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Dyson School of Design Engineering

Innovative Robot Hand Designs of Reduced Complexity for Dexterous Manipulation

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Abstract

This thesis investigates the mechanical design of robot hands to sensibly reduce the system complexity in terms of the number of actuators and sensors, and control needs for performing grasping and in-hand manipulations of unknown objects.

Human hands are known to be the most complex, versatile, dexterous manipulators in nature, from being able to operate sophisticated surgery to carry out a wide variety of daily activity tasks (e.g. preparing food, changing cloths, playing instruments, to name some). However, the understanding of why human hands can perform such fascinating tasks still eludes complete comprehension.

Since at least the end of the sixteenth century, scientists and engineers have tried to match the sensory and motor functions of the human hand. As a result, many contemporary humanoid and anthropomorphic robot hands have been developed to closely replicate the appearance and dexterity of human hands, in many cases using sophisticated designs that integrate multiple sensors and actuators—which make them prone to error and difficult to operate and control, particularly under uncertainty.

In recent years, several simplification approaches and solutions have been proposed to develop more effective and reliable dexterous robot hands. These techniques, which have been based on using underactuated mechanical designs, kinematic synergies, or compliant materials, to name some, have opened up new ways to integrate hardware enhancements to facilitate grasping and dexterous manipulation control and improve reliability and robustness.

Following this line of thought, this thesis studies four robot hand hardware aspects for enhancing grasping and manipulation, with a particular focus on dexterous in-hand manipulation. Namely: i) the use of passive soft fingertips; ii) the use of rigid and soft active surfaces in robot fingers; iii) the use of robot hand topologies to create particular in-hand manipulation trajectories; and iv) the decoupling of grasping and in-hand manipulation by introducing a reconfigurable palm.

In summary, the findings from this thesis provide important notions for understanding the significance of mechanical and hardware elements in the performance and control of human manipulation. These findings show great potential in developing robust, easily programmable, and economically viable robot hands capable of performing dexterous manipulations under uncertainty, while exhibiting a valuable subset of functions of the human hand.

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Dedication

I would like to dedicate this thesis to my newborn baby - Jingming Cheng.

Statement of Originality

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

The work presented hereafter is based on research carried out by the author at the Dyson School of Design Engineering at Imperial College London and it is all the author's own work except where otherwise acknowledged. No part of the present work has been submitted elsewhere for another degree or qualification.

Qiujie Lu

August 2021

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Chapter 1

Introduction

1.1 On Robot Hands and Their Design

This section reviews the literature relevant to the subject of this thesis. It mainly presents the state of the art of robot hands over the past century, focusing on their designs and applications.

1.1.1 Overview of Current Robotic Hands

Anthropomorphic Robotic Hands

Human hands have been known as the most complex and dexterity hands in nature. Many humanoid and anthropomorphic robot hands have been developed to closely replicate the appearance and dexterity of human hands with sophisticated designs integrating many sensors and actuators (Fig. 1.1). For instance, The Shadow Dexterous Hand [Sha19] is well known as a dexterous robot manipulator with 20 actuated degrees of freedom (DOF); it has a significant operational capability and is one of the closest mechanical approximation to the human hand. The MANUS-HAND [PRC⁺04] project developed a multifunctional upper-limb prosthesis; this design of kinematics triples the performance of existing commercial hand prosthetics. Faudzi et al. [FOG⁺17] proposed a human-like robotic finger using thin, soft muscles based on the Landsmeer Models I, II and III. This design can help

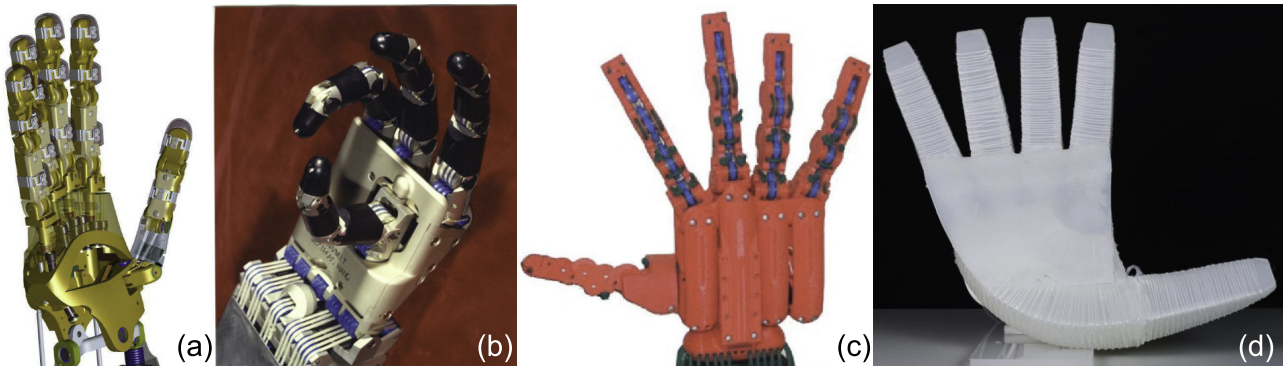


Figure 1.1: Examples of existing anthropomorphic hands of different types. Image of the Robonaut Hand courtesy of NASA; image of the Utah/MIT Hand courtesy of the computer History Museum. Image of the Pisa/IIT Hand (Image reproduced from [CGF⁺14]); image of the RBO Hand2 (Image reproduced from [DB16]).

researchers understand the human finger function better and help model human finger disorders. The CyberHand [CCM⁺06] is a cybernetic anthropomorphic hand with a focus on the control system. This bio-inspired hand provides proprioceptive information through a sensory system for grasp-and-hold tasks. The Gifu Hand series [KKU02, MKY⁺02] has 20 joints and 16 DOF, which are actuated by built-in servomotors; its control system is a real-time operating system on ART-Linux. The DLR-Hand II [BGLH01] is aimed to develop robonaut systems for space applications through improved autonomous grasping and fine manipulation without a forearm. Robonaut Hand [LD99] is a highly anthropomorphic human-scale robot hand designed for space-based operations (shown in Fig. 1.1(a)). This five-finger hand, combined with its integrated wrist and forearm, has fourteen independent DOF. UTHM Hand [ZYAW11] is a multi-fingered dexterous anthropomorphic hand with five fingers, each having four DOF, which can perform flexion, extension, abduction, adduction and also circumduction.

As the little finger of the human hand is not always necessary to perform most daily tasks, many four-fingered anthropomorphic hands have been developed to decrease control complexity. Some hands have four anthropomorphic fingers with three or four degrees of freedom; each attempts to reproduce the dexterity and complexity of the human hand. The MIT-Utah Hand [JIK⁺86] is one of the earliest four-finger robotic hands and was intended to become a general-purpose research tool (shown in Fig. 1.1(b)). KITECH-Hand [LPP⁺16] is a highly dexterous and modularised robotic hand that adopts a new ‘roll-pitch’ type metacarpophalangeal instead of ‘yaw-pitch’ structure. This new structure enhanced kinematic performance and greatly improved the mechanical design. Bruno Jau [Jau95]

developed a four-fingered sixteen DOF anthropomorphic hand controlled by an exoskeleton glove. The system is controlled by a high performance distributed control system. BUAA Hand [ZHZ⁺01] is a modular designed sixteen DOF anthropomorphic hand. Each finger is a compact module with eight-position sensors, and all four actuators are integrated into the mechanical structure of the finger module. NAIST Hand [UIKO05] is a hand developed as a platform for 'NAIST hand project' researches. This hand has four fingers, and each finger has 3 DOF. Instead of using a wire-driven mechanism, a specially designed gear mechanism is proposed to relax the restriction on the space for actuators. Some works have been developed based on the hand, with a focus on tactile fingertips, grasping, and in-hand manipulation [KOIO09, UKO10]. HYDRA Hand [KKN17] is a hydrostatically actuated anthropomorphic hand for handling heavy-duty tasks in the field or rough terrain. This hand uses an underactuated control method to control each finger by one tendon. Different tendon routing methods have been discussed for the hand design.

In the last few decades, many research groups have focused on simplification approaches for hand design; while retaining most of the advantages of anthropomorphic hand designs, but sensibly reducing the system complexity in both design and control regarding the number of actuators or sensors for instance. Underactuation, which refers to controlling the degrees of freedom of a system with fewer actuators than required, is very popular and valuable in gripper design research to reduce system complexity particularly for grasping operations. RBO Hand 2 [DB16] is a highly compliant soft pneumatic hand (shown in Fig. 1.1(d)). Each finger is underactuated by a single self-made PneuFlex actuator. Another two PneuFlex actuators are used to control the palm. Some research groups focused on using the minimalist number of actuators to strive for the most hand capabilities. Open Bionics Hand [KLZ⁺15] developed a differential mechanism that works as a button. Users can select the desired finger combinations intuitively to perform various grasping and gestures. With this differential mechanism design, the hand can achieve 16 different finger combination with a single motor. Gosselin et al. [GPL08] analysed the force transmission, the tendon driven geometry, and the differential mechanism of an anthropomorphic underactuated robot hand design with 15 DOF and a single actuator. Liu et al. [LZLX20] proposed an anthropomorphic multi-grasp hand design with several mechanisms to achieve enhanced grasping functionality by only used one motor. A continuum differential mechanism is used to generate the differential finger motions. A load adaptive variable transmission is

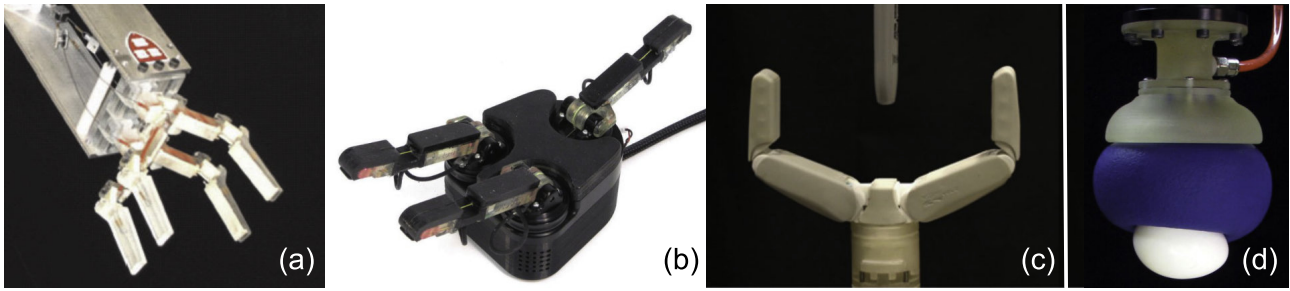


Figure 1.2: Examples of existing simplified robotic hands in different types. Image of the SDM Hand (Image reproduced from [DH10]); image of the IHY Hand (Image reproduced from [OJC⁺14]); image of the Velo Hand (Image reproduced from [CHH⁺14]); image of the Universal Gripper (image reproduced from [ABR⁺12]).

designed to magnify the grasping forces. A prismatic clutch is used to lower the motor's energy consumption. Another prevalent approach for underactuated anthropomorphic hands is the use of hand synergies. In neuroscience, the term 'synergy' means multiple elements working together towards a common goal to understand neural control of movement [SBG⁺16]. The framework of synergies has been applied successfully on robotic hands to create novel design and control concepts. Pisa/IIT SoftHand [CGF⁺14] is a robust and safe hand with 19 joints but only uses one actuator to activate its adaptive synergy (shown in Fig. 1.1(c)). The work investigates the principles of soft synergies and applies the soft synergy idea to various actuation schemes. This design aspect has been discussed and further developed in the literature, mainly for prosthetics [GCS⁺12b, DSGC⁺15, PDSC⁺16]. Delft Cylinder Hand [SPvdH14] proposed a super-lightweight upper limb prosthetic with articulating fingers. Baril et al. [BLGR13] introduce a mechanical lever to improve the force transmission ratio for grasping capabilities enhancement. Although those designs use only one motor, they sacrifice manipulation capability.

Simplified Robotic Hands

Here simplified robotic hands indicate those non-anthropomorphic robotic hand designs which have been leveraged for their use in industry (Fig. 1.2). To achieve force stability in three-dimensional space, a grasped object needs to have four contact points. Therefore, many four-fingered robotic grippers have been developed. For most of them, the finger positions are symmetrical, which refers to two fingers installed on one side, and the other two fingers installed symmetrically on the other

side. SDM Hand [DH10] is an adaptive and compliant grasper with viscoelastic flexure joints that can grasp objects spanning a wide range of size, shape, mass, and position/orientation using a single motor (shown in Fig. 1.2(a)). Additionally, soft-robotics approaches have been practical to achieve grasping versatility. Mizushima et al. [MOS⁺18] presents a four-fingered soft hand with granular materials corresponding to finger pulp. It has high adaption to objects shape under disturbances. Akin et al. [ACF02] developed a tendon-driven four-fingered robot hand for space operations. This hand can achieve cylindrical grasps while holding other tools. The study shows that over 90% cylindrical grasps can be achieved by a three-fingered hand.

Three-fingered hands usually have two hand configurations: trigonal and parallel. Bemfica et al. [BMM⁺13] proposed a trigonal positioned soft gripper for underwater applications. Spring Hand [CSS⁺04] is a paralleled positioned three-fingered prosthetic hand that can achieve a natural grasping behaviour and a good distribution of pinching forces. Backus et al. [BD16] designed an underactuated prismatically actuated gripper with rotational joints which allow the fingers to switch between spherical and cylindrical grasps passively. Bemfica et al. [BMM⁺14] later also proposed a cable-driven underwater gripper that can switch the grasping type from tripod to parallel grasp. Its kinematic configuration allows the execution of parallel power grasps and tripod precision grasps. In order to achieve different grasping types, many research groups have put efforts into the base joint of the fingers and the mechanical design of the palm. Laliberte et al. [LBG02] presented self-adaptive and reconfigurable hands which are underactuated and versatile. IHY Hand [OJC⁺14] is a three-fingered underactuated hand driven by five actuators (shown in Fig. 1.2(b)). Two fingers have a coupled adduction/abduction motion at the proximal joints to perform different grasps and simple re-position tasks.

In fact, two-fingered robotic hands are also very popular, especially for industrial applications. However, due to their simple design, two-fingered robot grippers are now being used in a wide variety of fields beyond factory settings to free or augment human labour. Kragten et al. [KBGH11] improved the underactuated hand precision grasp performance using a simple design modification: reshaping the distal phalanges of the fingers into a curved surface. Teeple et al. [TKGW20] designed a two-segment fluid-driven soft finger for pinch grasping. The Velo gripper can perform both parallel and fingertip grasps with a single actuator [CHH⁺14], being able to pick up small objects off a flat surface (shown in Fig. 1.2(c)). With the fast development in the field of soft robotics, for many simple tasks

like pick and place, granular jamming grippers [ABR⁺12] (shown in Fig. 1.2(d)) or suction-based grippers [CBB⁺16] have been proposed. Those grippers have high compliance and robustness even under uncertainties. Their control systems are also elementary. However, there are also some drawbacks. For example, the suction system has some requirements typically on the surface condition of grasped objects. Additionally, the pneumatic actuation method usually requires external air pump systems, which may not be convenient for a mobile system for instance.

1.1.2 Mechanical Design of Robotic Hands

Type of Hand Joints

Three types of joints are reviewed in this section: rigid, flexible, and soft continuous (Fig. 1.3). A rigid joint is a system where the links are connected using fixed mechanical elements (shown in Fig. 1.3(a)). Most of the rigid joint designs are revolute using pins to connect the phalanxes [Sha19, JIK⁺86, SPN⁺10]. Some of them use gears and belts to fix the joints [QWD⁺13, MO14, RZ17]. With pin design, tendon-driven fingers normally use springs as the backwards actuation. Due to the fixed and stable relative joint position, rigid joints can provide high force transmission and robust grasps. However, this can also be a disadvantage in uncertain environments. Especially the hands driven by gears or linkages, which are prone to damage when unpredictable forces act on them.

A flexible joint is a system where the links are connected with flexible elements (shown in Fig. 1.3(b)). This type of joint is usually driven by tendons and do not need the spring to restore the finger position

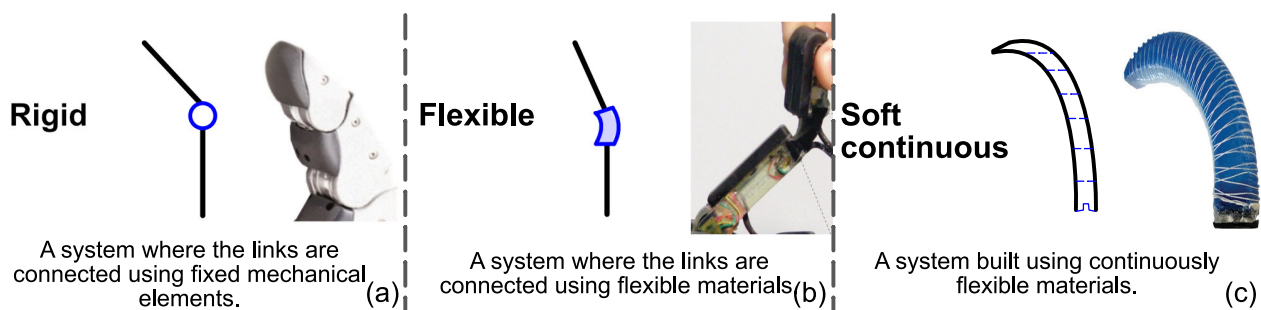


Figure 1.3: Different types of hand joints: rigid, flexible, and soft continuous. Image of the rigid, flexible, and soft continuous courtesy of DLR, the Open Hand project, and the Robotics and Biology Laboratory at Technische Universitat Berlin, respectively.

as the flexible material itself can do this job. Ma et al. [MOD13] proposed an open-source, low-cost, single-actuator 3D-printed underactuated hand with four adaptive fingers. This hand shows the capability of grasping with compliant flexure joints, following ideas previously presented in [Dol06]. Dollar et al. [DH11] also examined a joint coupling design of underactuated grippers for unstructured environments. Bai and Rojas [BR18] presented a self-adaptive one-step 3D printed robotic gripper, where the joints are based on a teeth-guided compliant cross-four-bar linkage. This basic single-material additive manufactured underactuated hand increases the precision of robotic fingers by removing nonlinear characteristics of flexures.

Soft continuous refers to a system built using continuously flexible materials to create a finger, usually called soft finger (shown in Fig. 1.3(c)). Many research groups are working on designing soft fingers for different applications [DB16, MOS⁺18, GGH⁺14]. For example, Shintake et al. [SCFS18] reviewed different soft grippers with various material sets, physical principles, and device structures. Soft fingers are usually actuated by a pneumatic system. Due to the high compliance of the flexible material, soft fingers usually perform well on gross grasping. However, given their continuous design, precision is low in these fingers. Therefore, some researchers have developed soft fingers in segments that can achieve a more precise grasp or even manipulations [MHP⁺15, TKGW20].

Type of Mechanism

Four types of mechanisms for robot hands are reviewed in this section: linkage, gear, tendon, and soft pneumatic (Fig. 1.4). A linkage mechanism is a system where the links are actuated via closed-loop kinematic chains (shown in Fig. 1.4(a)). One of the most common ways is to use a five-bar

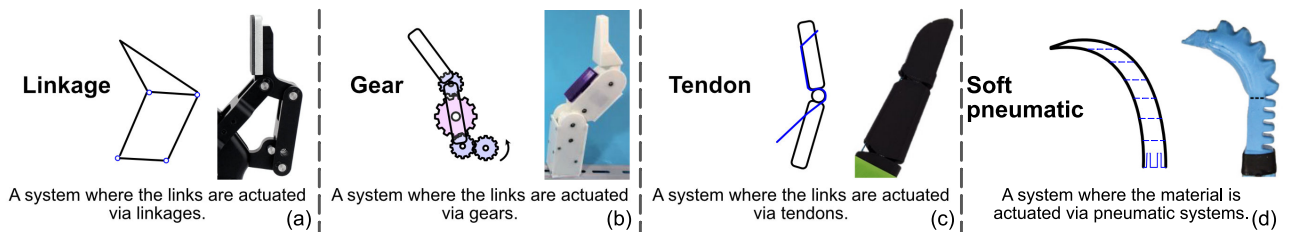


Figure 1.4: Different types of hand mechanisms: linkage, gear, tendon, and soft pneumatic. Image of the linkage, gear, tendon, and soft pneumatic courtesy of Robotiq, the Tsinghua University, the REDS Lab and the Harvard University, respectively.

linkage with coaxial joints and a spring as a finger [LBG02, YC17]. This linkage can be assembled in series [RCC06, JLLC13, DCN01] so that by actuating the bottom driving link, the self adaptability of the finger with any number of phalanges can be achieved. However, such a system can be structurally complicated and takes a large amount of space. In order to further increase the adaptability of linkage-based designs, improvements with unidirectional flexible phalanx have been proposed [LYZ⁺16]. It is a structure where the rigid finger phalanges are substituted with many short unit links connected in series so that the contact area can be further increased.

A gear mechanism (shown in Fig. 1.4(b)) is a system where the links are actuated via gears [SZ17]. There are many types of geared mechanisms, including planetary gear system as differential [QWD⁺13], a chain of gears with springs attached [MO14], pulley belt systems [SZ16], and empty trip mechanisms with coupled joints [RZ17, DSWZ17]. These designs are inspired by traditional mechanical transmission systems, requiring relatively high tolerances in manufacturing and usually exhibiting limited self-adaptability. In addition, indirect adaptability mechanisms have been proposed [WSTW17]. In such a system, there is a slider-rack mechanism implemented on the proximal phalanges. When it is in contact with the object, the exerted force is transmitted to rotate the distal phalanges.

A tendon mechanism is a system where the links are actuated via tendons (shown in Fig. 1.4(c)). Tendon-driven grippers, inspired by the tendons and muscles in the human hand, can provide high adaptability [BR18] yet usually lack precision for delicate grasping due to the nonlinear characteristics of tendon compliance [DH11, KYT91]. To achieve the actuation of multiple fingers, a differential pulley system is normally implemented [GCS⁺12a, WLCR20], which requires relatively large space and specific routing for different grippers. Such a system is though usually incorporated in anthropomorphic hand designs [JIK⁺86, GPL08, NRST14]. The tendon routing system can be very complex, with a well-analysed hand synergy; even with a single motor, the robot hand can perform different grasping tasks [CGF⁺14]. The force transmission of an underactuated gripper via various tendon routing structure has been analysed in [CLR21].

