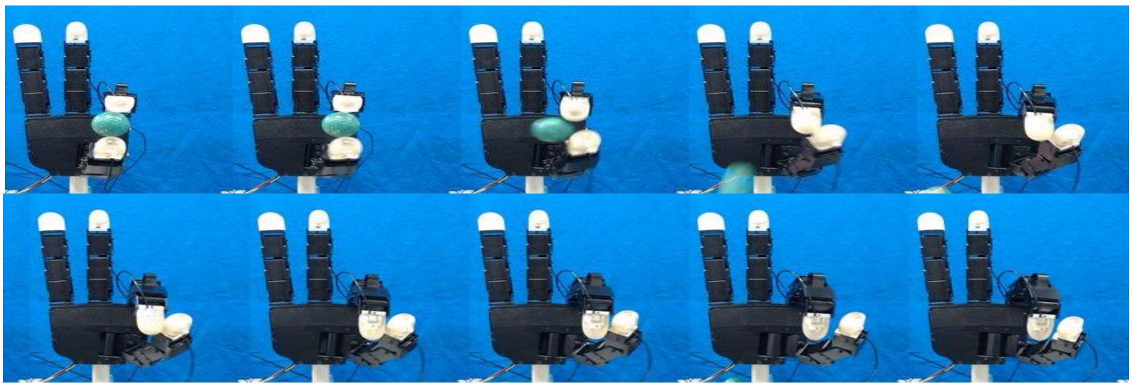
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