Soft pneumatic is similar to the previous review in the soft continuous section 1.1.2 (shown in Fig. 1.4(d)). As the special characteristic of the soft material, the soft fingers are made from elastic material; normally there is no exact joint or mechanism inside the fingers. The internal chamber

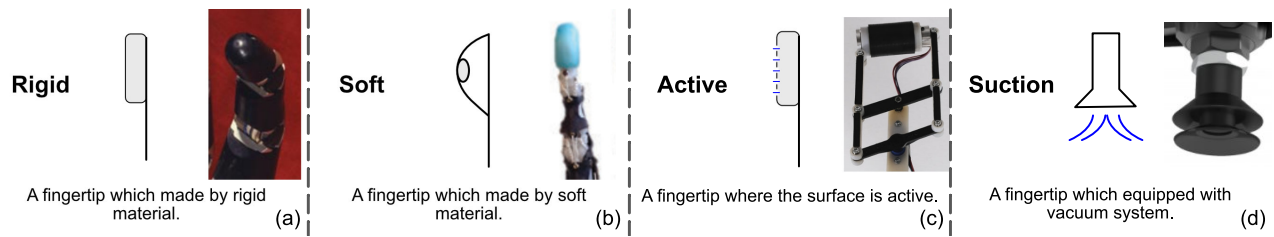


Figure 1.5: Different types of fingertip designs: rigid, soft, active, suction. Image of the rigid, soft, active, and suction are reproduced from [JIK⁺86, XT16, YENS20, Rob16], respectively.

and structure design of the soft fingers are usually considered as design characteristics to improve the finger performance [CRG⁺13, LWZ20]. The setup for a pneumatic system of the robot hand may count as the mechanism [DB16].

Type of Fingertip Design

Four types of fingertip design are reviewed in this section: rigid, soft, active, and suction (Fig. 1.5). Those robot hands designed over the last century usually used rigid fingertips, as flexible and soft materials were not easily available [JIK⁺86, Jau92, MV92]. Additionally, for some extreme environment and applications, e.g. space operation, high hazardous environments, rigid fingertips made by steel or other high-intensive material are needed [JIK⁺86, BGLH01, ACF02, LD99].

For general daily tasks, robot hands are often equipped with soft fingertips (shown in Fig. 1.5(b)) to achieve high compliance grasps. High grasping stability arises from the compliance of fingertips in the human hand since an increase in contact area from fingers results in a greater variety of moments to the grasped object [CMA05]. Thus, soft fingertips have become a suitable approach in robotics to handle excessive contact force in grasping and manipulation tasks. Maruyama *et. al* presented a gripper with incompressible fluid covered by rubber fingertips which can grasp fragile and brittle objects by controlling the contact pressure [MWU13]; and Manti *et. al* showed the dexterous grasping capability with simple control of a bioinspired soft gripper [MHP⁺15]. Sensing is another important feature for fingertips. Most tactile sensors are soft and elastic, which also count as soft fingertips [DRP⁺14, JA09, Kim04].

Recently, the active fingertip idea has been developed in multiple ways. Active fingertip (shown in Fig. 1.5(c)) usually requires additional actuation for the fingertip to achieve tasks beyond the grasps,

e.g. rolling, rotating, manipulating. The incorporation of actuated conveyor belts was examined in [DP85] in order to enhance the manipulation capabilities of a robotic grasper. This concept was further developed in recent works. Velvet hand [TCF⁺12] consists of two symmetrical fingers with two belts on each. This design can control the slipping between the active surfaces and the grasped object for smooth tip-grasp to power-grasp transition. Govindan et al. [GT19] presented a multimodal grasper consisting of two hybrid jaws with a rigid inner structure encompassed by a flexible, active surface working as a soft fingertip to provide shape conformation. Ma and Dollar [MD16] based on a similar conveyor belt principle designed a grasper consisting of an active one DOF thumb and an underactuated finger with passive rollers. Similarly, this principle can also apply to a three-fingered robot gripper [KNM16]. Roller-based hand [YENS20] combines the roller and the linkage system to the finger design, which can achieve a full six DOF nonholonomic spatial motion. Another type of active surface is considered as changing the surface condition, e.g. friction, stiffness, shape. Variable friction hand [SCD18] consists of a passive and active variable friction finger design to achieve the variable friction principle analogy to the human finger pad. With a popping out lower friction module, an object can slide on a low friction surface and rotate on the high friction surface. Chavan-Dafle *et al.* [CDMS⁺15, CDLR18] proposed an on-off fingertip which can change its shape to achieve point contact or firm contact.

A suction system (shown in Fig. 1.5(d)) is usually working as a single gripper to perform pick-and-place tasks. A standard suction cup works well on flat and smooth objects. Zhakypov et al. [ZHBP18] proposed an origami-inspired reconfigurable suction gripper to pick up more objects with different shape and size. Hasegawa et al. [HWN⁺17] presented a hybrid gripper with a suction cup in the middle of the palm. This design can increase the grasping capability of a standard two-fingered simple gripper, especially on flat and flexible objects. Recently, many works have put the suction system at the end of the fingertip to achieve better-grasping performance [CBB⁺16]. IGRIPP4 Hand [YHK13] has a suction mechanism at each fingertip that can perform some dexterous manipulation. A series of underwater grippers are using suction flow to pick up, sense, manipulate objects under the water [SWG⁺14, SBW⁺15, SWC18, NAMS20]. Ponraj et al. [PJVPL⁺19] evaluated the pinch grasp capability and suction modality of the gripper, which consists of the suction module at the tip of the finger.

1.1.3 Capability of Robotic Hands

Power Grasps and Precision Grasps

For robotic hands, there are two major types of grasps: power grasp and precision grasp. Power grasps also defined as caging grasps or form closure. Fingers normally have several contact points with the grasped objects. Power grasps are more tolerant to dynamic manipulation due to larger contact areas. Zhang et al. [ZG95] have analysed the definition and the force distribution of power grasps. Most of the underactuated grippers can only achieve power grasps [LZLX20, CGF⁺14, GCS⁺12b, DSGC⁺15, PDSC⁺16]. With high compliance of the soft fingertips, the increased contact area with objects results in a greater variety of moments to the grasped object [CMA05]. Most current research focuses on delicate power grasping by robotic grippers. For instance, Amend *et. al* proposed the well-known granular jamming universal gripper for grasping a wide range of objects [ABR⁺12]; Maruyama *et. al* presented a gripper with incompressible fluid covered by rubber fingertips which can grasp fragile and brittle objects by controlling the contact pressure [MWU13]; and Manti *et. al* showed the dexterous grasping capability with simple control of a bioinspired soft gripper [MHP⁺15].

The precision grasp is associated with handling objects between the fingertips, also called the pinch grasp. The ability of underactuated hands to perform precision grasps on objects is very limited because the precision grasp is ordinarily unstable. Kragten et al. [KBGH11] improved the underactuated hand precision grasp performance by simple design modification by reshaping the distal phalanges of the fingers into a curved surface. Teeple et al. [TKGW20] designed a two-segment fluid-driven soft finger for pinch grasping. The Velo gripper can perform both parallel and fingertip grasps with a single actuator [CHH⁺14], being able to pick up small objects off of a flat surface. Due to a limited number of contact points, 2-fingered grippers struggle to keep the object with additional dynamic forces from the robot arm. 3-fingered grippers show better stability under dynamic forces but still not enough. To provide equal contact forces, traditional 3-fingered grippers positions their fingers in a trigonal way during pinch grasp [TTS15, Rob16, OJC⁺14]. This finger position is typically restricted to pinch grasp regular objects with standard fingers. To improve the grasping capability for irregular objects, additional DOF is added at the base of the fingers for rotation or abduction to

achieve different grasping configurations [Rob16, OJC⁺14]. However, with a single motor actuation, the self-adaptability for all three fingers is limited.

Dexterous In-hand Manipulation

Recent research in dexterous in-hand manipulation has focused on achieving particular tasks or performing specific movements of a rigid object, for example, reorienting the object [ABC⁺20, DRP⁺14] or performing a prehensile spherical motion [MRD16a]. Anthropomorphic hands like the Shadow Dexterous Hand [Sha19] is an example of a robotic hand designed for human-level dexterity. This type of hands often requires sophisticated control schemes to achieve in-hand manipulation [ABC⁺20]. Owing to the difficulty in modelling such complex systems, there has been work in data-driven approaches that only train on a physical hand [FASL18, KGTL16, VHHNP15]. Conversely, others have trained this hand in both simulation and reality successfully to rotate a cubic in-hand and play Rubik's cube [OAA⁺19a, OAB⁺20] .

Improving the in-hand manipulation ability of robot grippers without increasing their design and control complexity has since become an active area of research in recent years [WCRL17, RMD16, BDR17, DRP⁺14, CDMS⁺15, CDLR18]. The most common in-hand manipulations for robot grippers that have been studied are sliding and rotating operations. Chavan-Dafle *et al.* achieved spinning point contact and firm contact by changing the finger-object contact geometry and varying the gripping force [CDMS⁺15, CDLR18]. Objects reorient about the axis between the contact points from a horizontal pose to a vertical pose due to gravity, however with limited reorientation direction and range. In-hand reorientation of grasped objects has been also demonstrated using tactile feedback [WCRL17]. Alternatively, adding or changing components of existing hand mechanisms is a common method for improving robot gripper abilities. The GR2 gripper increased the object range of motion by introducing an elastic pivot joint between the two fingers [RMD16], and Terasaki *et al.* designed a rotation mechanism attached to the tips of a parallel two-fingered gripper combined with a motion planning system to increase dexterity [TH94]. Several robotic hands have been developed by modifying existing underactuated designs in different ways to achieve translation and rotation of objects [BNA⁺20, MKC⁺20]. Della *et al.* [DSPG⁺18] designed an intelligent embodied tendon-driven

mechanism based on turning transmission friction from a disturbance into a design tool to perform a variety of grasping and manipulation tasks. Liu *et al.* [LZZX18] proposed a three-fingered gripper that is actuated by a single motor and is able to grasp objects and perform rolling manipulation with a working mode switching mechanism.

In-hand manipulation of soft objects with a simple degree of freedom gripper is not well explored as yet. The main difficulties are the actuation method, force control, and the soft fingertip model. Tactile sensors are commonly being employed on the fingertip to sense the grasping force [WCRL17] and measure the object surface texture and shape [JA09]. However, it is challenging to perform active deformation with those conventional tactile sensors. The relationship between soft fingertips and in-hand manipulation is not well defined as well. Due to the uncertainties of soft materials (*e.g.*, rolling, deformation), it is hard to model the exact manipulation of the grippers, and the dynamic motion of the soft objects [LR19, Kim04].

For deformable objects, the performances of grasping and manipulation interfere with each other. The robot hand needs to predict the deformation of the object and respond efficiently to the deformation; this requires a robust control law and an optimised motion planning algorithm. [Tay12, HW12] studied how to manipulate deformable objects by considering the grasping and manipulation separately: it was impossible to perform the in-hand manipulation of deformable objects. However, Hirai and Wada [HW00] proposed a robust and simple control law that considered the grasping and manipulation of deformable objects at the same time. Computer vision [WHI95, JDL98] is a common tool used for object deformation detection. Recently, virtual reality [CLE98] has also helped researchers to model object deformation. A great amount of research has been published on the motion planning of deformable object manipulation [SI06, FSS⁺14, FSAB11]. These contributions focus on robot arm motion planning, while the robot gripper is usually neglected. Salleh *et al.* [SSKH06] proposed an edge tracing method to separate towels with two robot grippers. In contrast, [KYF⁺95, SLM97] also studied the manipulation of deformable objects by using two robot manipulators.

1.2 Thesis Overview

This thesis is concerned with the mechanical and hardware enhancement of robot hands, focused on their capabilities for both grasping and in-hand manipulation, in order to sensibly reduce the system complexity in terms of the number of actuators and sensors, and the control needs. The research in this thesis aims to explore some robot hand design aspects and deliver a clear understanding of their efficacy and practicality for complex motions by investigating their in-hand manipulation performance on a wide range of objects.

Human hands have been known as the most complex and dexterity manipulators in nature. They can perform daily activity tasks (grasping, holding, pushing, pulling, manipulating, etc.), industrial tasks (placing, cleaning, operating, assembling, etc.), and social tasks (caressing, playing instruments, handshaking, all kinds of gestures, etc.). Since at least the end of the sixteenth century [ZO14], researchers have tried to match the sensory and motor functions of the human hand. However, the understanding of why human hands can perform such fascinating tasks still eludes full comprehension.

Many humanoid and anthropomorphic robot hands have been developed to closely replicate the appearance and dexterity of human hands with sophisticated designs integrating many sensors and actuators. For instance, Shadow Dexterous Hand [Sha19], Gifu Hand II [KKU02], DLR Hand II [BGLH01], and Robonaut Hand [LD99]. Those hands have achieved some interesting, eye-catching applications in laboratory settings, using complex control schemes or advanced but time/power consuming machine learning techniques [KKU02, BGLH01, LD99]. However, the applicability of these results to real-world problems seem limited and the solutions are certainly overly complex. In fact, it can be argued that by just replicating the human hand, the understanding of its real working principles and how to improve its functions is restricted. This is in part why, in recent developments [CBB⁺16, EHJ⁺16], achieving robust, simple controlled, and energy efficient solutions is becoming more popular when designing robotic hands.

For robust and repeatable grasping tasks, the approaches aiming at simplified designs provide notable benefits, where underactuated hands and simple grippers become very popular. A lot of research is

then being carried out in the field of robotic grippers and hands to satisfy the growing demands of specific design requirements such as compact structure (e.g., the Utah/MIT Hand [JIK⁺86], Gear Chain Hand [MO14], and TBM Hand [DCN01]), simple actuation (e.g., the Universal Gripper [ABR⁺12], Underactuation principles [LBG02], and Anthropomorphic Underactuated Hand [GPL08]), control accuracy [BPF11, DH11, JLLC13], multiple functionality [HLA⁺20, MOD13, MRCD02], and robust grasping [GGL⁺17, YC17, BLG07], to name some. Some hands retaining the advantages of anthropomorphic design but reducing the number of actuators and sensors can also achieve good grasping versatility, robustness, and reliability. For example, the Delft Cylinder Hand [SPvdH14] and Open Bionics Hand [KLZ⁺15].

However, robotic research has long been interested not just in the ability to grasp but also in the in-hand manipulation of a varied set of objects to improve the dexterity and applicability of robots. To this end, further research is indeed needed in the components of a dexterous manipulation robotic system, which are a robotic hand and a control policy, along with the object to be grasped and manipulated by the hand [HT98]. Improving the in-hand manipulation ability of robot grippers without increasing their design and control complexity has become an active area of research in recent years (e.g., the GR2 Gripper [RMD16, BDR17], Extrinsic Dexterity Hand [DRP⁺14, CDMS⁺15, CDLR18]). Indeed, performing reliable prehensile in-hand manipulation under both shape diversity and shape uncertainty with a robot hand is still an open problem [Bic00, BK19].

In this thesis, mechanical enhancements inspired by the human hand have been analysed to understand how grasping and in-hand manipulation can improve when designing robotic hands. Four types of mechanical enhancement aspects are explored in the following chapters. Chapter 2 studies the use of passive soft fingertips and their role in in-hand manipulation. Chapter 3 investigates how different active surfaces in fingers affect hand performance. Chapter 4 studies robot hand topologies to create particular in-hand manipulation trajectories. Finally, Chapter 5 focuses on decoupling grasping and in-hand manipulation with the help of a reconfigurable palm. The detailed thesis outline has been illustrated in Section 1.6.

1.3 Motivation and Objectives

In this thesis, the development of novel mechanical and hardware enhancements for robot hand design has been addressed with the following four objectives:

- 1) **Understand the role of soft fingertips for in-hand manipulation and propose an appropriate model for its analysis.** From the view of biomechanics, the human fingertips consist of rigid bones, soft glabrous fat and the epidermal skin layer. Many existing robot grippers and hands only replicate the rigid bone structure as their mechanical structure to achieve grasping or gestures. Some hands may add a layer of high friction material on the fingertip (similar to the epidermal skin layer) to achieve robust grasping. Actually, high grasping stability arises from the compliance of fingertips in the human hand, since the deformation of the soft glabrous fat has an increase in the contact area between fingertips and the grasped object [CMA05]. Thus, soft fingertips have become a suitable approach in robotics to handle excessive contact force in grasping and manipulation tasks. Indeed, multiple research works have been carried out on contact mechanisms of soft fingertips in static situations, but they are difficult to implement to analyse in-hand manipulation. In this thesis, a suitable contact model for soft fingertips is proposed, which is then analysed via in-hand manipulation performance experiments.
- 2) **Propose novel active surfaces and find out how they affect hand performance.** In human hands, fingertips get wrinkles when inserted into the water for a while. This phenomenon is the reaction of the subcutaneous nerve of the fingertip. From the view of biology, water is much smoother than air. Therefore, those wrinkles help to increase the fingertip friction for better underwater performance. The frictional properties of biological skin have been investigated to show that the effects of these parameters are essential for feedback and forward gripping control systems. In this thesis, instead of using water as a trigger to vary the fingertip surface, novel active surfaces of fingers have been proposed to find out their capabilities for both grasping and in-hand manipulation.
- 3) **Develop robot hand topologies to create particular in-hand manipulation trajectories.** There are 24 degrees of freedom in the human hand. This is one of the reasons why human

hands can perform many complex and dexterous in-hand manipulations. Deep reinforcement learning techniques have been developed fast in recent years to control anthropomorphic robot hands [OAA⁺19a, OAB⁺20]. However, it has become apparent that software control only cannot achieve reliable dexterous manipulation operations under both shape diversity and shape uncertainty. This is in part because the hand-object system formed during in-hand manipulation operations constantly generates multiple closed-loop kinematic chains that inherently impose constraints that modify the feasible movements of both the hand and the object. In this thesis, the design of robot hands, especially the hand topology, for dexterous manipulation have been developed to achieve complex predictable behaviours using low-level, simple non-position control schemes and a minimum number of actuators.

- 4) **Explore the decoupling of grasping and in-hand manipulation by using a reconfigurable palm.** Human hands are such powerful not only because of their sophisticated mechanical design but also because of the powerful brain system to control the hand. For different objects and types of in-hand manipulation, the brain system can choose different strategies to grasp the object to achieve the best performance. It has been shown that the primary mechanical function to achieve various grasping types in human hands is indeed the extra degree of freedom of the palm [inf18]. Taking this as an inspiration, in this thesis, a novel gripper using a reconfigurable palm is introduced. This gripper achieves not just grasping versatility but also the decoupling of grasping and in-hand manipulation control when relocating objects within the hand.

1.4 Contributions

The contributions of this thesis are:

- A novel, tractable approach for contact modelling of soft fingertips for in-hand manipulation settings have been proposed. The proposed method is based on a relaxation of the kinematic equivalent of point contact with friction, modelling the interaction between fingertips and objects as joints with clearances rather than ideal instances, and then approximating clearances

via affine arithmetic to facilitate computation. The trade-off between hardness and depth in soft fingertips to achieve better manipulation performance has been found out [LR19].

- A parametric, origami-inspired thin variable-friction surface has been proposed to improve the manipulation capabilities of a two-DOF simple gripper. Based on a deformation-limited mountain/valley fold structure, this active variable-friction surface exposes two different contact surfaces (high/low friction) using a single on-off actuator. This origami-inspired design is thin, flexible and compact; with high-level manufacturing skills, it can ideally become a variable-friction skin. The fingers of the robot gripper with this variable-friction surface can either slide over objects or firmly grasp them, similar to a human finger, without increasing the complexity of the control problem significantly [LCSR20].
- A coupled actuation and sensing fingertip based on a pneumatic system is proposed. This dual-functional fingertip has been equipped on a two-DOF simple gripper to perform in-hand translation and rotation of soft objects. The approach is based on enhancing the dexterity of robot hands via soft fingertips with tactile sensing and active shape-changing; such that pressurised air cavities act as soft tactile sensors to provide closed-loop control of fingertip position and avoid object's damage, and pneumatic-tuned positive-pressure deformations act as a localised soft gripper to perform additional translations and rotations [LHNR20].
- A hand topology has been proposed to generate spiral spatial trajectories of the hand-object system regardless of shape or size. This approach can be seen as a mechanical-intelligent technique to facilitate dexterous manipulation. Mechanical intelligence uses mechanical and other physical properties to create robotic systems adaptable to new external situations using simple control schemes. For example, the proposed three-fingered two-actuator underactuated robot hand exhibits self-adaptive precision grasping, in addition to helical prehensile in-hand motions of unknowing objects, by simple setting both actuators at a constant speed [LBBR].
- An underactuated robot hand with reconfigurable palm has been designed to perform systematic prehensile in-hand manipulations regardless of object size or shape. This novel layout allows decoupling grasping and manipulation, facilitating the planning and execution of in-hand manipulation operations. The reconfigurable palm provides the hand with large grasping

versatility, but it also allows easy computation of a map between task space and joint space for manipulation based on distance-based linkage kinematics. The motion of objects of different sizes and shapes from one pose to another is straightforward and systematic, provided the objects are kept grasped—which is guaranteed via underactuation [LBCR].

1.5 Publications

JOURNAL PAPERS

1. **Q. Lu**, N. Baron, A. Clark, and N. Rojas, "Systematic Object-Invariant In-Hand Manipulation via Reconfigurable Underactuation: Introducing the RUTH Gripper". *International Journal of Robotics Research (IJRR)*, 2021.
2. **Q. Lu**, A.B. Clark, M. Shen, and N. Rojas, "An Origami-Inspired Variable Friction Surface for Increasing the Dexterity of Robotic Grippers," *IEEE Robotics and Automation Letters (RAL)* and *ICRA*, 2020.
3. L. He, **Q. Lu**, SA. Abad, N. Rojas, and T. Nanayakkara, "Soft Fingertips With Tactile Sensing and Active Deformation for Robust Grasping of Delicate Objects," *IEEE Robotics and Automation Letters (RAL)* and *ICRA*, 2020.
4. **Q. Lu** and N. Rojas, "On Soft Fingertips for In-Hand Manipulation: Modeling and Implications for Robot Hand Design," *IEEE Robotics and Automation Letters (RAL)* and *RoboSoft*, 2019.

CONFERENCE PAPERS

1. **Q. Lu**, N. Baron, G. Bai, and N. Rojas, "Mechanical Intelligence for Adaptive Precision Grasp". *Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA)*.
2. **Q. Lu**, J Wang, Z. Zhang, G. Chen, H. Wang, and N. Rojas, "An Underactuated Gripper based on Car Differentials for Self-Adaptive Grasping with Passive Disturbance Rejection". *Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA)*.

3. Z. Zhang, W. Fan, G. Chen, J. Luo, **Q. Lu**, and H. Wang, "A 3D Printable Origami Vacuum Pneumatic Artificial Muscle with Fast and Powerful Motion". Proceedings of the 2021 IEEE International Conference on Soft Robotics (RoboSoft).
4. **Q. Lu**, N. Baron, A. Clark, and N. Rojas, "The RUTH Gripper: Systematic Object-Invariant Prehensile In-Hand Manipulation via Reconfigurable Underactuation," Proceedings of the 2020 Robotics: Science and Systems (RSS).
5. **Q. Lu**, L. He, T. Nanayakkara, and N. Rojas, "Precise In-Hand Manipulation of Soft Objects using Soft Fingertips with Tactile Sensing and Active Deformation," Proceedings of the 2020 IEEE International Conference on Soft Robotics (RoboSoft).
6. J. Wang, **Q. Lu**, A. Clark, and N. Rojas, "A Passively Complaint Idler Mechanism for Underactuated Dexterous Grippers with Dynamic Tendon Routing". Proceedings of the 2020 Towards Autonomous Robotic Systems Conference (TAROS)

1.6 Thesis Structure

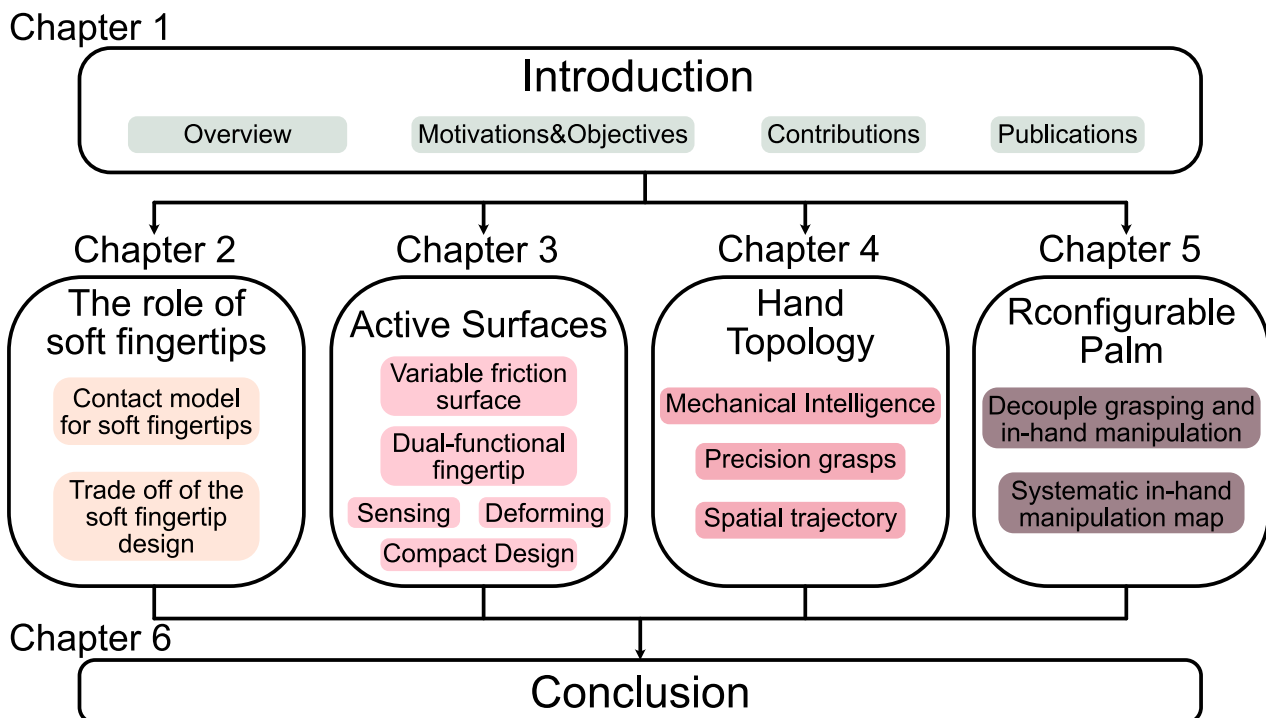


Figure 1.6: The thesis outline.

Chapter 2

The Role of Soft Fingertips for In-Hand Manipulation

This chapter is adapted via ©2019 IEEE. Reprinted, with permission, from [Q. Lu and N. Rojas, "On Soft Fingertips for In-Hand Manipulation: Modeling and Implications for Robot Hand Design," IEEE Robotics and Automation Letters (RAL), 2019].

Abstract

As mentioned in the motivation (Section 1.3), soft fingertips have become a suitable approach in robotics to handle excessive contact force in grasping and manipulation tasks. Indeed, multiple research works have been carried out on contact mechanisms of soft fingertips in static situations when information about contact forces and object position is known. However, they are challenging to implement for the analysis of in-hand manipulation since the location of the manipulated object is uncertain due to compliance and closed-loop constraints. In this chapter, a novel, tractable approach for contact modelling of soft fingertips in within-hand dexterous manipulation settings has been proposed to understand the role of soft fingertips for in-hand manipulation. Numerical and empirical experiments are conducted to analyse the effects of soft fingertips on manipulation operability; results demonstrate the functionality of the proposed approach and a trade-off between hardness and depth in soft fingertips to achieve better manipulation performance of dexterous robot hands.

2.1 Introduction

High grasping stability arises from the compliance of fingertips in the human hand, since an increase in contact area from fingers results in a greater variety of moments to the grasped object [CMA05]. Soft fingertips have thus become a suitable approach in robotics to handle excessive contact force in grasping and manipulation tasks. Indeed, multiple research works have been carried out on contact mechanisms of soft fingertips in static situations. For instance, Reznik et al. [RL96] proposed a dynamic mass-spring model to perform the deformation of the soft fingertip; moreover, Inoue et al. [IH08] proposed a parallel-distributed spring model for hemispherical soft fingertips by analytically formulating the elastic force and elastic potential energy equations. Subsequently, Ghafoor et al. [GDD04] used contact stiffness based on screw theory to model a soft finger contact, and presented an analytical approach to synthesise it.

Possible contact models when two objects touch, using the normal force and contact friction force, have been discussed in Ciocarlie et al. [CMA05], where several equations based on Coulomb's model are proposed to describe *point contact with friction* and *soft finger* contact models. Kim [Kim04] discussed a model for soft fingertips under motion by using a simplified spring and damping model; this approach analyses the behaviour of the fingertips when they interact with a manipulated object. These methods are all sound and are able to calculate the precise deformation of a soft fingertip when its design parameters, the contact forces, and the object position are known.

Despite the described advantages, the above soft fingertip models are difficult to implement for the analysis of in-hand manipulation, as knowledge about the object's position is required. This information is uncertain, due to the compliance and closed-loop constraints of the hand-object system. Indeed, the precise input parameters required by these models lead in general to complex equations that are unable to characterise an object's uncertainty. Reinforcement learning techniques based on the randomisation of numerous physical properties [OAB⁺20] could be combined with these models to deal with the unpredictability resulting from deformation and multiple contact forces; however, it is unclear how the resulting control policies could be transferred to different robot hands, and limited insights would be obtained regarding how to improve the design of fingertips for a better dexterous manipulation performance.

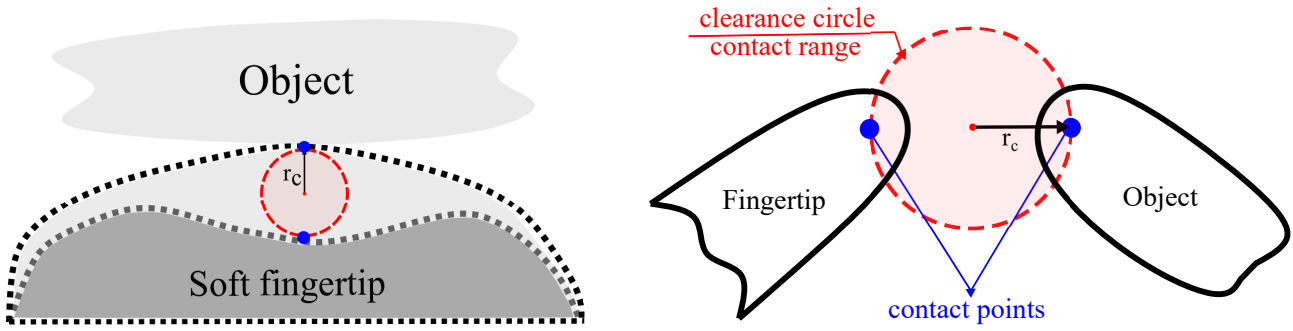


Figure 2.1: Despite it being known that the use of deformable fingertips increases grasp stability, the relationship between compliant fingertips and in-hand manipulation performance is not clear—and has received limited attention in literature. A novel, tractable approach for contact modelling of soft fingertips has been proposed to study within-hand dexterous manipulation performance. **Left:** Soft fingertip deformation model based on approximating interactions as joints with clearances. **Right:** The clearance circle defines an area where the contact between fingertip and object can occur. ©2019 IEEE. Reprinted, with permission, from [LR19]

The relationship between soft fingertips and in-hand manipulation is certainly not well defined as yet, with little work done so far in the area (*e.g.*, [BGD15, ANHD00, CC95]). In this chapter, a novel, tractable approach for contact modelling of soft fingertips has been proposed, for use in the study of in-hand dexterous manipulation. The proposed method is based on a relaxation of the kinematic equivalent of point contact with friction. In this technique, the interaction between fingertips and objects is modelled as joints with clearances (see Fig. 2.1), which are then approximated via affine arithmetic to facilitate computation.

It can be argued that the introduced contact model has similarities with how humans manipulate objects, as our experience shows that rather than exact locations of contact points between objects and fingertips, we rely on contact areas where the interaction can occur for a successful manipulation. In the proposed model, the contact situation between an object and a soft fingertip is not defined as a specific point—as is the case in the traditional soft finger model; instead, I assume that the object can have contact with the soft fingertip anywhere within a given range that is related to the hardness. Without the need for numerous precise inputs, the proposed model has high robustness and fault tolerance, which additionally makes it computationally tractable. These ideas are herein introduced via planar manipulation, using a two-fingered robot hand with fingertips of different hardness and geometry, as a case study to predict reachable workspaces. Numerical and empirical experiments are carried out to study the effects of soft fingertips on manipulation performance.

The rest of this chapter is organised as follows. Section 2.2 explains some basic techniques used in the creation and simulation of the new contact model for soft fingertips. In Section 2.3, the proposed contact model is detailed, describing the simulation framework and experimental setup of a two-fingered robot hand manipulating objects with soft fingertips of diverse hardness. The results from the simulation, including the prediction and experiment results for different object size and different fingertips are presented in Section 2.4. Section 2.5 discusses the relationship between the soft fingertips and the manipulation capability of the two-fingered robot hand from our findings. Finally, Section 2.6 concludes the findings of this chapter and their capabilities for in-hand manipulation.

2.2 Basics

2.2.1 Bilateral Method

By using the bilateration method, the intersection coordinates of two intersecting circles can be calculated by giving their radii and the distance between their centres. In the simulation herein discussed, this method is used to calculate the joint positions and object positions. Another method, called triangulation, has a similar function but depends on angles while bilateration only depends on distances.

Suppose two vectors $\mathbf{p}_{A,B}$ and $\mathbf{p}_{A,C}$ are connecting points A to B and points A to C . Thus, these two vectors can form a bilateration matrix, $\mathbf{Z}_{A,B,C}$, and then $\mathbf{p}_{A,C}$ can be computed as:

$$\mathbf{p}_{A,C} = \mathbf{Z}_{A,B,C} \mathbf{p}_{A,B}, \quad (2.1)$$

where $s_{i,j}$ is the squared distance between points i and j , and

$$\mathbf{Z}_{A,B,C} = \frac{1}{2s_{A,B}} \begin{bmatrix} s_{A,C} + s_{A,B} - s_{B,C} & -4\Delta_{A,B,C} \\ 4\Delta_{A,B,C} & s_{A,C} + s_{A,B} - s_{B,C} \end{bmatrix}, \quad (2.2)$$

with

$$\Delta_{A,B,C} = \pm \frac{1}{4} \sqrt{(s_{A,C} + s_{A,B} + s_{B,C})^2 - 2(s_{A,C}^2 + s_{A,B}^2 + s_{B,C}^2)}. \quad (2.3)$$

$\Delta_{A,B,C}$ is the oriented area of the triangle defined by points A , B , and C (Δ_{ABC}), which can be either positive or negative depending on the orientation of $\mathbf{p}_{A,C}$ relative to $\mathbf{p}_{A,B}$. If C is to the right of vector $\mathbf{p}_{A,B}$, the oriented area is negative; otherwise it is positive. The detailed description of these formulae can be found in [Roj12].

2.2.2 Affine Arithmetic

Affine arithmetic is a self-validated computational model which can alleviate the dependency problem in computations based on intervals [DFS04]. This arithmetic has been used as a computational technique when calculating the soft fingertip model. The dependency problem becomes the main obstacle when using standard interval arithmetic to estimate ranges. The interval is guaranteed to comprise the exact (unknown) value during a computation in standard interval arithmetic, however, it usually calculates an interval much wider than the exact range of the computed function, as it may count each calculation as independent. Following several steps in complex and repeatable calculations, interval ranges are then overestimated. In order to mitigate this problem, affine arithmetic keeps track of first-order correlations between computed and input quantities, while recording a range for each ideal quantity; these correlations are automatically exploited in primitive operations. This supports affine arithmetic to maintain tight estimated ranges after many chained computations, where standard interval arithmetic would suffer error outburst. In affine arithmetic, an ideal quantity x is represented by a first-degree polynomial affine form $\hat{x}$ [SdF03]:

$$\hat{x} = x_0 + x_1\varepsilon_1 + x_2\varepsilon_2 + \cdots + x_n\varepsilon_n. \quad (2.4)$$

where x_0 is the mid value of the affine form; the coefficients x_i are finite floating-point numbers corresponding to partial deviations of $\hat{x}$; and the ε_i are noise symbols which have unknown value, but assumed to lie between -1 to 1.

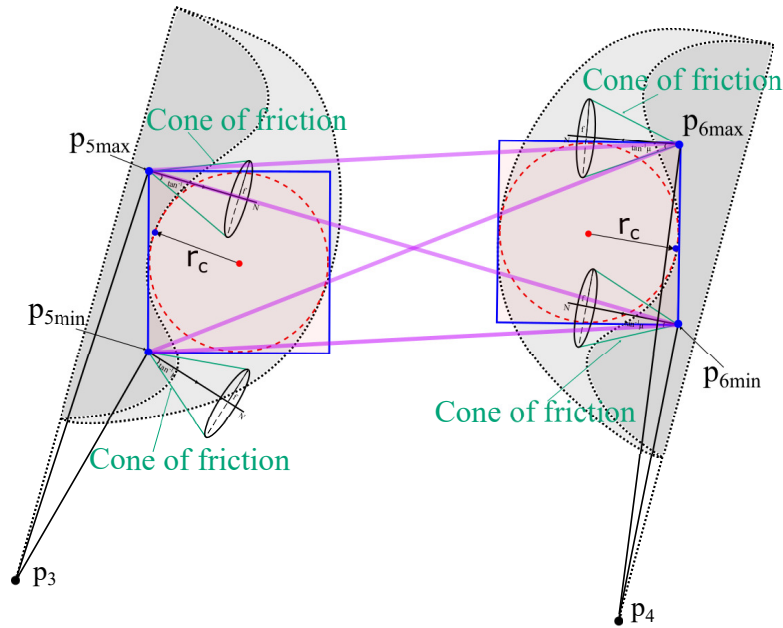


Figure 2.2: Friction cone constraints on deformed soft fingertips. Blue squares indicate the affine arithmetic method to cover the clearance circle which simulate the approximate contact range. Four purple lines indicate the direction of contact forces at each condition. ©2019 IEEE. Reprinted, with permission, from [LR19]

2.3 Methods

2.3.1 Modelling of soft fingertips

The superiority of deformable human fingertips in grasping and manipulation tasks has led to a number of investigations with robot hands employing soft fingertips. Soft fingertips are a more efficient way to maintain comfortable contact than some compliance control strategies [CK89]. Some methodologies have been proposed to investigate the relationship between soft fingertips and in-hand manipulation. For instance, Bullock et al. [BGD15] proposed compliant finger pad designs with different inner solid structures to compare manipulation performance empirically. Arimoto et al. [ANHD00] proposed a geometry-based control model for a two-fingered gripper, but it requires information about mass and has low adaptability to uncertainty. Chang [CC95] determined the kinematic effects of soft fingertips during rolling manipulation by experimental results only.

In this chapter, I propose a new contact model based on a relaxation of the kinematic equivalent of point contact with friction, modelling the interaction between fingertips and objects as joints with clearances rather than ideal instances [Fig. 2.1], and then approximating clearances via affine arith-

metic to facilitate computation [Fig. 2.2]. The kinematic equivalent of a contact type corresponds to a kinematic constraint which defines the constrained motion between two contacting bodies [RD16a]. For rigid fingertips, the contact model can be assumed as point contact with friction and the kinematic equivalent of that is a revolute joint in the planar case [SR83]. Soft fingertips are usually modelled using the soft finger model which is a contact type that idealises a point contact that resists moments along the contact normal due to the large contact area [Sal82]. But this model is inappropriate to model the rolling and deformation effects of real soft fingertips—the contact model for a soft fingertip should not be a single point.

For soft fingertips, the deformation occurs when they are grabbing a rigid object. Our human experience tells us that the brain detects when fingertips are deformed but does not provide information about the precise nature of the deformation. Following this principle, instead of having complex equations to display the exact deformation, we propose an approximate dynamic approach based on the idea of clearances in order to simulate the contact situation and analyse robot hand operability. On the basis of the compliance characteristics of soft fingertips, the contact situation between a rigid object and a soft fingertip is no longer a single point but an area.

In Fig. 2.1 (left), the dark grey area indicates the deformed soft fingertip when grasping a rigid object; as there are no sensors installed on the fingertips, the contact force is unknown, the deformation is unknown as well. In this case, we use a fuzzy theory approach to assume the contact location (blue dots) between a rigid object and a soft fingertip is in a certain area. This flexible area can be seen as equivalent to a joint with clearance in mechanical design. Fig. 2.1 (right) shows the enlarged contact principle of a revolute joint with clearance. The size of the clearance circle is based on the hardness of the fingertip. This model assumes that the contact location between a rigid object and a soft fingertip can be anywhere in the clearance circle (the area in red). Fig. 2.2 presents the contact model in detail, applied to two soft fingertips in planar manipulation, in which the contact area circle (the area in red) is perpendicular to the fingertip link. To achieve a mathematical and computational tractable model, this contact area circle is approximated using affine arithmetic (blue square). Therefore, a single contact point, say p_5 or p_6 , is transformed into an interval whose size depends on the softness of the fingertip.

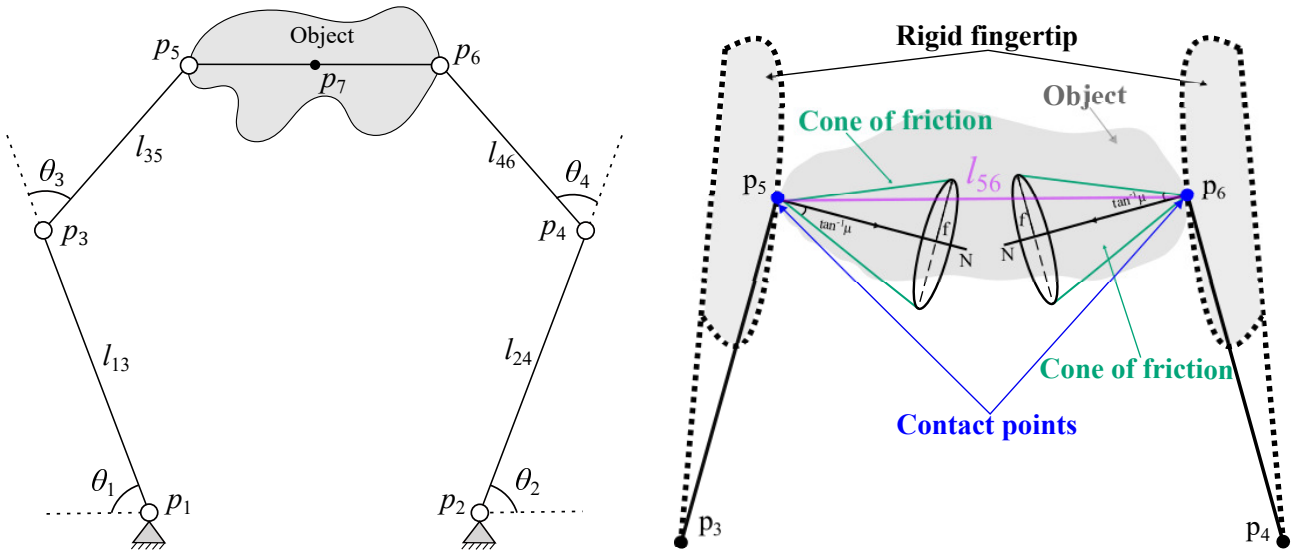


Figure 2.3: **Left:** A two-fingered robot hand with rigid fingertips can be modelled as a six-bar mechanism with revolute joints when grasping a rigid object. **Right:** Friction cone constraints for rigid fingertips. ©2019 IEEE. Reprinted, with permission, from [LR19]

2.3.2 Simulation Model

For a rigid fingertip, the kinematic equivalent of point contact with friction is a revolute joint in the planar case, so the object grasping system by a two-fingered gripper is similar to a six-bar mechanism with revolute pairs [Fig. 2.3(left)]. Therefore, in simulation, this contact model is represented as an ideal revolute joint plus a friction cone. The cone of friction is a method to combine the coefficient of friction and the angle of friction [Fig. 2.3(right)].

The simulation to compute the reachable workspace of a rigid object manipulated by a two-fingered robot hand with rigid fingertips assumes that the contact points between the fingertip and the object are fixed during the movement, what is called precision manipulation in the dexterous manipulation literature [RD16b]. According to the notation of Fig. 2.3, this simulation begins by calculating via bilateration p_3, p_4 and p_5 from a given size of the gripper ($l_{13}, l_{35}, l_{24}, l_{46}$), the angle limits of joints p_1, p_2 and p_3 ($\theta_1, \theta_2, \theta_3$), and the location of the centres of the palm joints (p_1 and p_2). Then, from the object size, represented by length l_{56} , valid values for p_6 and θ_4 are computed.

This is a reliable and much quicker way to find all feasible values for p_6 instead of working out p_6 by using θ_4 . Then several constraints are applied to the simulation to approach the real model. Since the gripper is modelled as a closed linkage, the contact forces must be collinear. This means that for

each feasible p_6 the line l_{56} must lie into the friction cones of both fingertips, in other words, the purple line l_{56} in Fig. 2.3 (right) should be inside both friction cones (depicted in green). The friction coefficient is conservative, using the silicone on plastic coefficient (an estimated value of 1 [Obe12]) as parameter. This creates a friction cone of 0.785 rad about the axis of the normal reaction of the contact point by using $\mu = \tan\lambda$, where μ is the coefficient of friction and λ is the angle of the friction cone.

Other constraints are also used to avoid the contact point moving to the opposite side of the fingertip. For instance, when calculating the included angle between the fingertip link and the line connecting two contact points, if this angle is smaller than the friction cone, then it passes the constraint. As the contact points are simulated as revolute joints, the simulation cannot tell whether the object is contacting the front side of the fingertip or the back side. By finding the sign of the area defined by $\triangle_{456}$ this problem is solved.

For the case of soft fingertips, most of the constraints to compute the reachable workspace need to change since p_5 and p_6 are no longer single points [Fig. 2.2]. For the friction cone, the rigid model uses the line connecting p_5 and p_6 to determine whether it is a valid configuration. However, a single line cannot connect the interval associated to the relaxation of p_5 and p_6 as revolute joints with clearance. It can only connect single points in the interval. The friction cone is then defined using the left vertices of the interval related to p_5 (p_{5min} and p_{5max}) and the right vertices of the interval related to p_6 (p_{6min} and p_{6max}). This way, four lines (purple lines in Fig. 2.2) are defined between these four points (p_{5min} , p_{5max} , p_{6min} , p_{6max}) to determine valid configurations. For each line, if it is included in the friction cone of both vertices, a success is counted. Then, for each set of four lines for a given configuration, the interval p_6 is considered feasible if there exists at least one success.