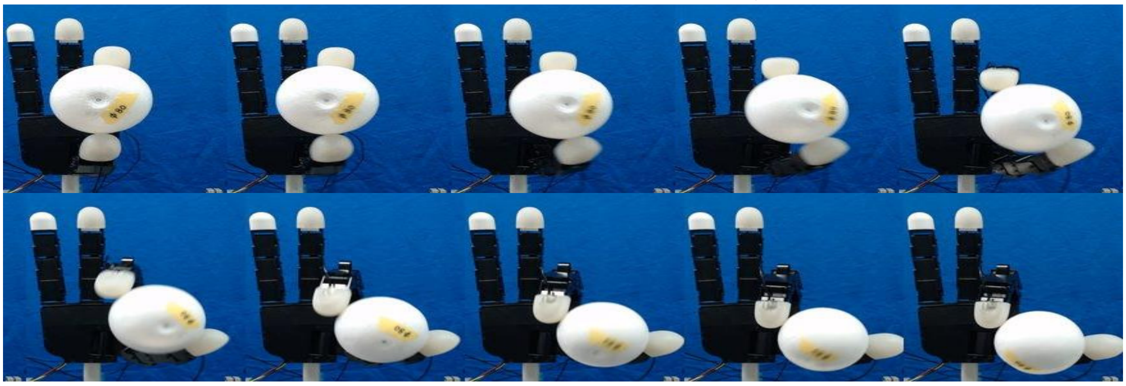


(c) Combined control without soft skin

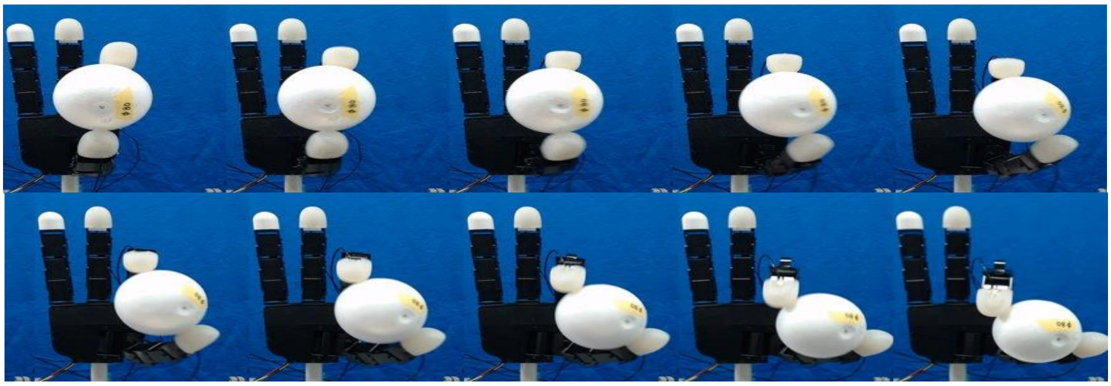


(d) Interpolation control only without soft skin

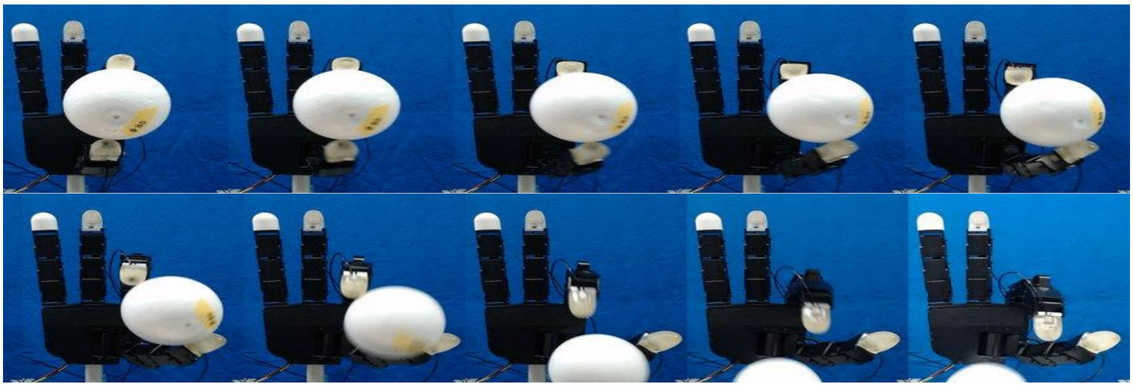
Motion A/ Φ 80 Solid Spherical object



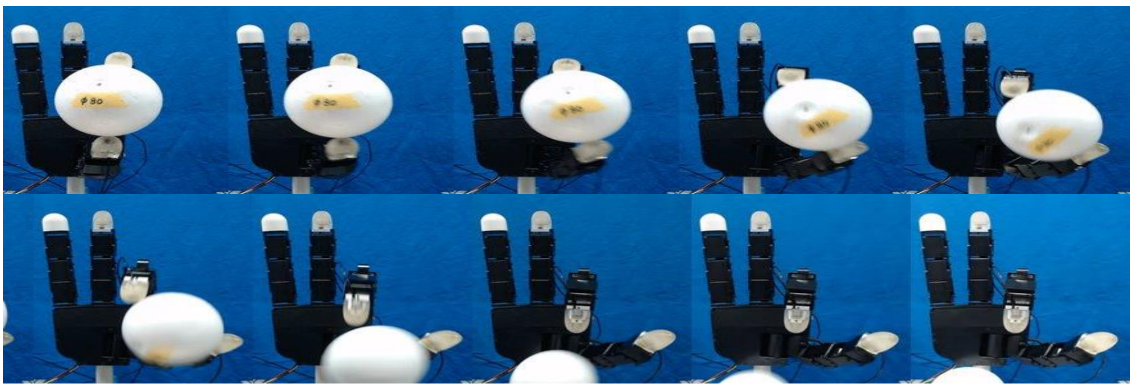
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