2.3.3 Experimental Setup

To obtain the object workspace experimentally, a two-fingered robot hand with different softness in the fingertips was developed as shown in Fig. 2.4. All experiments were performed horizontally. The two-fingered robot hand is adapted to be fully actuated from the underactuated designs of the Yale

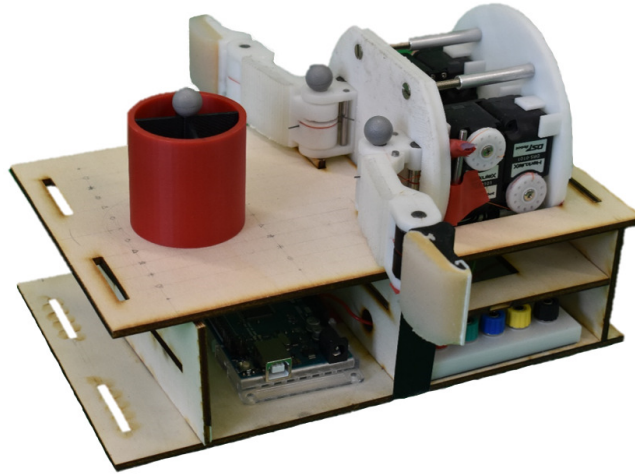


Figure 2.4: Experimental setup to study the implications of soft fingertips during in-hand manipulation. The diameter of the red cylinder is 50mm. ©2019 IEEE. Reprinted, with permission, from [LR19]

OpenHand project. The original OpenHand has a block (hard stop [MOD13]) designed at the distal joint to prevent the fingertip over bending. The developed robot hand eliminates the hard stop to have a larger range of rotating angles for θ_3 and θ_4 . Each finger has two revolute joints that are driven by two Herkulex smart actuators (DRS-0101) through wire controls. The fingertip was redesigned to be changeable by slotting different designs using a single fingertip base, as exemplified in Fig. 2.5. Motion cameras (OptiTrack Flex 3) were used to record the object movement. The vertical board underneath the object platform is removable. When it is removed, the platform can be bent to check whether the hand has grasped the object properly or not.

Five different fingertips with different hardness were made to manipulate seven different sizes of cylinders. The size of the cylinders ranges from 10mm to 130mm with an increment of 20mm. Table 2.1 lists the details of these 5 fingertips and Fig. 2.5 shows the appearance overview of them. Type 1 is made of ABS which is the hardest fingertip among the 5 types implemented and can be seen as a rigid fingertip. A silicone tape layer is added on the rigid and urethane fingertip surface to reach the similar friction coefficient as the silicone fingertip. Type 2 - type 5 are used to test soft fingertip conditions. The softness is increased from type 1 to 5 which is tested by a type C durometer. The thickness of type 5 (3cm) is different from the other four (0.7cm). The possible maximum deformation of the fingertips was measured using a caliper at the middle grasping position when the gripper grasped a 50mm cylinder tightly; it was determined that the deformation of fingertips type 2, 3, 4, and 5 is

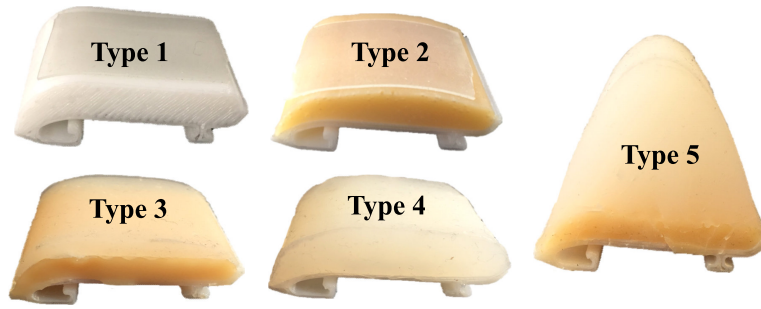


Figure 2.5: Different fingertip designs on the basis of different material with different softness and depth. ©2019 IEEE. Reprinted, with permission, from [LR19]

Table 2.1: Fingertip parameters

Type	Material & Softness	Silicone Depth	Fingertip Depth
1	ABS with silicone tape (Shore C-88)	0.4mm	0.7cm
2	Urethane Vytaflex-30 with silicone tape (Shore C-75)	0.4mm	0.7cm
3	Urethane Vytaflex-30 with a layer of silicone Ecoflex-10 (Shore C-30)	3mm	0.7cm
4	Silicone Ecoflex-10 (Shore C-23)	5.5mm	0.7cm
5	Type 3 with a thicker layer of silicone Ecoflex-10 (Shore C-17)	23mm	3cm

approximately 0.1cm, 0.2cm, 0.3cm, and 1cm, respectively.

2.4 Results

2.4.1 Simulation

The final object workspace is plotted based on p_7 which is the centre point of the cylinder. For soft fingertips, simulation results were computed using the affine arithmetic method which the representation is a quadrangle. Therefore, a group of quadrangles is used to present the soft fingertips workspace [Fig. 2.6] instead of the scattergram used to present the rigid fingertip workspace. In general, mirrored results will be plotted to include all possibilities, but for Fig. 2.6 mirrored results were removed for clearer demonstration. For each configuration, there are four sets of angles to test the friction cone. If all four sets are in the friction cone condition, the quadrangle is yellow; if three sets of angles are in the conditions, the quadrangle is red; the quadrangle is green when two sets of angles are inside the

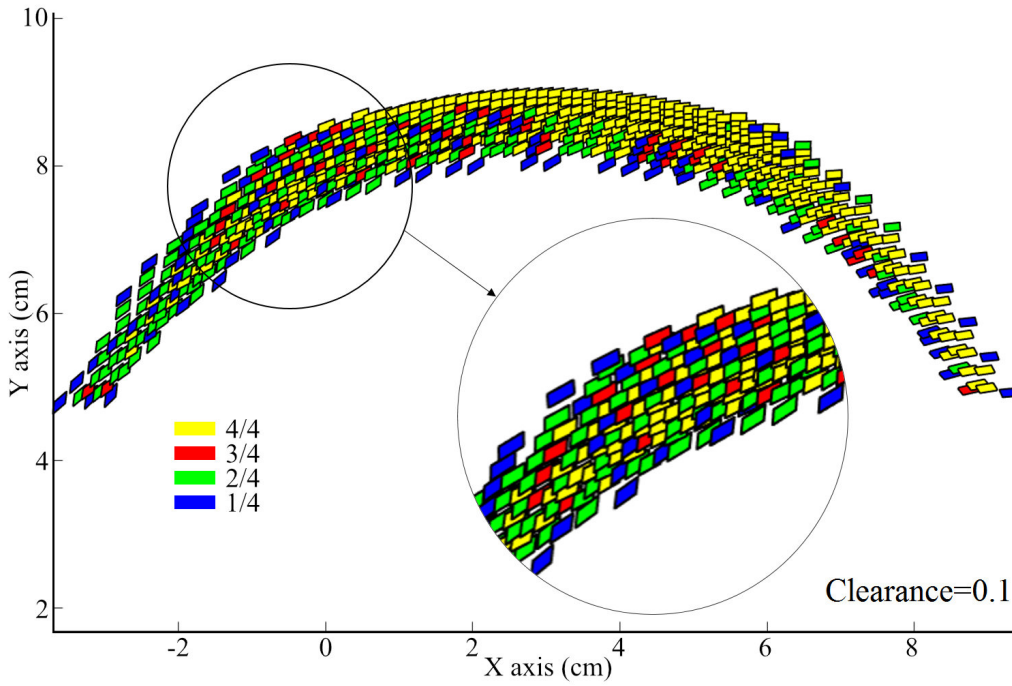


Figure 2.6: The affine workspace of fingertip with 0.7cm depth and maximum deformation (clearance) of 1mm. The colour means the rate of 'success' for each set of the lines of the friction cone test. (*i.e.* a higher rate of success indicates higher stability). A zoomed in detailed display is shown. ©2019 IEEE. Reprinted, with permission, from [LR19]

friction cones; if only one set of the angles is in the friction cone condition, the quadrangle is blue. The colour thus illustrates the 'success' rate of each set of the lines which indicates the stability of the grasp at that particular position.

Fig. 2.7 illustrates the plotted workspaces of the 50mm cylinder manipulated by rigid fingertips and the configurations of the two-fingered robotic hand at some boundary points. Fig. 2.7 (top-left) is the simulation workspace calculated using the rigid contact model. Each dot represents one feasible position which, subsequently, correspond to different finger configurations. Nine critical boundary points have been selected to show the configuration of the robotic hand [Fig. 2.7 (bottom-left)] which give a clear understanding of how the manipulated object moves within the gripper. Fig. 2.7 (top-right) shows the experimental workspace of the cylinder manipulated by rigid fingertips (type 1). Fig. 2.7 (bottom-right) demonstrates the same configuration setup as the simulation on the left and the corresponding object locations are highlighted in the top right workspace (orange dots). In the experiments, the cylinder was rolling during the movement in order to balance out the bending force of the fingers. Once the collinear forces between the two fingertips are beyond the friction cones,

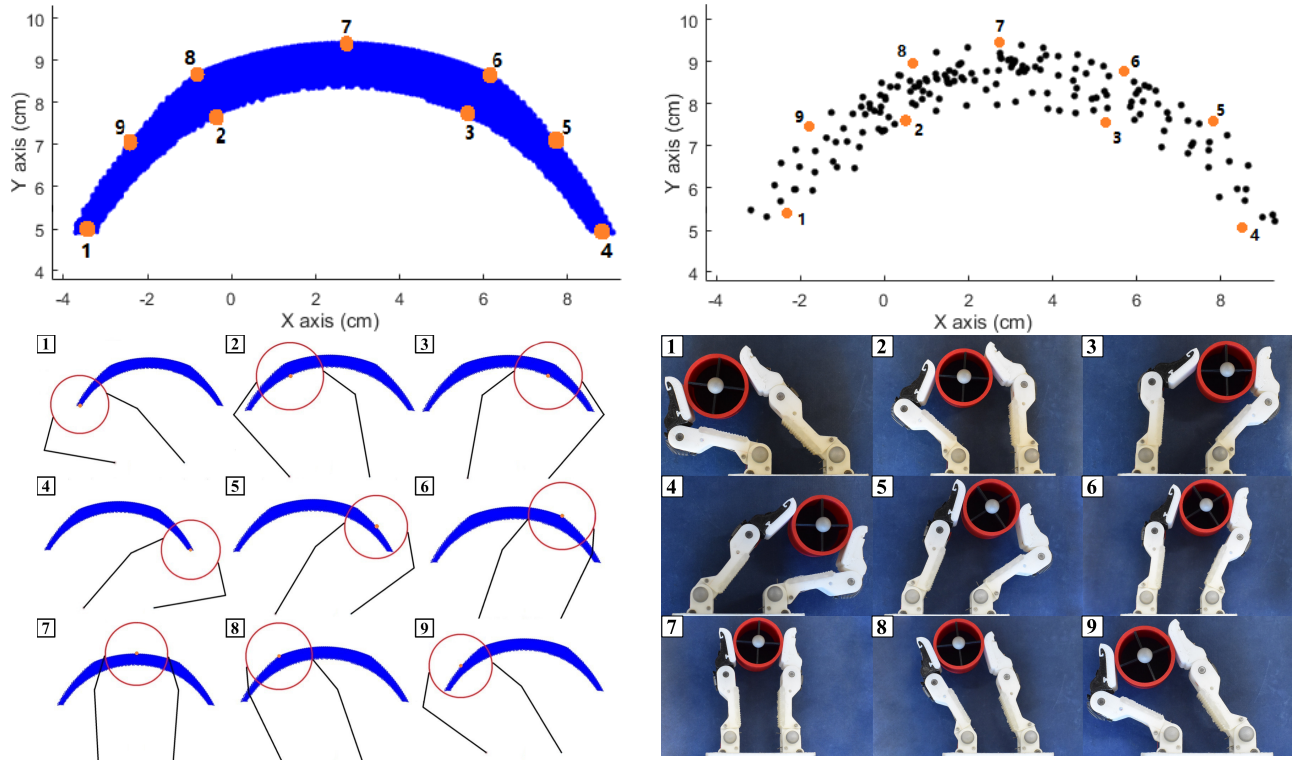


Figure 2.7: Results of rigid fingertips. **Top-left:** 50mm cylinder's planar reachable workspace simulated with nine boundary points highlighted. **Bottom-left:** The corresponding configurations of this two-fingered robotic gripper at each boundary point. **Top-right:** Experimental reachable workspace for the 50mm cylinder. **Bottom-right:** The same boundary configurations as bottom-left performed experimentally. ©2019 IEEE. Reprinted, with permission, from [LR19]

slippage occurs.

The size of the object workspace corresponds to the robotic hand operability. In order to optimise the operability, the robotic hand should have a larger workspace. The AlphaShape method [EKS83] is used to calculate the area of the object workspace by using all feasible p_7 . AlphaShape is a generalisation of the convex hull computation of a finite set of planar points; it corresponds to a family of piecewise linear simple curves in the Euclidean plane that can capture notions of *fine shape* and *crude shape* of a point cloud. For rigid fingertips, the simulation results consist of points, so the area of the workspace can be calculated directly. However, for soft fingertips, the results are affine workspaces [Fig. 2.6] which are made up of quadrangles, not points. An additional step is required to transfer the quadrangle into points by plotting the vertexes of it and then applying AlphaShape on this result.

Fig. 2.8 illustrates the AlphaShape area vs the size of the cylinder which is manipulated by different fingertips. Four sets of fingertips with different hardness and 13 different sizes of cylinders were

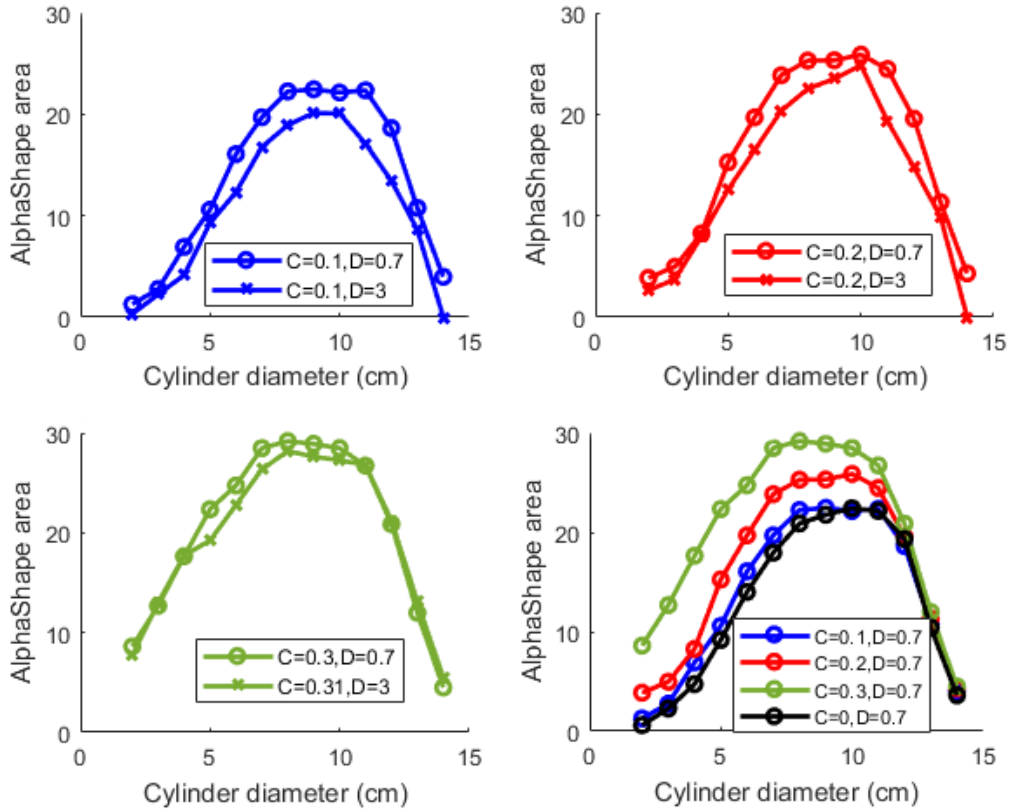


Figure 2.8: Simulation AlphaShape area vs different sizes of object by different types of fingertips. C indicates the clearance which is the size of the deformation and D indicates the depth of the fingertip. Units: *cm*. ©2019 IEEE. Reprinted, with permission, from [LR19]

tested. In the simulation, the clearance indicates the hardness of the fingertip (*i.e.*, the larger the clearance the softer the fingertip). It is assumed that the depth of the fingertip is not affected by the size of the clearance which means that while the depth of the fingertip increases, the hardness of the fingertip remains the same (top two: for different D , the C remains the same for each set of fingertip). This assumption is made to check how the depth of fingertips effects the workspace. In reality, fingertips may get softer when increasing the depth. Fig. 2.8 (bottom left) presents this scenario by increasing the size of clearance slightly. Fig. 2.8 compares the area of workspace on different fingertips including the rigid fingertips (bottom-right) and different depth of fingertips. The clearances change from 0.1cm to 0.3cm and the depth of the fingertips are 0.7cm and 3cm.

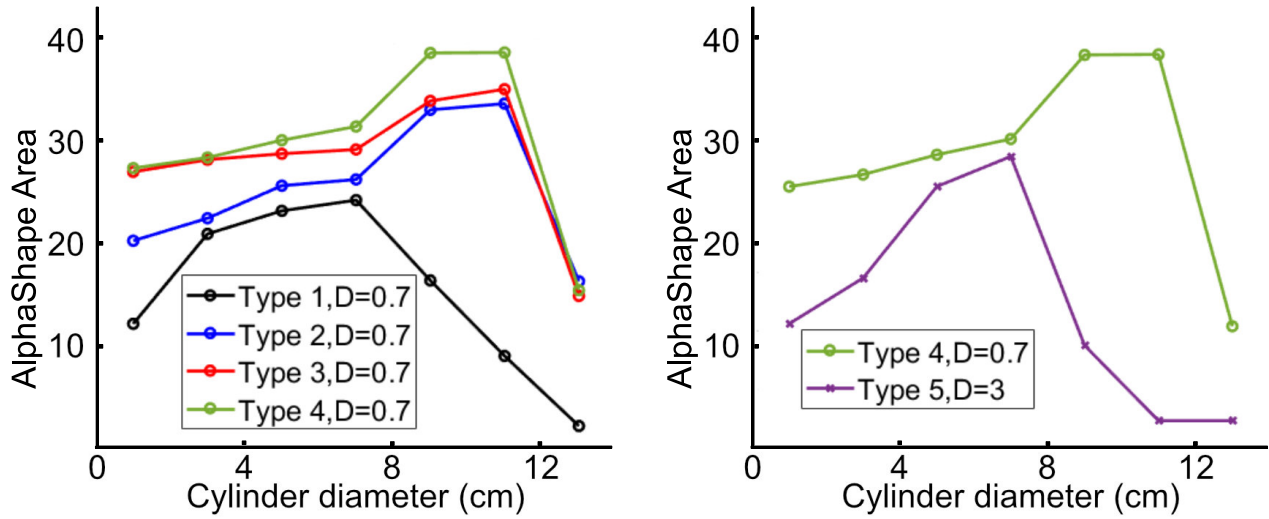


Figure 2.9: Experimental AlphaShape area vs different sizes of cylinders manipulated by 5 types of fingertips. ©2019 IEEE. Reprinted, with permission, from [LR19]

2.4.2 Experiments

For the experiments, seven different sizes of cylinders were tested using 5 different softness fingertips. Fig. 2.9 shows the experimental AlphaShape area results. The black line shows the results of rigid fingertips (type 1) which have the smallest workspace. The blue line indicates the urethane fingertips (type 2) which has a little improvement between cylinder size from 10mm to 70mm, however, also indicates a significant improvement on cylinder size 90mm and 110mm; this trend occurred on the remaining two fingertips (type 3 and 4). The left subfigure illustrates that with the same fingertip depth, the softer fingertip has a better manipulation workspace for different sizes of cylinders. The right subfigure shows the AlphaSpace area of two fingertips (type 4 and type 5) with different fingertip depth (0.7cm and 3cm). Type 5 fingertip has less AlphaShape area on all of the sizes of the cylinders, particularly for cylinder size 90mm and 110mm.

Fig. 2.10 illustrates the shape of the workspace for both simulation and experiments. It compares the workspace for three different hardness fingertips with the 70mm cylinder. The left figure shows the simulation workspace and the clearance change from 0.1cm to 0.3cm. The right figure is the experimental workspace of type 2, 3, and 4 fingertips. Both simulation and experiments show that the workspace increases when the softness of the fingertip increases.

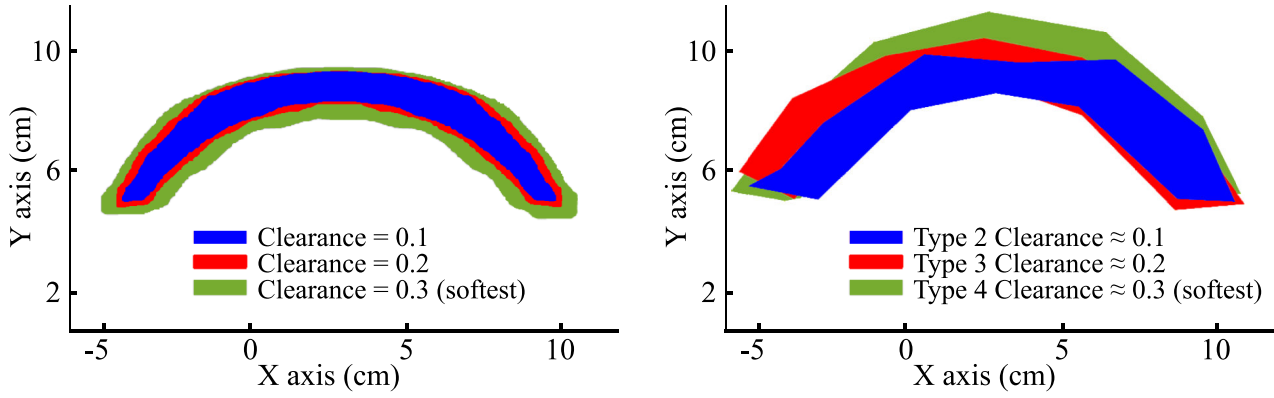


Figure 2.10: **Left:** The numerical 70mm cylinder’s reachable workspaces manipulated with three different hardness fingertips. **Right:** Experimental results for the same cylinder manipulated by 3 types of fingertips. ©2019 IEEE. Reprinted, with permission, from [LR19]

2.5 Discussion

The trend of type 1 fingertip and type 5 fingertip is different from others in Fig. 2.9. According to the appearance of the fingertip [Fig. 2.5], the design of the fingertips follows a curved shape; as rolling occurred in the experiments, for some boundary points, objects were grasped by the extreme area of these shapes (i.e., the tip of the fingertips), which is steep. Because of the lack of softness of the type 1 fingertip, the objects have more chance to escape when grasp around the tip, and large objects have higher possibility to have contact with that area. In the case of the type 5 fingertip, objects have less space for rolling, and this worsens when the size of the object increases.

By contrasting Fig. 2.8 and Fig. 2.9, the overall experimental AlphaShape area is greater than the overall simulation AlphaShape on account of rolling. The experimental trends are much the same as the simulation trends with a shift on peak position. According to my simulation results, the maximum workspace occurs when the cylinder is in the range 80mm to 100mm [Fig. 2.8]. In the experimental case, the maximum workspace occurs when the cylinder is in the range 90mm to 110mm [Fig. 2.9]. The main reason that may cause this difference is the position of the contacts. In simulation, the contact points correspond to the intersection points between diameter and the circumference (and from it the clearance circle is built), which means that the contact distance equals to the diameter of the cylinder. However, in the experiments, the contact distance can be less than the diameter of the cylinder due to rolling, which means that the centre of the cylinder is not aligned with the contact points. This causes a shift to the right in the trend of experimental results.

Fig. 2.10 shows the workspace has improvements at both ends, as some bad rolling occurs at the fingertip during the manipulation at boundary configurations, *i.e.* the contact point moves from the middle of the fingertip to the top. Moreover, the number of data recorded for the experimental results is small when compared to the number of samples used in simulation. This decreases the accuracy of AlphaShape area values from experiments. When slippage occurs, the cylinder will be placed at the starting position which will be different from the rolling position. For type 2 rigid fingertip, it is more likely to have slippage, which causes the narrow workspace at the middle. During the experiments, the object starts from centre to right then back to centre and move to left. As there are many uncertainties in the experiments, the accuracy of the results for the left parts is not as good as the right parts in Fig. 2.10.

According to the AlphaShape area comparison results, the simulation shows that the softer is the fingertip, the larger is the workspace until a certain limit—see Fig. 2.8 (bottom-left) for instance. This is indeed confirmed by the experimental results. Back to the fingertip table (Table 2.1), the type 5 fingertip is slightly softer than the type 4, both made of the same material. In theory, the manipulation workspace of the type 5 fingertip should be better than the type 4 outcome. However, the results are completely opposite where type 5 fingertip has less AlphaShape area on all of the cylinder sizes, particularly for cylinder size 90mm and 110mm. This shows that, given material, there exists a trade-off between the depth of the fingertip and its softness to improve robot hand operability.

The proposed model of soft fingertips gives satisfactory results on estimating the object workspace manipulated by a two-fingered robotic hand. These results express the correct workspace area tendency across object size and fingertip design; they also demonstrate that the robotic hand performs better on objects which have a similar size to it. The model requires a small quantity of input parameters which allows it to have high compatibility to other robotic hand designs and not just restricted to two-fingered robotic grippers. Simplicity and reduced computational costs are other advantages of the proposed model, in which a designer can analyse multiple robotic hands in a short period of time without special expertise.

2.6 Conclusion

The proposed model gives a simple and elegant way to assess the dexterous manipulation ability of a gripper. It can simulate the end effector positions based on the parameters of soft fingertips, rather than assuming the manipulated object's position to determine the resulting deformation of fingertips. The proposed model was used to find the reachable workspace of a two-fingered robot hand. The ideas were introduced using a planar manipulation setting to facilitate discussion and experimentation. The results have shown that to increase the robot hand's workspace for in-hand manipulation; a fingertip needs to be soft and thin; designers must resolve this trade-off. Furthermore, soft and thin fingertips may behave as a rigid contact if the object touches the corresponding support. Although the proposed simulation framework results do not demonstrate complete accuracy in prediction as expected given the simplifications and assumptions made, the study demonstrates that this numerical analysis can be used to solve the mentioned conundrum regarding softness and thickness.

A limitation of the proposed contact model is that it is impossible to simulate different shapes of the fingertip or object geometry as the model is based on point contact with friction that does not consider curvature information. The other limitation of this current model is that only planar manipulation has been studied; indeed, the overall approach can be leveraged to study spatial manipulation by modelling the soft fingertips as spherical joints with clearance and extending the use of affine arithmetic to maintain tractability. This extended spatial contact model has been analysed with a two-fingered robot hand, composed of four-DOF fingers [SLC⁺]. Furthermore, keeping the initial grasp condition for the proposed soft fingertip model has been used as a constraint to solve the redundancy of high-DOF robot fingers and obtain an exact solution for the in-hand manipulation problem.

Overall, the role of soft fingertips for in-hand manipulation has been studied in this chapter. The proposed approach for contact modelling of soft fingertips has helped find out the design trade-off between hardness and depth in soft fingertips when designing robot hands, especially for better manipulation performance. Results show that fingertips need to be soft and thin to increase the robot hand's workspace for in-hand manipulation. Moreover, this proposed model of soft fingertips can give an estimation of the object workspace within a short period of time without special expertise.

Chapter 3

Active Surfaces for In-Hand Manipulation

This chapter is adapted via ©2020 IEEE. Reprinted, with permission, from [Q. Lu, A.B. Clark, M. Shen, and N. Rojas, "An Origami-Inspired Variable Friction Surface for Increasing the Dexterity of Robotic Grippers," IEEE Robotics and Automation Letters (RAL), 2020] and [Q. Lu, L. He, T. Nanayakkara, and N. Rojas, "Precise In-Hand Manipulation of Soft Objects using Soft Fingertips with Tactile Sensing and Active Deformation," Proceedings of the 2020 IEEE International Conference on Soft Robotics (RoboSoft)].

Abstract

Human fingertips can get wrinkles when inserted into the water for a while. From the view of biology, water is much smoother than air. Therefore, those wrinkles help to increase the fingertip friction for better underwater performance. Human hands also have the ability to firmly grip object surfaces, as well as slide over object faces. This aspect aids the enhanced manipulation of objects within the hand without losing contact. The variable friction principle analogy to the human finger pad has been described by Spiers *et al.* [SCD18]. They discussed that human finger pads could perform sliding via light contact on the epidermal layer and pivoting via heavier touch with compression of glabrous fat. This behaviour was then emulated via a suspended low friction surface. An object can slide on a low friction surface and rotate on high friction surface to enhance the in-hand manipulation performance. By adding an actuator to control the suspended low friction surface, this becomes an active surface. In this chapter, two types of active surfaces of fingers have been proposed to find out their capabilities

for both grasping and in-hand manipulation. Firstly, a novel origami-inspired thin surface for robotic fingers which allows obtaining the benefits of variable friction for dexterity in a much more compact setting has been proposed in Section 3.1. Additionally, an active soft fingertip has been proposed to enhance the dexterity of robot hands via the dual-functionality with tactile sensing, and active shape-changing in Section 3.2; such that pressurised air cavities act as soft tactile sensors to provide closed-loop control of fingertip position and avoid object's damage, and pneumatic-tuned positive-pressure deformations act as a localised soft gripper to perform additional translations and rotations.

3.1 An Origami-Inspired Variable Friction Surface

3.1.1 Introduction

Due to their mechanical simplicity, low cost, reliability, and low control complexity, two-fingered low-degree-of-freedom robot grippers are prevalent in industrial tasks, especially for pick and place operations [GGL⁺17]. However, robotic research has long been interested in not only the ability to grasp, but also the in-hand manipulation of a varied set of objects in order to improve the dexterity and applicability of robots. Many efforts have indeed been made to replicate the functionality of the human hand, the best example of a dexterous system. Well controlled anthropomorphic robotic hands have been developed [UKO10, CDIM04, SWUL17], which are good at performing complex hand gestures. However, these systems have shown significant limitations and challenges for in-hand manipulation in unstructured environments due to over-constrained structures, uncertainties, and compound errors and failures in actuation and sensing. Improving the in-hand manipulation ability of robot grippers without increasing their design and control complexity has since become an active area of research in recent years [RMD16, BDR17, DRP⁺14, CDMS⁺15, CDLR18].

The most common in-hand manipulations for robot grippers that have been studied are sliding and rotating operations. Chavan-Dafle *et al.* achieved spinning point contact and firm contact by changing the finger-object contact geometry and varying the gripping force [CDMS⁺15, CDLR18]. Objects reorient about the axis between the contact points from a horizontal pose to a vertical pose due to gravity, however with limited reorientation direction and range. In-hand reorientation of grasped ob-

jects has been also demonstrated using tactile feedback [WCRL17]. Alternatively, adding or changing components of existing hand mechanisms is a common method for improving robot gripper abilities. The GR2 gripper increased the object range of motion by introducing an elastic pivot joint between the two fingers [RMD16], and Terasaki *et al.* designed a rotation mechanism attached to the tips of a parallel two-fingered gripper combined with a motion planning system to increase dexterity [TH94]. Recently, Yuan *et al.* placed active driven rollers to the fingertips to achieve full six degree of freedom nonholonomic spatial motion.

In human hands, the soft and pulpy tissue of the fingertip can comply around the shape of objects, gripping them firmly when a force is applied. The use of soft material on gripper fingertips provides a compromise between compliance and strength [CMP⁺08], and has been shown to provide a larger workspace and adaptability [LR19]. With a more rigid, smooth contact however, sliding can be achieved more easily as the system behaves as an inclined plane. In fact, friction also plays an important role in object manipulation [TLC07]. The frictional properties of biological skin has been investigated to show that the effects of these parameters are essential for feedback and forward gripping control systems. Comaish and Bottoms for instance showed that the coefficient of friction between the skin and various materials is not portrayed by the simple laws of friction, but by a complex viscoelastic relationship, especially under hydrated and lubricated environments [CB71]; while Adams *et al.* concluded that the human finger pad contact frictions are complex, and mainly influenced by fingerprint ridges [AJL⁺13]. By assuming the surfaces of the fingerprint ridges as thin water films, these last authors observed a decrease in friction at larger sliding velocities.

Spiers *et al.* described a variable friction principle analogy to the human finger pad, and presented a passive and active variable friction robot finger design to achieve a similar effect [SCD18]. They discussed that human finger pads can perform sliding via light contact on the epidermal layer and pivoting via heavier touch with compression of glabrous fat. This behaviour was then emulated via a suspended low friction surface, where an object can slide on a low friction surface and rotate on high friction surface. This variable friction finger design had the ability to change the friction mode and achieve isolated translation and rotation using a simple two-fingered two-degree-of-freedom gripper. Following this principle, in this section a novel origami-inspired thin surface for robotic fingers has been proposed which allows obtaining the benefits of variable friction for dexterity in a much more

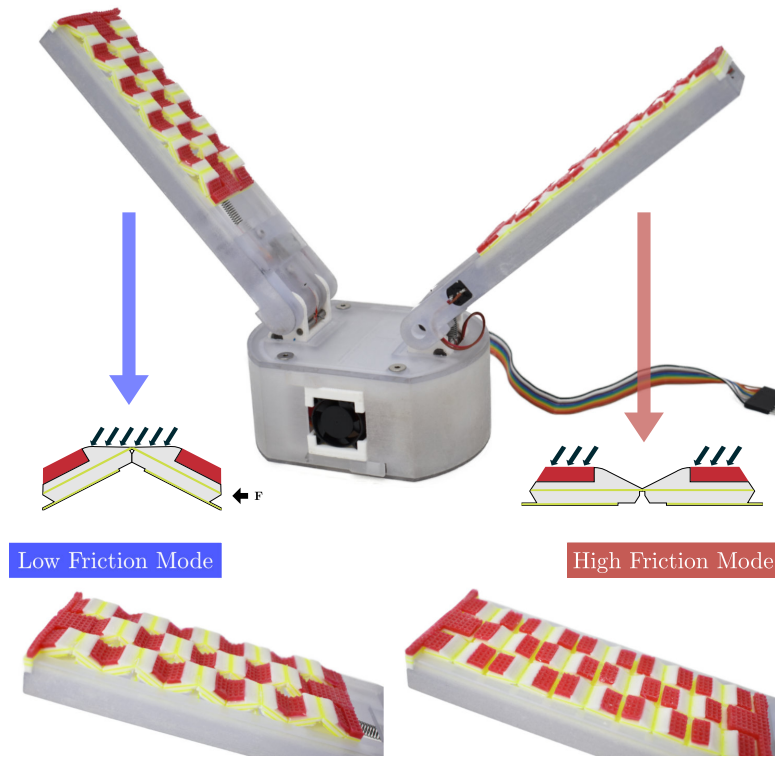


Figure 3.1: Two-fingered two-degree-of-freedom gripper with fingers using the proposed origami-inspired variable friction (O-VF) surface. The controlled states of low friction (left finger) and high friction (right finger) are depicted, demonstrating the varying contact surfaces (black arrows). ©2020 IEEE. Reprinted, with permission, from [LCSR20].

compact setting.

The introduced origami-inspired variable friction (O-VF) surface, based on a deformation-limited mountain/valley fold structure, exposes two different contact surfaces (materials) using a single on-off actuator. Fig. 3.1 shows the proposed concept and a two-fingered two-degree-of-freedom gripper with fingers equipped with O-VF surfaces. Thanks to the possibility of controlling states of low and high contact friction, the fingers of the robot hand can either slide over objects or firmly grasp them, similar to a human finger, without increasing the complexity of the control problem significantly. In Section 3.1.2, the design of the novel origami-inspired variable friction surface has been presented, and the design parameters and required folding force have been analysed. I then present the implementation of multiple prototypes with various design parameters, and evaluate the in-hand manipulation (translation and rotation) performance of the developed O-VF surfaces with objects of different size and shape (Section 3.1.3). Finally, I discuss the experiment results in Section 3.1.4, and conclude the section in Section 3.1.5.

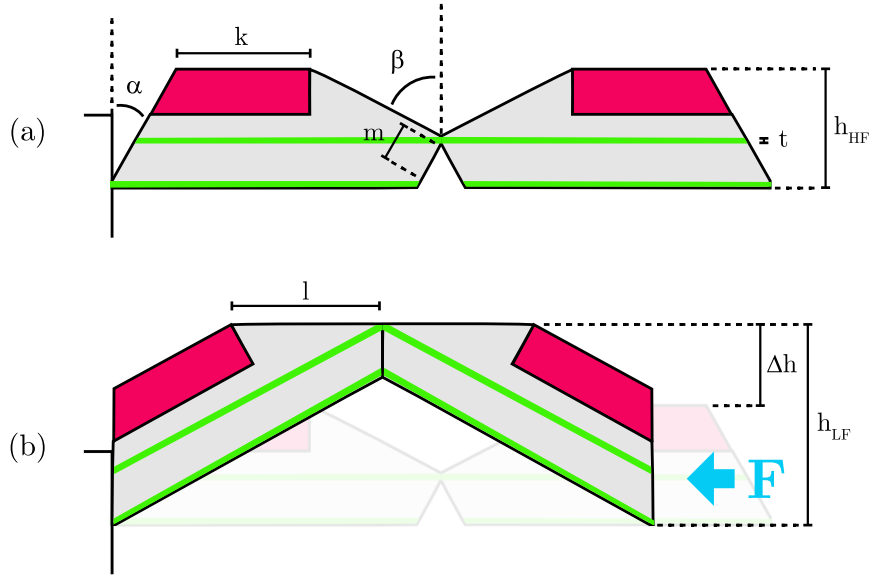


Figure 3.2: Specifications of the folding pattern, defining the area ratio of variable friction surfaces and change in thickness between modes: **(a)** high friction and **(b)** low friction. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

3.1.2 Design and Numerical Analysis of O-VF Surface

Using origami folding processes, complex robots can be fabricated by simple approaches [RT18]. Due to the diversity of origami patterns, these folding processes create a large number of potential possibilities. For instance, the Mirura-Ori pattern allows the entire structure to be folded or unfolded in two directions [Miu85] using a single motion. Alternatively the Kresling Crease pattern, which resembles a chiral tower, combines longitudinal and rotational motion simultaneously, similar to a screw motion [Kre12]. This O-VF surface design is based on a deformation-limited accordion pattern, which allows for the changing of friction modes using only one actuator. The detailed design process of this structure is shown next.

To allow for a variation in friction, and due to the lack of single materials with easily variable friction, the finger contact surface had to contain both a low friction component and a high friction component. By altering the configuration of the surface structure, the exposed component would act as the current overall friction of the surface. To allow for this, a deformation-limited accordion fold structure was proposed, where an angular change of the surface raised the active friction component, whilst preventing contact with the alternate friction component. The working principle of this design can be

seen in Fig. 3.2, where under the compression of a force the structure folds up to a pre-defined limit, changing the outer-most face in contact with a grasped object.

Parametric design

The folding structure was defined in a parametric form, allowing for the variation of the structure based on the desire of the user. The variables that define the topology, detailed in Fig. 3.2, are the length of the low friction area, l , and the length of the high friction area, k , which is defined as a percentage of l as $k = Rl$. The folding angle is also pre-defined, α , as the bending angle required to transition between friction modes. To ensure a flat surface is achieved after folding, and the low friction offset angle (β) is defined as well, such that $90^\circ = \alpha + \beta$.

The thickness of the folding layers of the structure, t , depends on the strength and flexibility of the selected material. To prevent the structure from over-folding, limiting faces has been implemented, defined by length m , as indicated in Fig. 3.2, which prevents the structure from excessive folding due to their contact once folded. Fig. 3.2 shows a single folding unit of the surface, where the number of units in one surface (the pattern density) is represented by N . The change in thickness of the overall structure between the friction modes, Δh , is defined as $\Delta h = h_{LF} - h_{HF}$, where h_{HF} is the thickness in high friction mode and h_{LF} is the thickness in low friction mode. It can be verified via trigonometry that:

$$h_{LF} = (Rl \sin \alpha + \frac{h_{HF}}{\cos \alpha}) \text{ and}$$

$$h_{HF} = 2t + l \sin \alpha + m \cos \alpha.$$

Here can see the Δh is related to α , l , R , t , and m , where the minimum value of the thickness of the folding layers t is dependent on the 3D printer resolution and the minimum limiting face m size required to prevent over bending. For this proposed design, these two parameters have been considered as constants and the values have been selected that give a reduced thickness and a reliable performance with $t = 0.3$ mm, and $m = 2$ mm. I analysed the relationship between the rest of the parameters and the change in thickness of the overall structure between friction modes, with results shown in

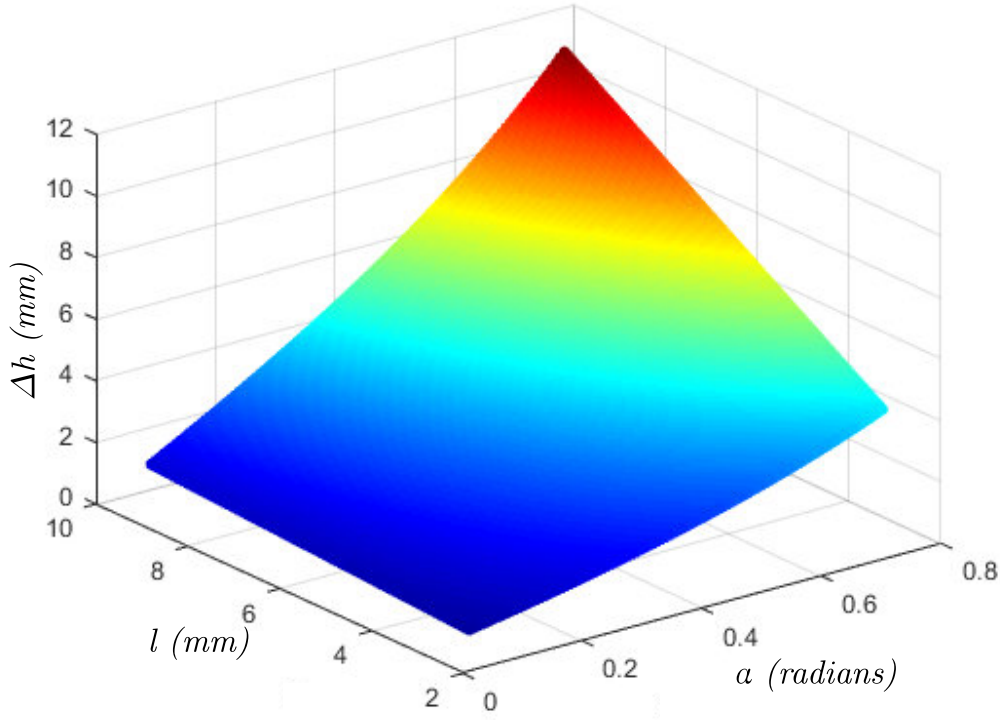


Figure 3.3: Surface plot showing the relationship between the length of low friction area (l), the folding angle (α), and change in thickness of the overall structure between friction modes (Δh). ©2020 IEEE. Reprinted, with permission, from [LCSR20].

Fig. 3.3. Further constraints have been applied on the parameters due to the manufacturing capability and the entire surface length, resulting in α set between 0.175 and 0.785 radians and l between 3 and 10 mm. From Fig. 3.3, it can be seen that a smaller value for α and l give the minimum change in overall height between friction modes.

Material selection

Knowledge of the stress experienced when folded was required to ensure the elastic limit of the material composing the joints was not exceeded, causing permanent deformation of the structure, thus allowing the structure to revert to its previous unfolded state when deactivated. To calculate this stress, finite element analysis was performed through Solidworks Simulation for both the material Acrylonitrile Butadiene Styrene (ABS) and Thermoplastic Polyurethane (TPU), with rough yield strengths of 39 MPa and 8.6 MPa, respectively [Ult18], as the design was intended to be easily 3D printed by a common, single nozzle, desktop 3D printer. The results showed a maximum von Mises stress of 540 MPa for ABS, and 4.6 MPa for TPU. Had the structure been printed out solely of the significantly

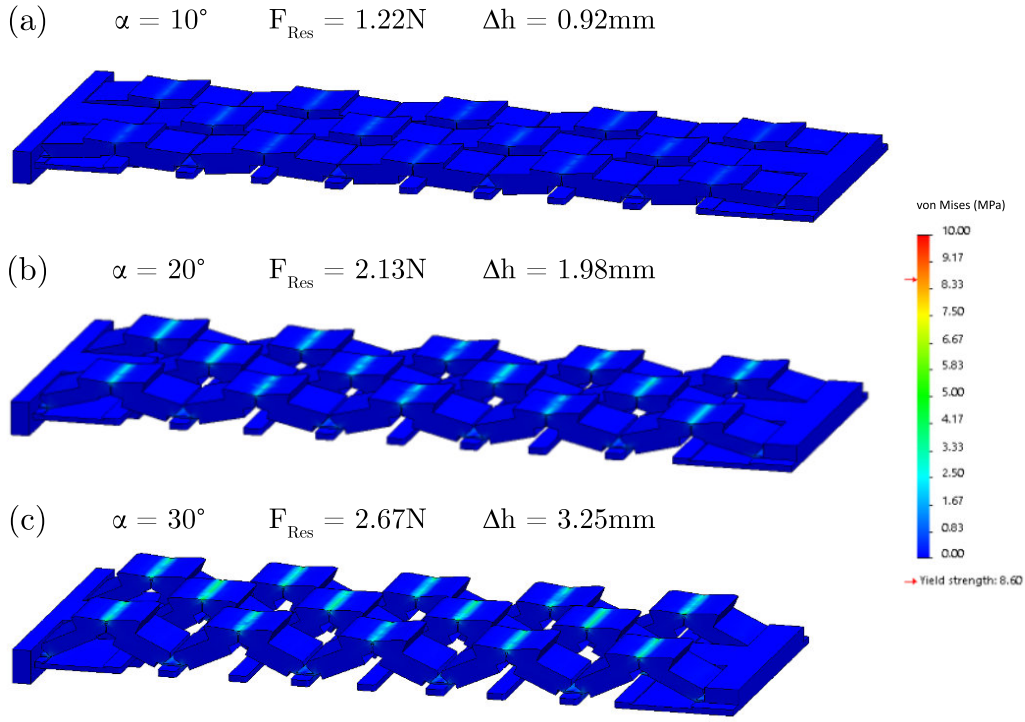


Figure 3.4: Static simulation of the deformation required to fully fold each design with α at values (a) 10° , (b) 20° , and (c) 30° . The resultant force (N) required to fully fold each specification is also shown. Simulation surface colours indicate the observed stress on the thermoplastic polyurethane (TPU) material. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

more rigid ABS, it would have therefore undergone plastic deformation. To prevent this, while ensuring the rest of the structure remains rigid, layers of TPU (shown in green in Fig. 3.2) were introduced to the model at the stress concentrations at the folding areas, which as indicated by the simulation would not exceed the elastic limit. The simulation results for the experienced stress of the structure formed from TPU can be seen in Fig. 3.4, with the yield stress indicated on the colour legend.