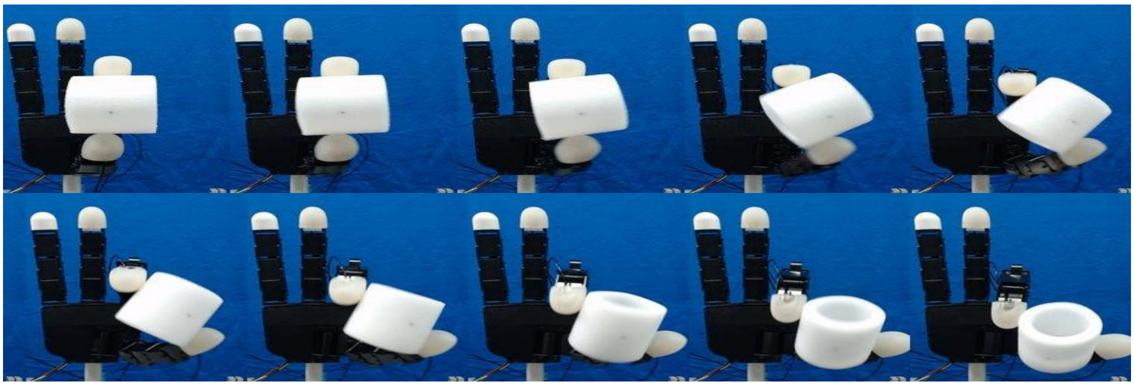


(c) Combined control without soft skin

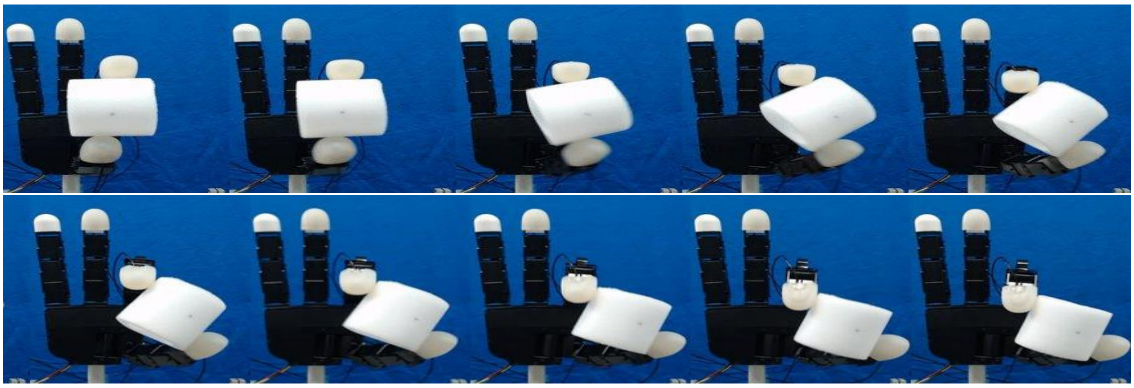


(d) Interpolation control only without soft skin

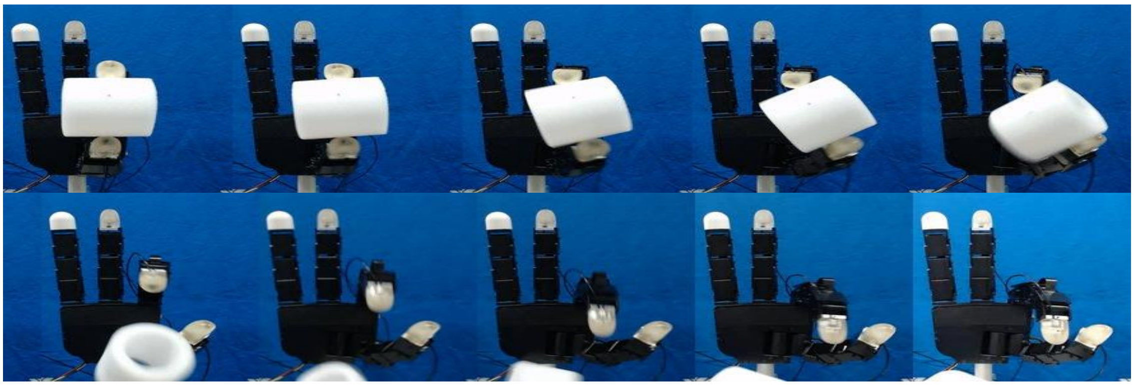
Motion A/ Φ60 Solid Cylindrical object



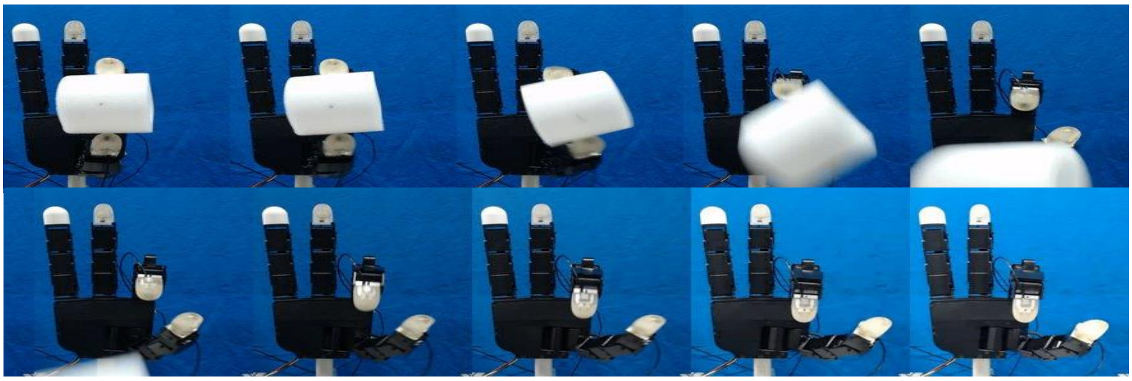
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