Fig. 3.4 also presents the force required to fold the structure, with α at values 10° , 20° , and 30° . As α increases, the distance over which a force needed to be applied increased, with a 1.9 mm compression at 10° , 7.5 mm compression at 20° , and 16.8 mm compression at 30° . The resultant force needed for compression also increased with α , with a maximum force of 2.67N at $\alpha=30^\circ$, as shown in Fig. 3.4. In selecting a value for α , Δh had to also be considered. For low values of α a low Δh was produced, which is ideal for minimising the height of the overall structure. However, Δh must also be large enough to ensure no accidental contact is made with the alternate friction surface. Therefore, a value of 30° was selected for α to ensure no unwanted contact, and the compression force was deemed

Table 3.1: Coefficient of friction (unit: μ) between ABS and different materials.

PETG, ABS, and PLA are sanded to obtain a smooth surface, whereas the Ecoflex are tested with surface finishes: planar, ridged, and checkered.

Material	PETG	ABS	PLA	Ecoflex 00-10			Ecoflex 00-20			Ecoflex 00-30		
				—	┐	⋈	—	┐	⋈	—	┐	⋈
Coefficient of friction	0.08	0.08	0.08	0.63	0.72	0.77	0.57	0.55	0.64	0.52	0.54	0.61

respectable at small values across all values of α .

In the selection of materials for the folding structure friction surfaces, the coefficient of friction between ABS and 6 types of materials in 12 conditions were measured, shown in Table 3.1. ABS was used as a constant comparative surface, as it allowed multiple objects to be easily 3D printed later for manipulation. For the low friction material, ABS, Polylactic Acid (PLA), and Polyethylene Terephthalate Glycol (PETG) were tested after sanding the raw 3D printed surface. The testing samples gave identical results, therefore ABS was chosen as it formed the strongest bond (and thus printed the best) with TPU. For the high friction material, three types of silicone with varying hardness (SmoothOn Ecoflex 00-10, 00-20, and 00-30) were tested in 3 conditions: Planar (indicated by a straight line), ridged (indicated by a line with a 'step'), and checkered (indicated by a zig-zag line). The highest coefficient of friction was shown by Ecoflex 00-10 in a checkered pattern, which was therefore selected for the high friction surface.

3.1.3 Prototype Implementation

Prototype Design

The O-VF surface was designed, as mentioned, to be easily 3D printed by a standard, desktop 3D printer with single nozzle. This allowed the low friction and high friction contact surface to be customized by changing the printing materials, or by adding a new material using layer deposition. In this work, the low friction contact surface is formed from ABS material and the high friction contact surface from Eco-Flex 10 silicone moulded with a checkered pattern. In the fabrication process, I first printed the O-VF surface structure, shown in Fig. 3.4, in ABS material for rigid parts with TPU for flexible hinges using a CraftBot Plus printer. As most consumer 3D printers are not capable of

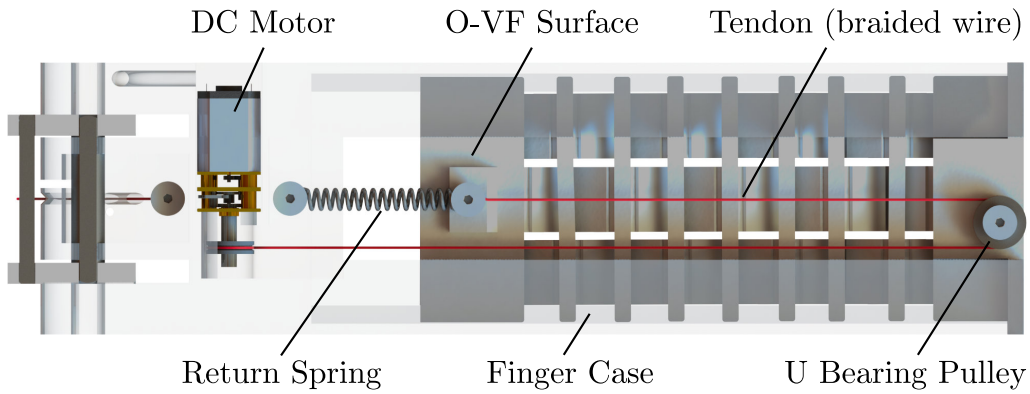


Figure 3.5: Section view of the CAD model finger showing the actuation method and tendon routing on the rear of the O-VF surface. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

printing silicone, the silicone surface was molded separately and attached to the surface using adhesive. Depending on the material selection, it is straightforward for the fabrication process of the O-VF surface to be simplified to a single step using a multi-material 3D printer.

The selected actuation method for the O-VF surface was tendon driven via DC geared motors. A DC geared motor is slotted into the finger and connected with the O-VF surface via braided wire (SeaKnight 15 lb Classic Line). A 10 mm diameter U bearing pulley is attached at the back of the surface for smooth actuation and provides a central activation force. In the initial flat position, the surface is in high friction mode. By activating the DC motor, the surface is folded into the low friction mode. Once folded, the motor is deactivated, and the resistance of the DC motor gearbox maintains the low friction mode. When the DC geared motor is reversed, the structure is pulled back to its initial flat configuration by a tension spring. The arrangement of these components in the rear of each finger can be seen in Fig. 3.5.

Experimental Setup

The developed two-fingered two-degree-of-freedom gripper (Fig. 3.6) was based upon the design of the Yale OpenHand [MD17], with several modifications. The fingers are redesigned to contain two slots to accommodate the O-VF surfaces and DC geared motors (dimension of 173 x 51 x 16.3 mm), and are controlled by tendons driven by two Power HD servo motors (LF-20MG). All of the hand components were printed on Stratasys Objet 260/500 printers and CraftBot Plus printer in Vero Clear

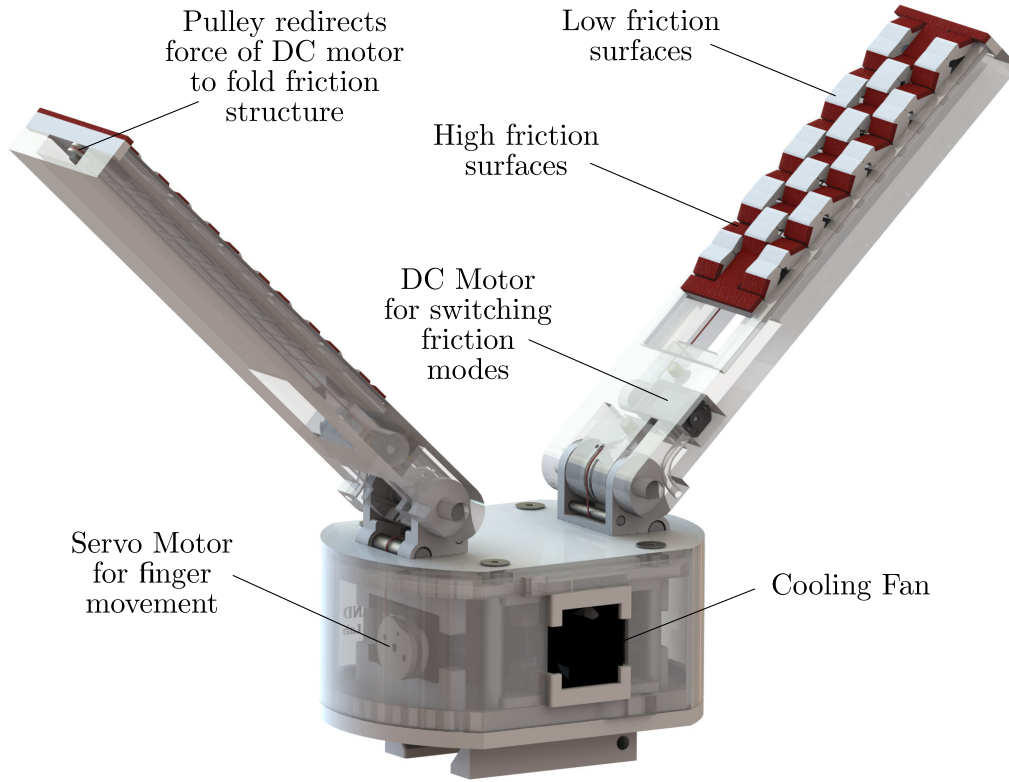


Figure 3.6: CAD model profile of the developed gripper showing the visual and positional difference of the variable stiffness surfaces (left finger in high-friction mode, right finger in low-friction mode), as well as the positioning of the motors for finger motion and control of the friction. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

and ABS, respectively. The weight of the hand averages around 650 g (varying with different O-VF surfaces) and the dimension of the hand base is 109 x 88 x 55 mm.

Six different finger surfaces were developed to evaluate the design parameters' effect on the developed gripper. Fig. 3.7 shows the appearances of the finger surfaces. Type (a) and (b) are typical finger surfaces with low friction (ABS) and high friction (EcoFlex-10), respectively. Type (c), (e), (g), and (i) are all surfaces based on the O-VF folding structure, representing a weighted surface with differing values for k and l (c), a medium density surface where $N = 5$ (e), a low density surface where $N = 3$ (g), and a high density surface where $N = 8$ (i). Based on the previous parametric analysis, some parameters remain constant with their optimum value across all O-VF surfaces, where $\alpha = 30^\circ$, $m = 2$ mm, and $t = 0.3$ mm. For the surface (c) with weighted l and k length, where $l = 3$ mm and $k = 8$ mm, the $\Delta h = 4.59$ mm. The other three O-VF surfaces with middle ($l = k = 5$ mm), low ($l = k = 9.6$ mm), and high ($l = k = 4$ mm) unit density, produce a Δh equal to 3.25 mm, 5.90 mm, and 2.67 mm, respectively.

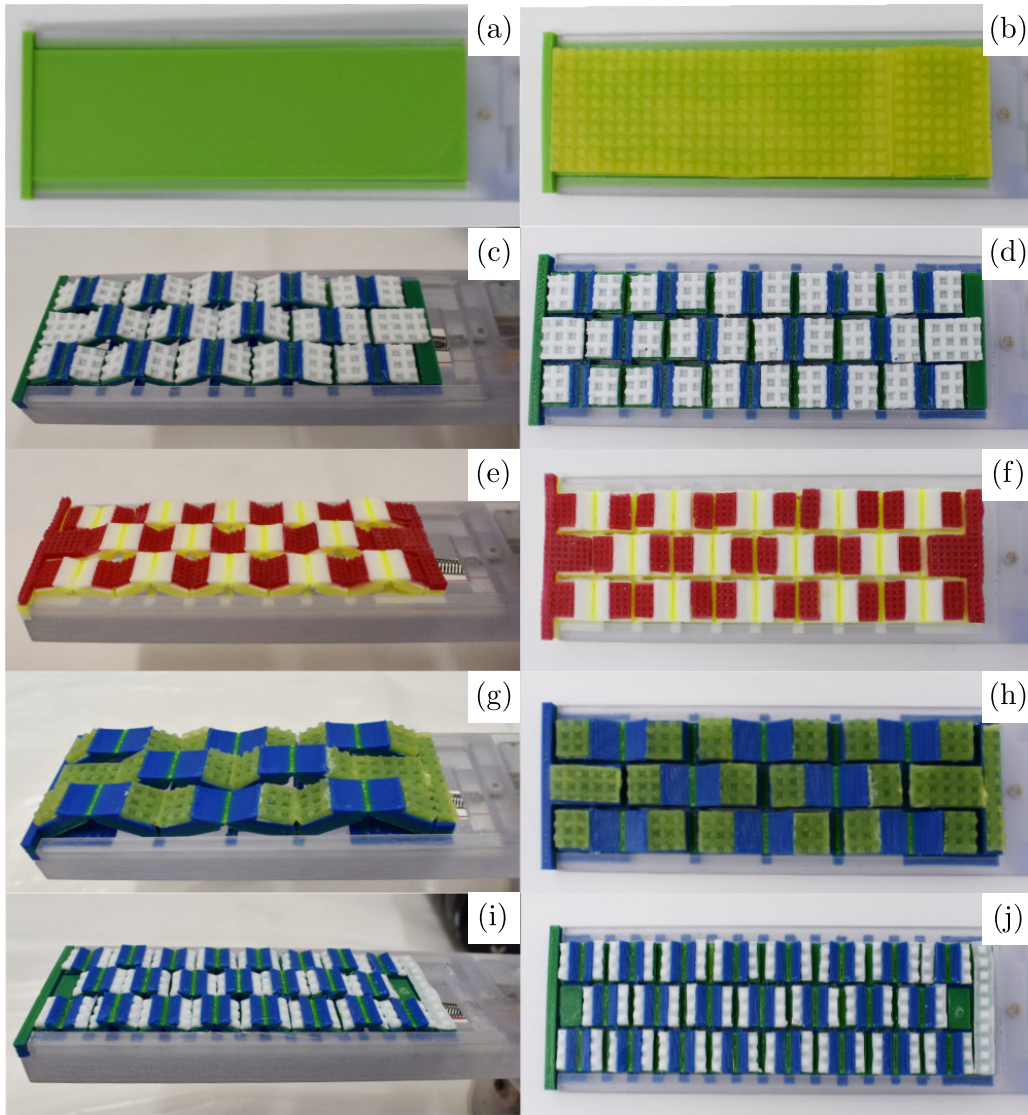


Figure 3.7: Testing surfaces: **(a)** low friction normal surface, **(b)** high friction normal surface, **(c, d)** weighted O-VF surface, **(e, f)** O-VF surface with medium density, **(g, h)** O-VF surface with low density, and **(i, j)** O-VF surface with high density. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

The hand and O-VF surface were controlled by an Arduino Mega. A simple control approach was applied, using position control for the servo motors and time and speed control for the DC geared motors. To achieve this control of the DC geared motors, a H bridge was used providing both speed and direction control, with time control provided by the Arduino.

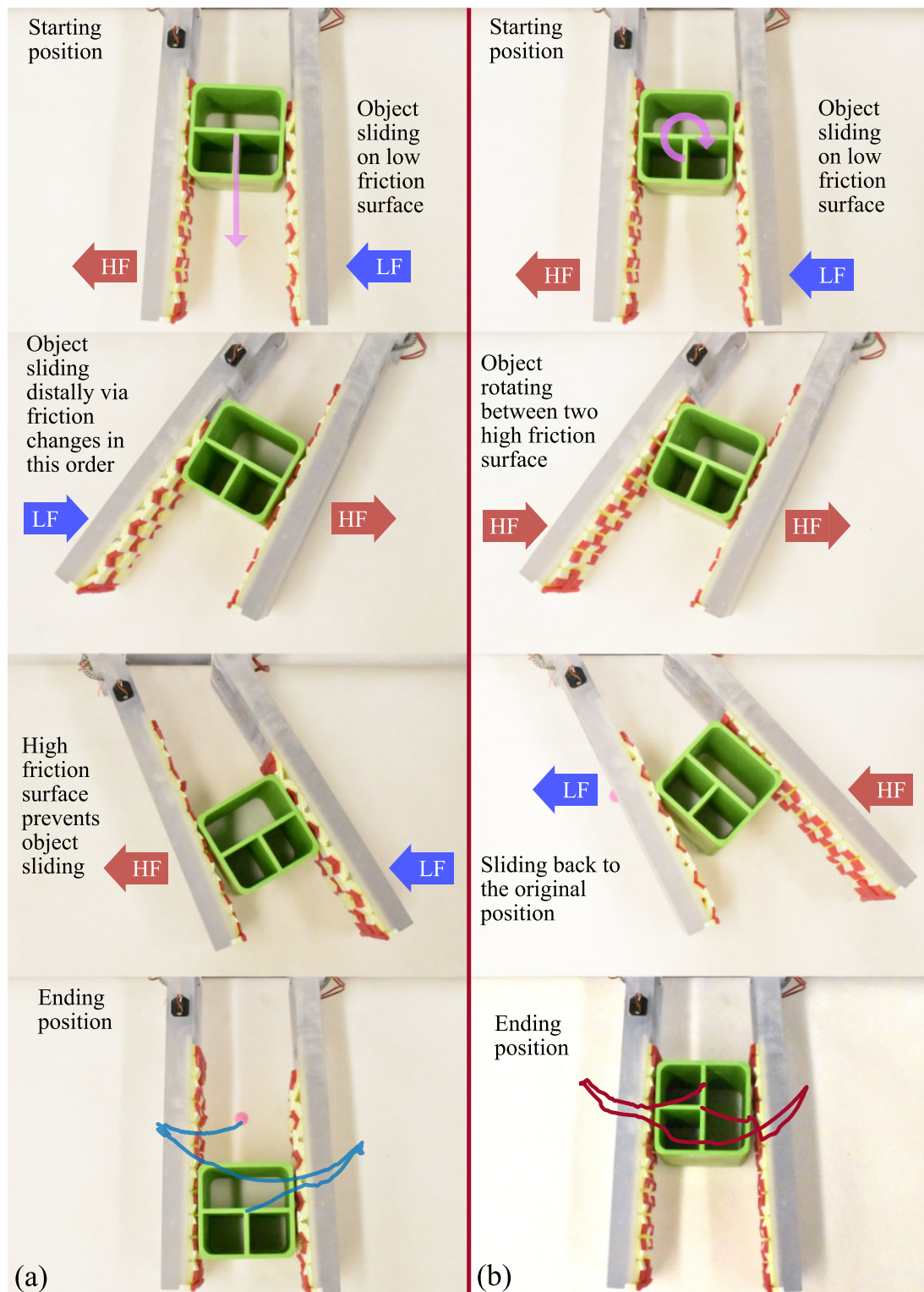


Figure 3.8: Method for achieving translation (a) and rotation (b) of a 50 mm width square object by actively controlling the variable friction surfaces while actuating the fingers. HF indicates high friction surface activated. LF indicates low friction surface activated. The arrow represents the finger moving direction. The blue and red curves in the final row show the trajectories of the manipulated objects. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

In-hand Manipulation Realisation

From inspiration in how humans can manipulate an object in hand, we implemented control sequences for both rotating and translating an object between two fingers by applying different frictions while rotating the fingers.

Active finger object translation: Fig. 3.8(a) illustrates the distal translation of a 50 mm square from the base of the phalanges to the fingertips of both fingers using the developed gripper with O-VF surfaces. The control sequence for this distal translation is as follows:

1. Actuate two fingers to grasp the object in the starting position. Switch to low friction mode on right finger.
2. Rotate the fingers clockwise to maximum angle. The object slides distally on the right finger. When the fingers reach to the maximum angle, switch both finger surface friction modes (left to low, right to high).
3. Rotate the fingers anticlockwise to maximum angle. The object slides distally on the left finger. When the fingers reach to the maximum angle, switch both finger surface friction modes again (left to high, right to low).
4. Rotate the fingers clockwise back to the starting position.

Active finger object rotation: Fig. 3.8(b) illustrates how to actively rotate and translate a 50 mm square to achieve an isolated rotation (only rotation with no translation compared to the starting position).

The control sequences for this isolated rotation are as follows:

1. Actuate two fingers to grasp the object in the starting position. Switch to low friction mode on right finger. Rotate the fingers clockwise to let the object slide distally on the right finger to prepare a larger rotation interspace.
2. Rotate the fingers anticlockwise with both fingers in high friction surface mode to maximum angle. The object rotates in the fingers by pivoting on a corner. When the fingers reach the maximum angle, switch left finger surface friction mode to low.

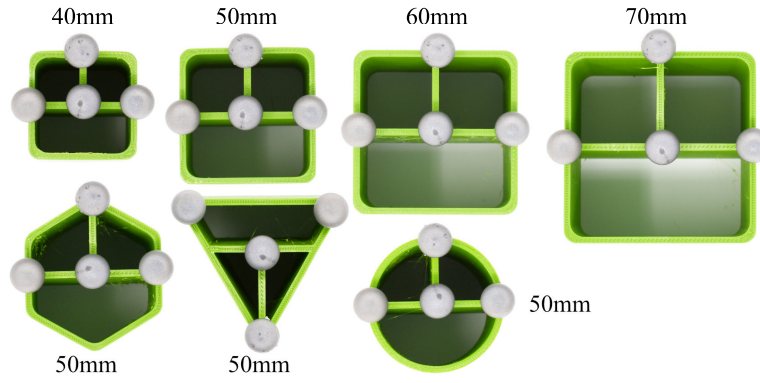


Figure 3.9: The 7 different objects evaluated: 4 squares of width 40 mm to 70 mm and 3 alternative shapes of width 50 mm. The height of all the objects is 60 mm. Motion tracking marker positions for each shape are also shown. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

3. Rotate the fingers clockwise back to the starting position.

Both sequences can be repeated to achieve larger movement, and are suitable for objects in different size and shape. By reversing the methodology, translation and rotation in the opposite direction can be achieved (proximal translation towards the base of the fingers, counter clockwise rotation).

3.1.4 Performance Evaluation

In this section, the translational and rotational performance of the 6 types of friction surfaces on the designed gripper using 7 different objects has been evaluated (4 squares of width 40 mm to 70 mm and 3 alternative shapes of width 50 mm) detailed in Fig. 3.9. The gripper was mounted on a Universal Robots UR5 robot arm with the objects placed on a planar surface, and followed the procedures described in section: in-hand manipulation realisation. The control algorithm of the servo motor was kept consistent while testing all 6 finger surfaces, and each finger rotates to its maximum position to cover the full gripper workspace. The trajectories of the testing objects were recorded by motion tracking cameras (OptiTrack Flex3) and the results were post processed in MATLAB. Each test consisted of 5 repeated trials to generate reliable performance results.

Fig. 3.10 shows the translation trajectory of the 40 mm square manipulated with the constant friction and O-VF middle density surface under the same control algorithm of the servo motors. Fig. 3.11 shows the variation of translation and rotation capabilities for varying square sizes and shapes with

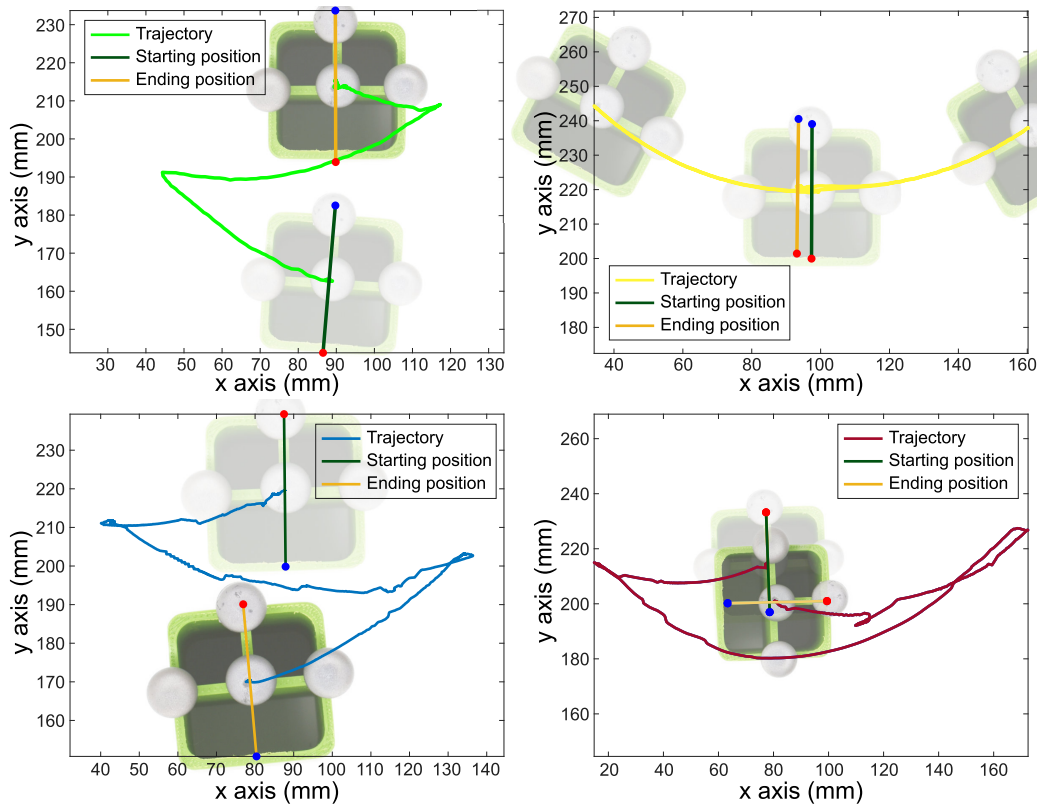


Figure 3.10: Trajectories of a 40 mm square manipulated with normal and O-VF surface (medium density). **Top:** Low friction normal surface trajectory (left) and high friction normal surface trajectory (right). **Bottom:** Translational trajectory (left) and rotational trajectory (right) of O-VF surface. Red and blue dots indicate the two markers on the object. The green and yellow lines indicate the object starting and ending position, respectively. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

these 6 finger surfaces. In this test, I set the performance of constant friction surface as the baseline results. We then compare the O-VF surfaces performance to the baseline to observe the manipulation improvement. Additionally, I compare the performance between O-VF surfaces to see the effect of different design parameters.

In Fig. 3.11, the green and yellow lines are the manipulation results for constant low friction and high friction surfaces. The translation distance of various square sizes are similar for the high friction surface, but for the low friction surface the performance varies for different object sizes, which is related to the nominal gap between the two fingers on the hand design. The nominal gap of this hand design is around 50 mm. When grasping smaller objects (<50 mm), the fingers rotate pointing towards to each other instead of staying parallel, which means there are gaps between the fingers and the objects at the starting position. Once the finger rotates with the objects, the hand object system become as a slider-crank, the object slides towards to the finger base. On the contrary, for larger

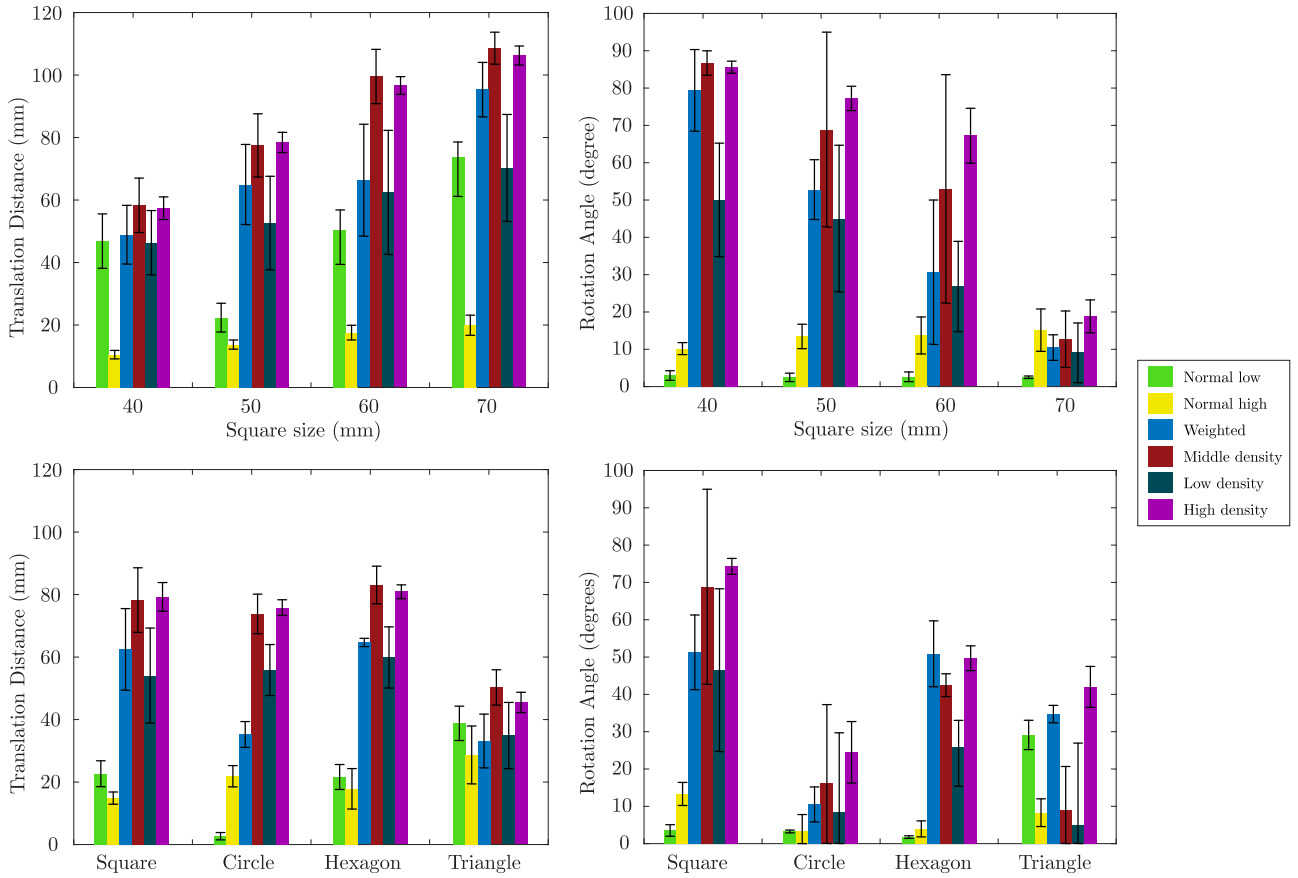


Figure 3.11: Graphs showing the variation in translation and rotation capability for varying shapes and sizes for the six tested finger surfaces (low friction normal, high friction normal, weighted O-VF, medium density O-VF, low density O-VF, and high density O-VF), with standard deviation for each bar shown. Upper two graphs show the translational and rotational capability on 4 sizes of squares, while the lower two graphs show the same capability on 4 alternative shapes. ©2020 IEEE. Reprinted, with permission, from [LCSR20].

objects (>50 mm) the objects slide towards the fingertips. This also explains why the translation distance of the 50 mm square is significantly smaller than others, as the direction of object translation is not affected by the fingers. For the constant high friction surface, the objects are more likely to rotate between the nominal gap of the hand instead of sliding. From Fig. 3.10 (top right) the object rotates along the fingers during the manipulation, but returns to its original position roughly at the end of the manipulation. Further, both translation and rotation for constant friction surfaces are not controllable.

The overall performance of the O-VF surfaces on square objects are better than the constant friction surfaces (Fig. 3.11). The gripper with active O-VF surface fingers had a significantly larger rotation angle, ranging from a mean of 13.46 mm to 83.27 mm, compare to the normal constant friction surface

gripper, whose range is from a mean of 6.18 mm to 8.24 mm. The size of the object has a significant influence on the rotation capability of the O-VF surfaces, with larger objects showing a decrease in rotation. For the 70 mm square, the O-VF surfaces cannot significantly improve the rotation better than the constant friction surfaces due to the nominal gap of the hand design is only around 50 mm.

In contrast, the translation distances show no obvious trend for each of the different shapes. However, the translation differences between the O-VF surface and constant friction surface are significant, especially on square, circle, and hexagon. For the constant friction surface, the average translation distances of the square, circle, hexagon, and triangle were 19.8, 12.6, 20.3, and 38.6 mm. The results show the O-VF surface increases the translation ability of the gripper greatly, apart from the triangle object. This may be because the contact type for the triangular object is different from the other shapes, as it cannot achieve surface (planar) contact for both fingers at the same time, achieving instead one finger with pivot contact and the other with planar contact. When the finger object contact model is pivot at a high friction surface, the object will rotate, or must wait for the finger pad to rotate to instead generate a planar contact model to perform sliding. Therefore in this case, for the same control scheme, fingers need to rotate more to achieve the same amount of translation.

Fig. 3.11 (bottom right) shows the rotation angles for different objects. For most of the O-VF surface design, the rotational capability of circle and triangle are limited, with the circle showing almost no overall rotation (less than 15°), while the hexagon showed a greater value (average of 43.25°) but still smaller compared to that of the square (60.74°). With the constant friction surface, the gripper showed consistent performance across shapes, however the rotation angles were minimal with a mean of 14.84° for the square, 3.16° for the circle, 3.89° for the hexagon, and 20.21° for the triangle.

Some of the rotation results show large standard deviations (more than 20°), indicating the rotation capability of the O-VF surfaces with certain design parameters are not stable under the same open-loop control approach. This can be explained due to the object contact model with the O-VF surface. If the object shape and the finger pad are more likely to generate pivot contacts with the low friction surface, the rotation of the object will be harder to control, as objects will have self-alignment (rotation) generating a stable contact model (in this work, a planar contact model). In Fig. 3.11(bottom right), the results show that the active O-VF surface works well on square and hexagon shapes, which

both can have planar contact with both fingers, whereas the circle shows almost no change in rotation as it is always in point contact with both fingers, therefore making sliding motion hard to control.

By adjusting the design parameters of the O-VF surfaces, a variation in the performance of the gripper was achieved. Overall, the weighted high/low friction length design performed worse than the equally weighted surfaces. With a weighted design, the object has higher possibility of getting stuck in the gaps while sliding over the low friction surface. On the other hand, with the higher ratio on high friction length, the design performed better on rotating various shapes. Unit density is another factor I evaluated in the experiments. According to the mathematics model, higher density has lower overall structure height change (Δh), and smaller valley gaps. Experimental results showed that the Δh effected the in-hand manipulation capability a lot. Higher density showed better manipulation capability and was more stable. Although the mean value of the translation distance and rotation angle of the middle and high density design are similar, the standard deviation of the high density are much smaller, indicating a higher reliability. The low density O-VF surface in comparison performed worse, showing similar performance to the weighted design.

In comparison to the hand developed by Spiers *et al.* [SCD18], the proposed surface design achieved the same rotation per cycle ($\sim 90^\circ$) in a more condensed form. As our gripper and finger size are different, the values of the translation are incomparable, as they are limited by the length of the finger and range of motion of the fingers, not the surface. Additionally, they did not evaluate shapes such as the triangle or hexagon. Further, I have provided additional experimentation on objects larger than the gripper nominal gap. Most importantly, the O-VF design is parametric and can be optimised to provide enhanced manipulation if the object sizes are known.

3.1.5 Conclusion

This work proposes and evaluates a novel origami-inspired variable friction (O-VF) surface design, producing a simple two-fingered two-degree-of-freedom robotic gripper capable of achieving translation and rotation object manipulation. The proposed O-VF surface design is parametric, and the design parameters and material selection were explored considering the effect on in-hand manipula-

tion. The design is also capable of matching requirements in terms of the size and thickness of the surface, the ratio of the high to low friction contact areas, the change in structure height after folding, and the coefficient of friction of the high and low friction surfaces. Using an open loop control approach, 6 finger surfaces (2 constant, 4 O-VF) were evaluated in terms of translation and rotation. Results show the unit density is one of the main aspects observed to improve the gripper performance, showing a higher manipulation magnitude per cycle with a higher reliability. For the objects manipulated, it was also observed that objects with faces parallel to each of the fingers produced a larger manipulation as the contact friction could be varied, unlike in point contact. For future work, the performance of the O-VF surface could be improved to move an object to a target position and orientation via closed-loop control, with the addition of vision or tactile sensors to monitor translation and rotation magnitude. In addition, the size of the O-VF surface could be scaled down while increasing the unit density to manufacture an origami soft skin.

3.2 Soft Fingertips with Tactile Sensing and Active Deformation

Instead of using a motor as an actuator for the active surface, using a pneumatic system is another method. In this section, a pneumatic actuated active surface with sensing capability has been proposed. In Chapter 2 the role of soft fingertip for in-hand manipulation has been analysed. Here, soft fingertips have shown additional capabilities for enhancing the in-hand manipulation of the gripper. In recent years, soft robotics have developed very fast. While soft fingertips have shown significant development for grasping tasks, its ability to facilitate the manipulation of objects within the hand is still limited. Thanks to elasticity, soft fingertips enhance the ability to grasp soft objects. However, the in-hand manipulation of these objects has proved to be challenging, with both soft fingertips and traditional designs, as the control of coordinated fine fingertip motions and uncertainties for soft materials are intricate. This section presents a novel technique for in-hand manipulating soft objects with precision. The approach is based on enhancing the dexterity of robot hands via soft fingertips with tactile sensing and active shape changing; such that pressurised air cavities act as soft tactile sensors to provide closed loop control of fingertip position and avoid object's damage, and pneumatic-tuned positive-pressure deformations act as a localised soft gripper to perform additional translations and

rotations. I model the deformation of the soft fingertips to predict the in-hand manipulation of soft objects and experimentally demonstrate the resulting in-hand manipulation capabilities of a gripper of limited dexterity with an algorithm based on the proposed dual abilities.

3.2.1 Introduction

Precise in-hand manipulation is an important and essential ability for robot grippers to achieve small-scale adjustive manipulation tasks without unnecessary large arm motions. Recent research in dexterous in-hand manipulation has focused on achieving particular tasks or performing certain movements of a rigid object, for example reorienting the object [ABC⁺20, DRP⁺14] or performing a prehensile spherical motion [MRD16a]. However, the development of robotic grippers that can precisely in-hand adjust soft objects has received limited attention. For grasping soft objects, soft fingertips with tactile sensors perform better than rigid fingertips due to their high grasping compliance. With rigid fingertips, robotic grippers can achieve a repeatable stable grasping force and high precision control with the ease of integrating high standard sensors and control algorithms [TTS14, WCRL17]. Nevertheless, rigid fingertips lack adaptability and compliance, and they are prone to damage and may deform very fragile and soft objects.

With high compliance of the soft fingertips, the increased contact area with objects results in a greater variety of moments to the grasped object [CMA05]. Most current research focuses on delicate grasping by robotic grippers. For instance, Amend *et. al* proposed the well-known granular jamming universal gripper for grasping a wide range of objects [ABR⁺12]; Maruyama *et. al* presented a gripper with incompressible fluid covered by rubber fingertips which can grasp fragile and brittle objects by controlling the contact pressure [MWU13]; and Manti *et. al* showed the dexterous grasping capability with a simple control of a bioinspired soft gripper [MHP⁺15]. However, these gripper and fingertip designs do not have the capability of in-hand and precision manipulation.

In-hand manipulation of soft objects with a simple degree of freedom gripper is not well explored as yet. The main difficulties are the actuation method, force control, and the soft fingertip model. The dexterity of robotic grippers can be increased by changing the friction of the fingertip [LCSR20,

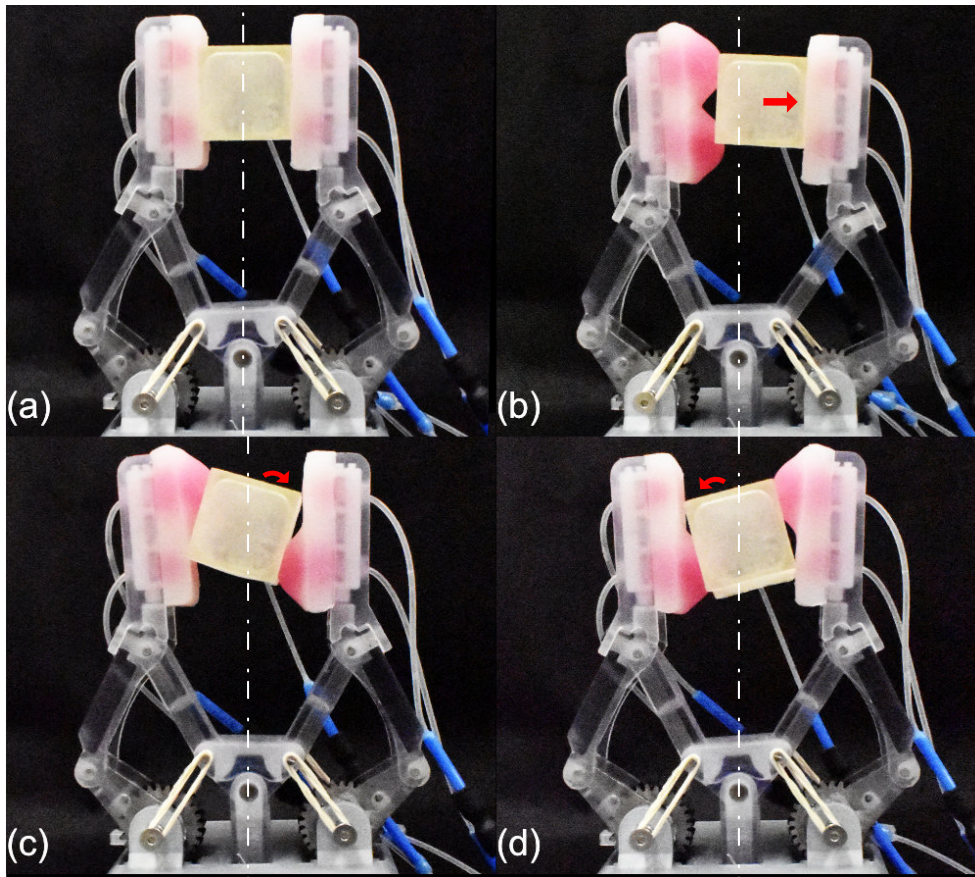


Figure 3.12: The ability of robot hands to manipulate soft objects with precision can be enhanced using soft fingertips with adaptive sensing and active shape changing (a). Embedded air cavities in these soft fingertips allow the dual purpose of soft tactile sensing, via internal pressure variation, and active in-hand translation (b) and rotation (c, d), via positive pressure. White dotted lines indicate the center line of the gripper. Red arrows indicate the object's motion (semi-transparent square). ©2020 IEEE. Reprinted, with permission, from [LHNR20]

SCD18] or by applying external forces [DRP⁺14]; however, these approaches are not suitable for soft objects. Tactile sensors are commonly being employed on the fingertip to sense the grasping force [WCRL17] and measure the object surface texture and shape [JA09], but it is difficult to perform active deformation with those conventional tactile sensors. The relationship between soft fingertips and in-hand manipulation is not well defined as well. Due to the uncertainties of soft materials (*e.g.*, rolling, deformation), it is hard to model the exact manipulation of the grippers and the dynamic motion of the soft objects [LR19, Kim04].

In this section a novel soft fingertip design has been proposed for in-hand manipulating soft objects via embedded air cavities (Fig. 3.12). This fingertip has dual purpose of tactile sensing and active deformation which allows the GR2 gripper [RMD16] to robustly grasp [HLA⁺20] and in-hand ma-

nipulate soft objects. Soft objects can be displaced within the gripper to a certain extent only by controlling the shape of fingertip air cavities. The tactile pressure sensing in the fingertip air cavities can be used for closed loop control of contact force during object manipulation.

Then, I detail the fingertip design and the control algorithm for soft objects (Section 3.2.2); characterise and model the deformation of the soft fingertip to predict the motion of the objects (Section 3.2.3); evaluate in-hand manipulation (translation and rotation) performance of the developed dual purpose soft fingertips with a soft object (Section 3.2.4); and discuss the simulation and gripper performance in Section 3.2.5 and conclude this proposed fingertip performance in Section 3.2.6.

3.2.2 Fingertip characterisation & control

Fingertip & gripper design

Figure 3.13 (a) shows the schematic of the dual fingertip design holding a soft square object, where the two embedded air cavities (red sections) are evenly distributed in each fingertip made from silicone rubber (white sections). The special finger-base structure is 3D printed by Objet 260 in VeroClear, which is designed to secure the silicone fingertip and the air, and ensure the inflate direction is growing as desire. Both the soft fingertips and the half-cylindrical air cavities are made from the same silicone material (Ecoflex-30). The shore hardness of the fingertip is around 25 HC with the material and around 20 on the cavity at 0 kPa (relative to atmospheric pressure), measured by a type C durometer. Here, the soft square object is also 3D printed by Objet 260 but with a soft material (FLX 9960-DM). The proposed fingertip is attached to the fingers of a redesigned GR2 gripper [RMD16] (Fig. 3.12) to perform in-hand manipulation tasks. Instead of tendon driven actuation, the implemented gripper uses a gear mechanism (KHK 28) to increase manipulation accuracy.