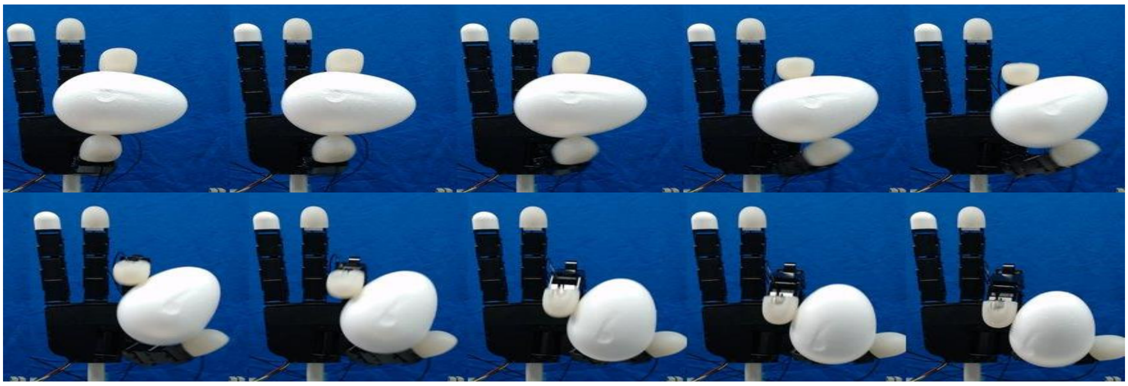


(c) Combined control without soft skin

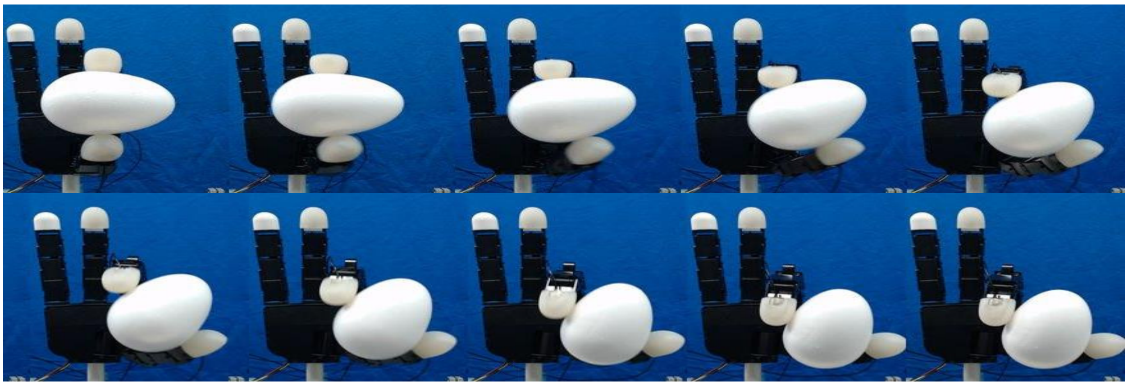


(d) Interpolation control only without soft skin

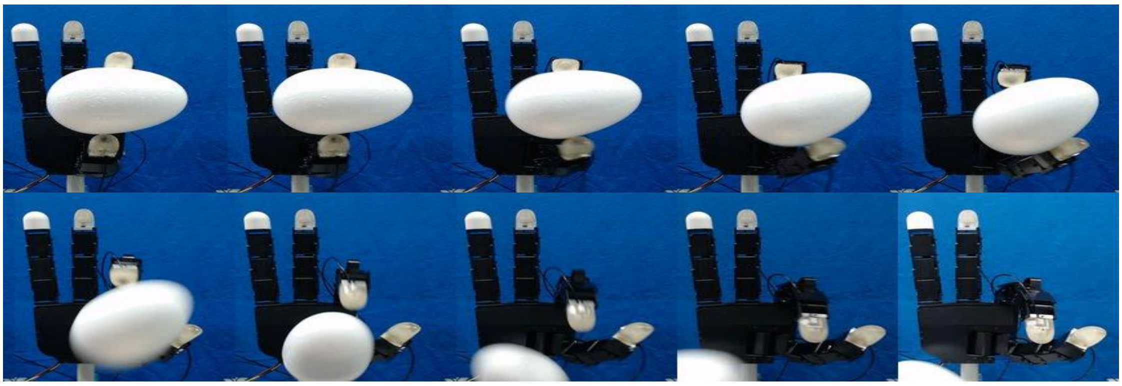
Motion A /approximate Φ60/ Solid Egg



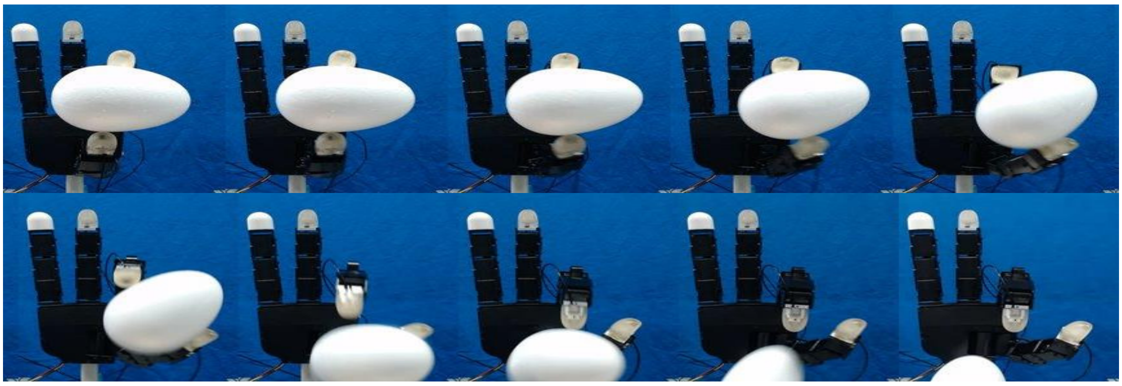
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

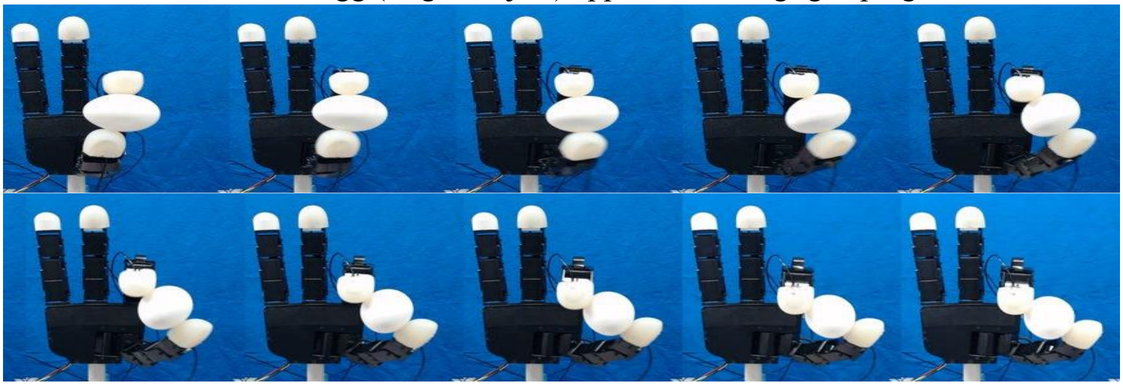


(c) Combined control without soft skin

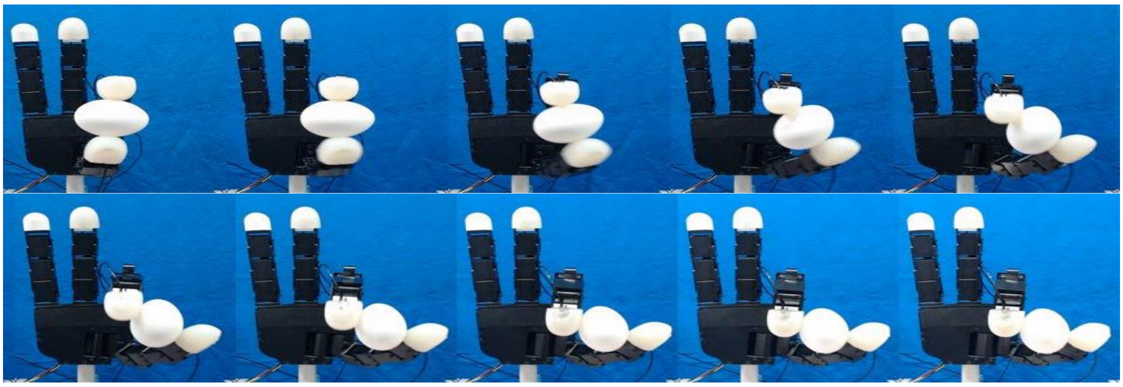


(d) Interpolation control only without soft skin

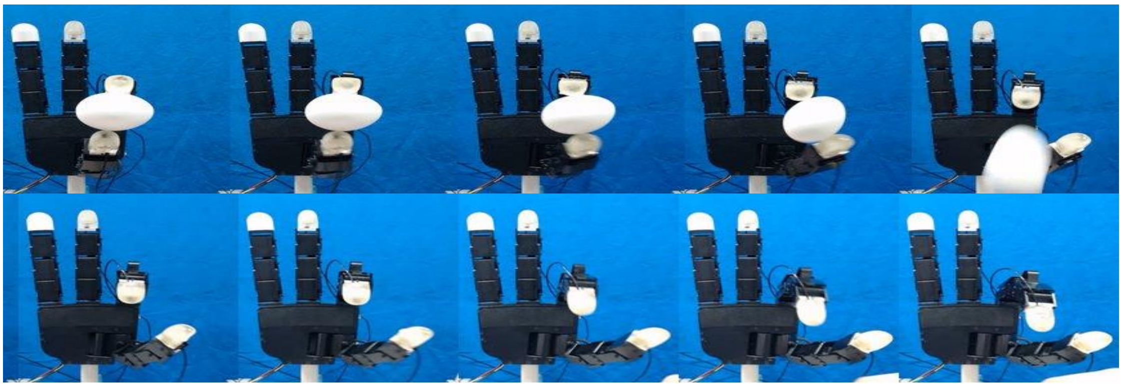
Motion A/real egg (fragile object)/approximate 30gf grasping force



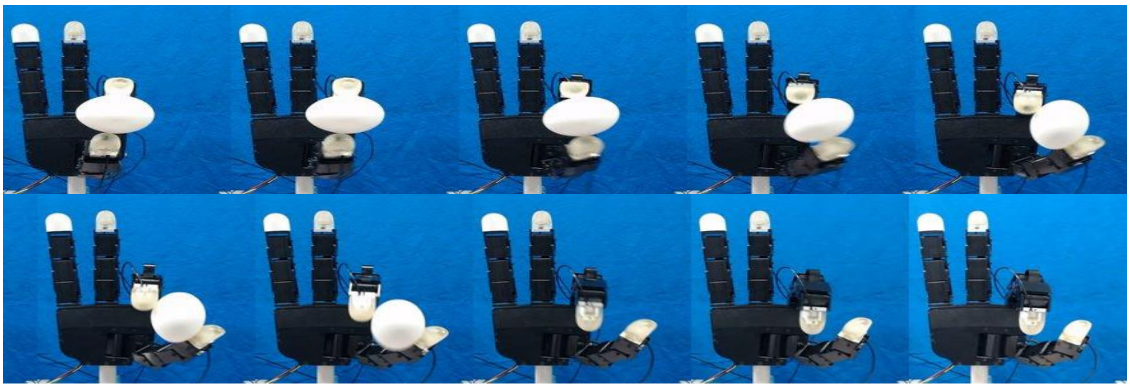
(a) Combined control with soft skin



(b) Interpolation control only with soft skin

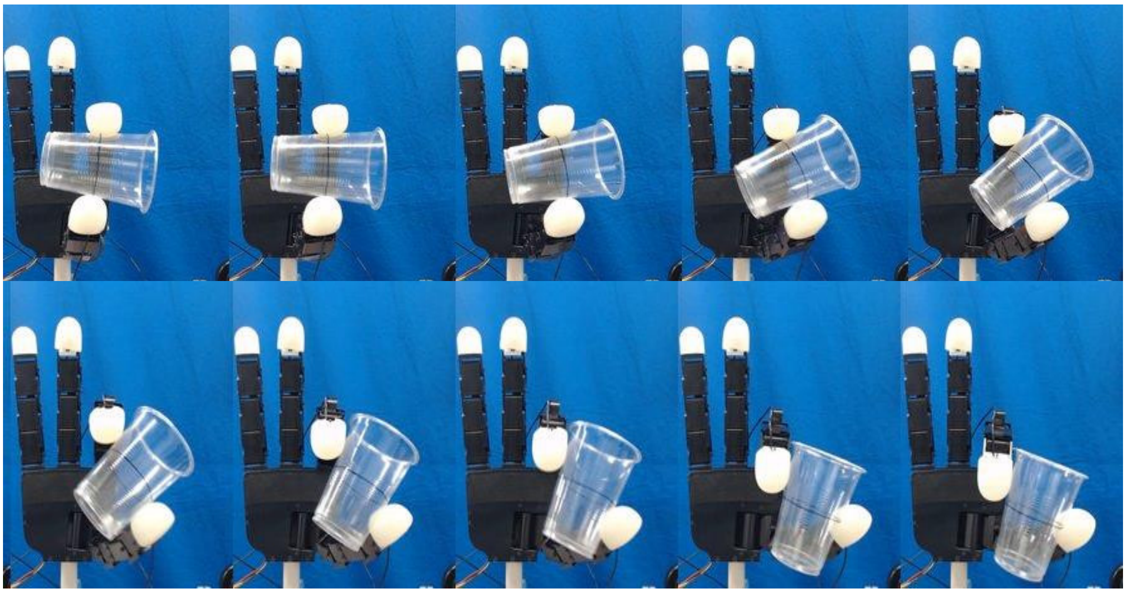


(c) Combined control without soft skin

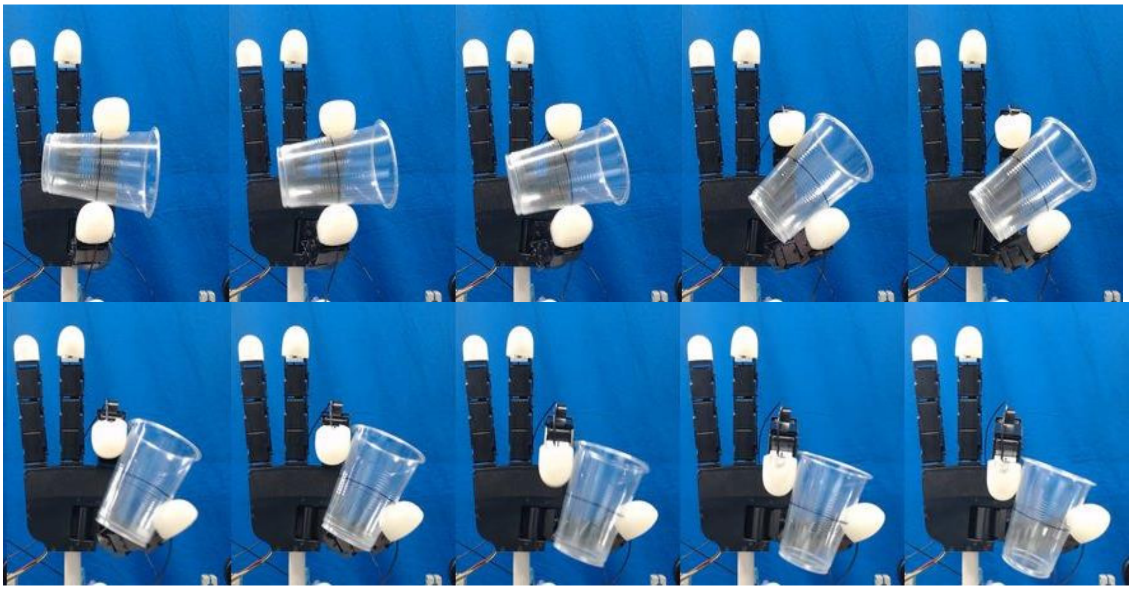


(d) Interpolation control only without soft skin

Motion A/Plastic cup (soft object) /approximate 30gf grasping force



(a) Combined control with soft skin



(b) Interpolation control only with soft skin

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Tokyo, October 2017
Keung Or

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