Fingertip characterization

The embedded air cavities are used as soft tactile sensors to control the gripper position to in-hand manipulate soft objects via the internal pressure variation. Fig. 3.14 shows the fingertip deformation

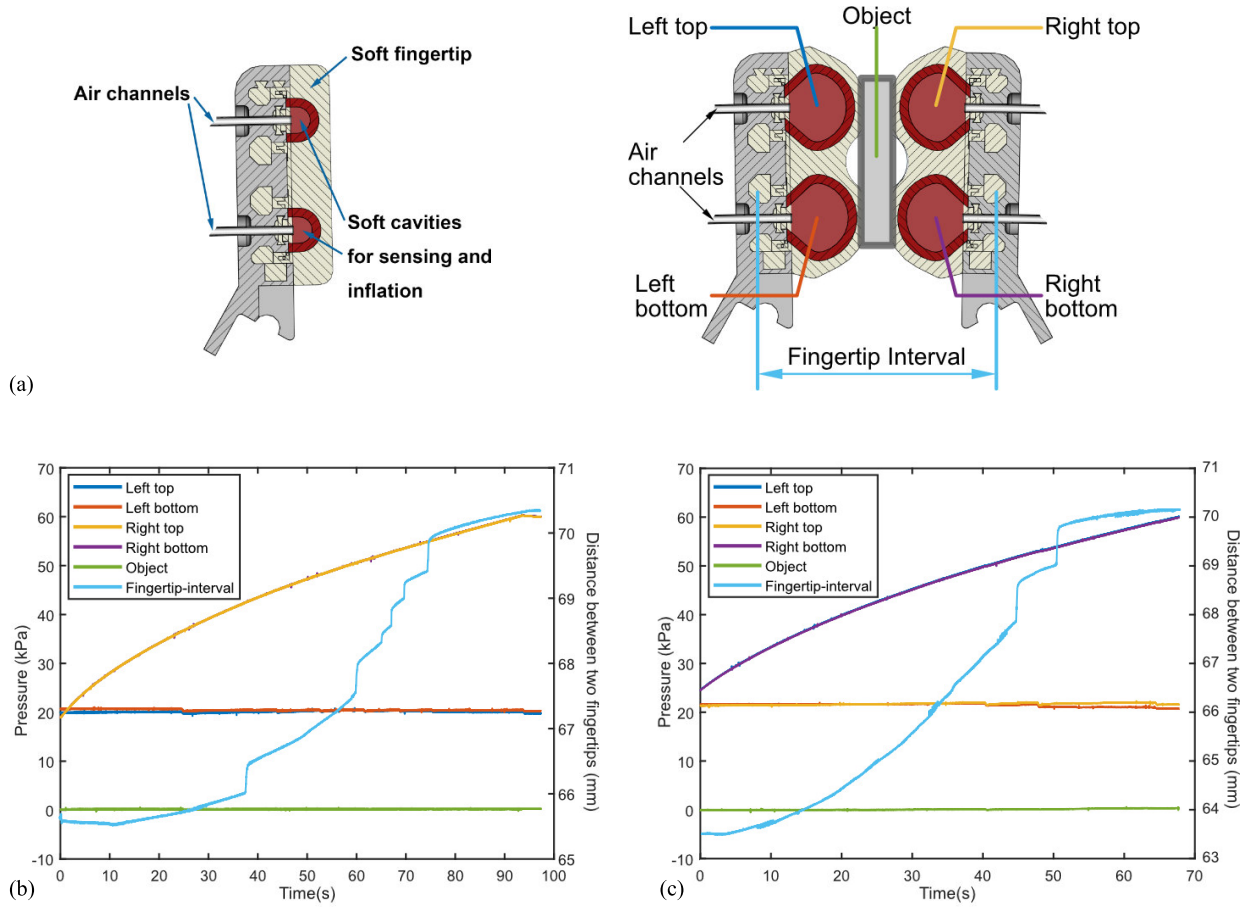


Figure 3.13: (a): Schematic of the dual function fingertip design. The line graphs show the internal pressure data of four air cavities and soft object manipulated (green), and distance between two fingertips (light blue) (recorded by motion tracking cameras) for a translation task (b) and a rotation task (c). ©2020 IEEE. Reprinted, with permission, from [LHNR20]

with pressure, when the air cavity is inflated, the deformation of the air cavity causes shape change of the fingertip. In order to characterize this behaviour, the fingertip deformation value is measured by a caliper at the widest part of the fingertip. First the baseline bias due to atmospheric pressure is removed. Then the biased-removed internal pressure can rise to a maximum of 60 kPa during inflation. The curves in Fig. 3.14 represent the average data of 5 trials of inflation/deflation tests. A detailed hysteresis and sensitivity analysis can be found in [HLA⁺20].

Control algorithm

The four soft air cavities and the soft square object (*i.e.*, the red bubbles and the semi-transparent object in Fig. 3.13 (a), respectively) were connected with 5 pressure sensors (PSE 543-R06) and 5

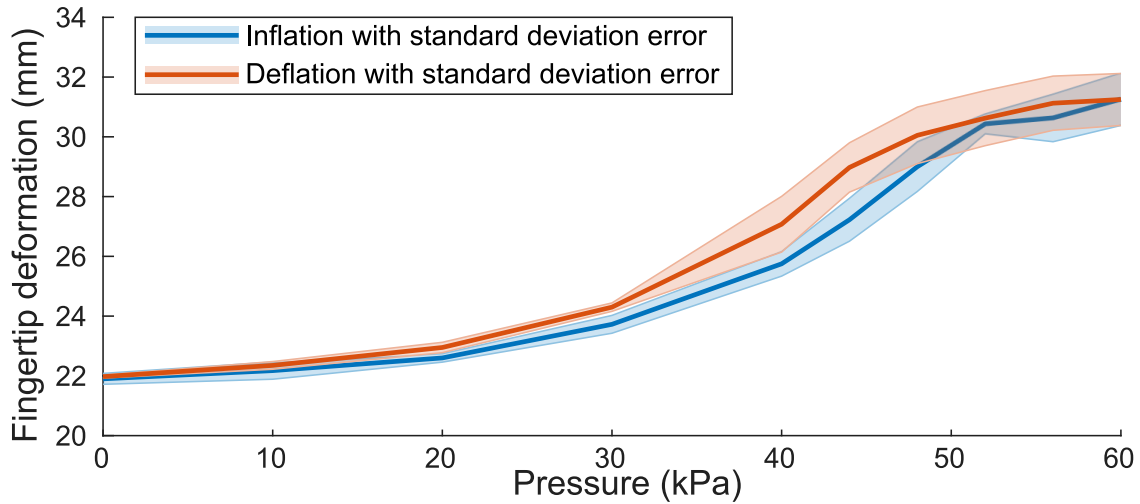


Figure 3.14: Fingertip characterization: fingertip maximum deformation variation of inflation (blue) and deflation (red). ©2020 IEEE. Reprinted, with permission, from [LHNR20]

solenoid valves (Z031C), one air reservoir, and an air pump. Labview 2018 was used to measure the internal air pressure via a National Instrument DAQ (USB-6341) and control the gripper servo via a U2D2 USB communication converter. For both translation and rotation, the initial grasping air pressure of the fingertip is 20 kPa. The aim is to in-hand manipulate the soft object without over increasing the object internal air pressure via active sensing and active deformation. The control algorithm for in-hand translation and rotation is described below.

Translation As demonstrated in Fig. 3.12 (b), both air cavities of left fingertip are inflated for moving-right translation tasks. Instead, both air cavities of right fingertip are inflated for opposite translation direction. The rest of the fingertip is acting as an active tactile sensor to ensure the contact forces between fingertips and soft object are constant during manipulation by actuating the servo motors. Fig. 3.13 (b) shows the internal pressure reading of all air cavities and the object. When right-top and right-bottom air cavities are inflated from 20 kPa to 60 kPa (active deformation), the left top and bottom air cavities are set to keep the pressure under 22kPa to ensure the object internal pressure reading is steady (green). The gripper position is then controlled by the air cavities automatically, in this case, if either the left-top or left-bottom air cavities' internal pressure is higher than 22 kPa, then the left motor opens one degree more until the pressure is under 22 kPa.

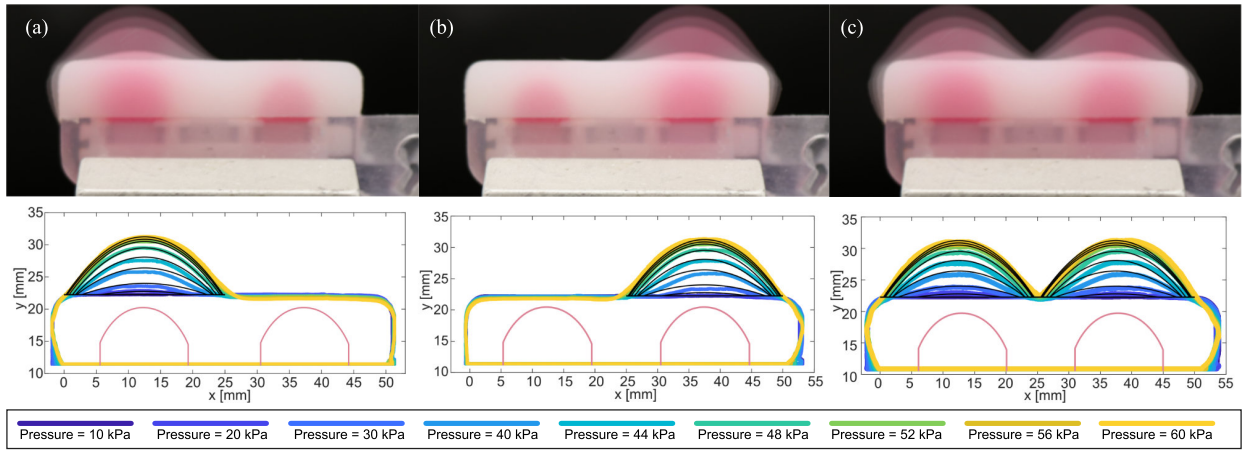


Figure 3.15: Numerical deformation of the fingertip based on image processing of a real inflated and deflated fingertip on various pressure levels. ©2020 IEEE. Reprinted, with permission, from [LHNR20]

Rotation Figure 3.12 (c) and (d) illustrate the in-hand rotation of the soft object. When the left-top and right-bottom air cavities are inflated together, the grasped object rotates clockwise. Instead, if the left-bottom and right-top air cavities are inflated together, the grasped object rotates anti-clockwise. Fig. 3.13 (c) shows the internal pressure reading during a clockwise rotation task. This time, only one air cavity of a single fingertip is inflated, so both fingertips have the active tactile sensor on, and the gripper can open in both directions. When the left-top and right-bottom air cavities are inflated from 20 kPa to 60 kPa, if either the left-bottom or right-top air cavities' internal pressure is higher than 22 kPa, then the corresponding motor opens 1 degree more until the pressure is under 22 kPa. The light blue curves illustrate the distance changes between two fingertips during the manipulation.

3.2.3 Simulation model

The proposed simulation models the deformation of the soft fingertips to predict the in-hand manipulation of manipulated objects.

Method

To characterise how the fingertip deforms when different pressure conditions are applied to the air cavities, image processing was used to extract the planar fingertips outlines. The fingertips were

Table 3.2: Dual fingertip pressure characterisation

Pressure P (kPa)	0	10	20	30	40	44	48	52	56	60
D_{max} (mm)	21.9	22.3	22.8	24.1	26.4	28.1	29.5	30.5	30.9	31.3

placed in front of a camera where a set of pictures were captured corresponding to different internal air pressure conditions. Image data were processed with MATLAB Image Processing Toolbox. Each air cavity is assumed to be symmetric with its peak lying on the center line. The vertical coordinate y of the peak point at the pressure condition p is assumed equal to the characterised fingertip width $D_{max}(p)$. Second order polynomial functions were used to fit the outlines of the fingertips. The two air cavities are assumed to be independent during inflation and interference between the two inflated air cavities are neglected. Fig. 3.15 shows the images used for analysis and the fitted models with pre-characterised parameters.

Model

The boundary of the fingertip based on Fig. 3.15 is described by the following equation

$$y(x) = \begin{cases} K(p)(x - 12.5)^2 + D_{max}(p) & \text{if } 0 \leq x < 25 \\ K(p)(x - 37.5)^2 + D_{max}(p) & \text{if } 25 \leq x \leq 50 \end{cases}, \quad (3.1)$$

where the origin is located at the top corner of the fingertip base, x is the width of the fingertip and y is the thickness of the fingertip. Both K and D_{max} are pressure related variables of the equations, such that

$$K(p) = 0.082p^3 - 8.3p^2 + 99.5p + 1.387 \times 10^{-3} \quad (3.2)$$

$$D_{max}(p) = 0.025p^2 + 0.0244p + 21.6897, \quad (3.3)$$

where p is the instant pressure. The expression of D_{max} is poly-fitted from Table 3.2 and $K(p)$ is poly-fitted of the quadratic coefficients of these second order polynomial outline functions.

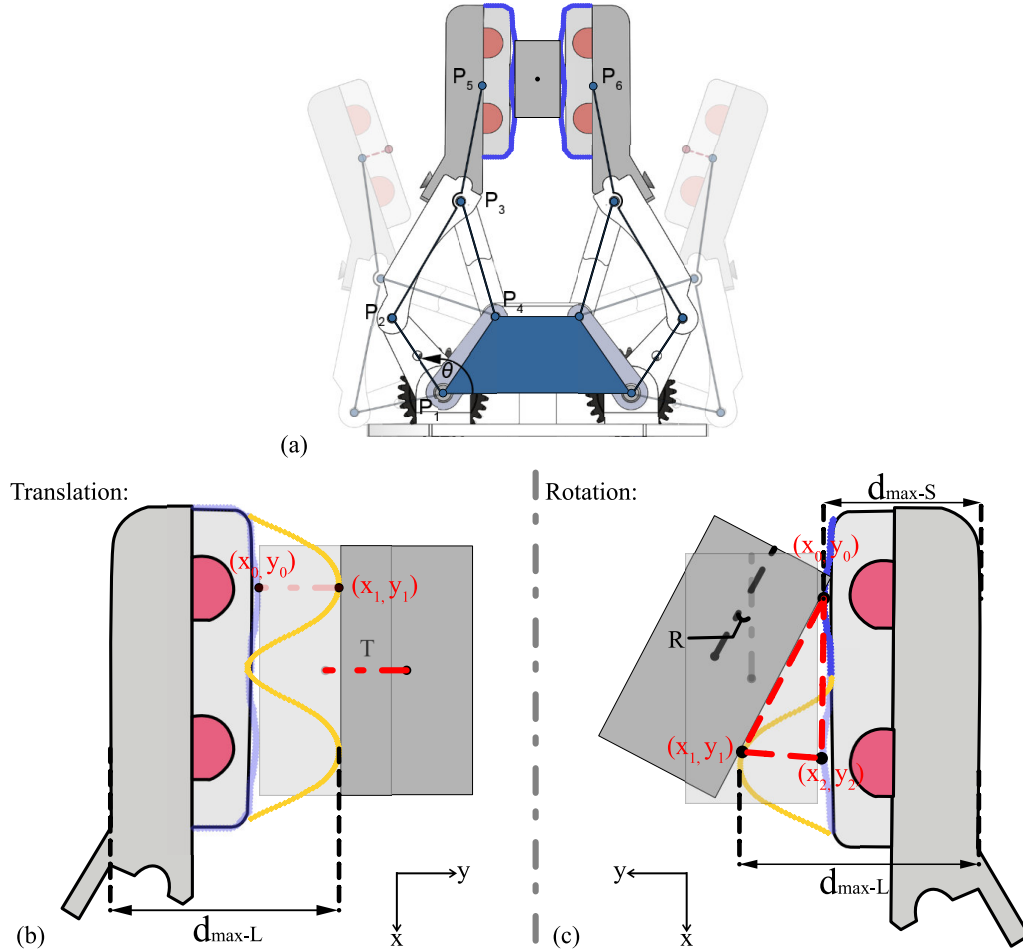


Figure 3.16: Simulation model illustration. **(a)**: Kinematic chain of the gripper. P_1, P_2, P_3, P_4 are revolute joints on the left gripper. P_5 and P_6 determine the fingertip interval distance. θ is the motor input actuation angle. **(b)**: Translation task model: the faded blue boundary indicates the initial grasping position (x_0, y_0) and the yellow boundary indicates the fingertip inflated position (x_1, y_1) . The translation distance is T . **(c)**: Rotation task model the contact point (x_1, y_1) is the tangent point on the inflated boundary curve that passes through point (x_0, y_0) . The rotation angle is R . ©2020 IEEE. Reprinted, with permission, from [LHNR20]

Based on the control algorithm, the simulation models of translation and rotation task are illustrated in Fig. 3.16(b) and (c). The figure only illustrates half of the gripper to facilitate explanation. In this simulation, I assume the grasping force is minimal where the fingertip has no passive deformation during the manipulation. The object translation distance T is determined from the object center point distance between the initial stage and final stage where the variable is the pressure level p . It can also be expressed as the active inflated deformation

$$T^2 = (x_1 - x_0)^2 + (y_1 - y_0)^2, \quad (3.4)$$

where (x_0, y_0) and (x_1, y_1) are the coordinates of the contact point at initial and final stage, respectively. I assume the contact point is always at the center of the air cavity, in this case $x_1 = x_0$, so this equation can be simplified as

$$T = |y_1 - y_0|. \quad (3.5)$$

Only one air cavity is inflated to rotate the object for one fingertip, I assume that one of the contact points, (x_0, y_0) , is always at the center of the uninflated air cavity and the other one is the tangent point (x_1, y_1) on the inflated air cavity through the fixed contact point. Then, (x_1, y_1) can be computed from the equation of the tangent going through these points and the value for y_1 from equation (3.1), such that

$$y_1 = K(p)(x_1 - 37.5)^2 + D_{max}(p), \quad (3.6)$$

$$\frac{(y_0 - y_1)}{(x_0 - x_1)} = 2K(p)x_1 - 75K(p). \quad (3.7)$$

By replacing equation (3.6) into (3.7), I obtain a quadratic equation in terms of x_1 .

All of the three points of the dotted red triangle in Fig. 3.16, namely (x_0, y_0) , (x_1, y_1) , (x_2, y_2) , are known or can be computed. The rotation R of the object can then be calculated as the intersection angle between the initial object boundary and final object boundary. The simulated translation distances (T) and rotation angles (R) are obtained using this simulation model. The dimension of the fingertip is $50 \times 22 \times 32$ mm, the pressure range is from 20 kPa to 60 kPa. At the middle grasping configuration, the desired translation (T) is 8.5 mm, and rotation (R) is 18 degrees in one direction. At other grasping positions the object has an initial rotation angle (due to gripper design and rolling), the model assumes that the total translation and rotation range does not change in these cases.

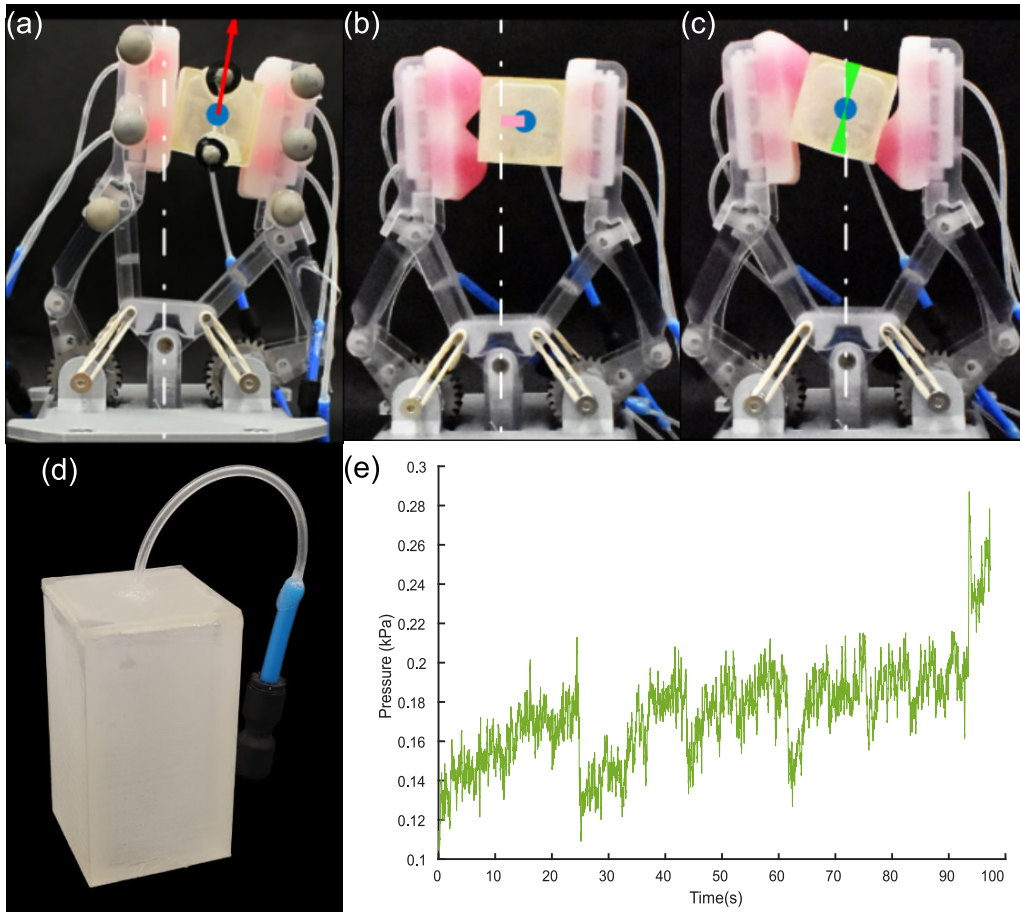


Figure 3.17: Illustration of the experiments. Object at grasping position with an initial rotation angle (a), translation (b), and rotation (c). The soft object is shown in (d) and (e) shows the object internal pressure variation during translation task (zoomed-in of the data presented in Fig. 3.13(b)). ©2020 IEEE. Reprinted, with permission, from [LHNR20]

3.2.4 Implementation

Experimental setup

The aim of this experiment is to show the dual purpose soft fingertip can perform precise in-hand manipulation of soft object with a limited dexterity gripper. The testing object is a 3D printed 30mm soft square in material FLX 9960-DM which is airtight and connected to a pressure sensor (Fig. 3.17 (d)). Its internal pressure variation (Fig. 3.17 (e)) is used to exam the capability of this gripper on manipulating soft object. The gripper translated and rotated the soft square at 7 different grasping positions. The trajectories of the testing object were recorded by motion tracking cameras (OptiTrack Flex3) and post processed in MATLAB.

Results

Fig. 3.17 shows the method of evaluating the gripper performance and the interpretation of Fig. 3.18. Fig. 3.17 (a, b, and c) illustrate the results in Fig. 3.18 which the arrows show the object's initial rotation stages due to the gripper design and rolling aspect, the precise translation (pink shaded area) and rotation (green shaded area) due to active fingertip deformation via positive pressure. The main purpose of this experiment is to keep the soft object safe during the precise in-hand manipulation, in this case, maintaining the internal pressure of the soft object at low level. The internal pressure was unbiased at the beginning of each test to keep the initial reading of the internal pressure of the soft object at 0 kPa (relative to atmospheric pressure). Here, based on the control algorithm in Section 3.2.2, we consented the internal pressure of the soft object should be less than 0.3 kPa without breaking it. Fig. 3.17 (e) shows a clear pattern of the internal pressure of the testing object which is the same result as Fig. 3.13 (e) in large scale. When the air cavities inflate, the soft object receives external force to have slight deformation, the internal pressure increases. Once the gripper opens due to the soft tactile sensing, the internal pressure of the soft object decreases. Those happen repeatedly until the air cavities reach to their limit.

3.2.5 Discussion

The translation and rotation capability of the gripper with the dual purpose fingertips has been shown clearly in Table 3.3 and Fig. 3.18. We observed that the relative position between the fingertip and the object affects the in-hand manipulation performance and both translation and rotation range decrease when the initial rotation angle of the object increases. In a rotation task, if the object has an initial rotation stage in the same direction of the target rotation (*e.g.* the object is held at position 6 and intended to rotate to right), the inflated air cavity will have a gap between the grasping object (Fig. 3.17 (a)). During the inflating stage, the air cavity will touch the object first, and then rotate the object. Therefore, in this case, the object rotation angle is smaller than normal. Conversely, if the initial rotation direction and the target rotation angle are opposite (*e.g.* the object is held at position 6 and intended to rotate to left), the rotation angle will be larger than normal. In Fig. 3.18 at position 6, it is obvious that the size of the green shaded area on the right side of the arrow is less than the right one.

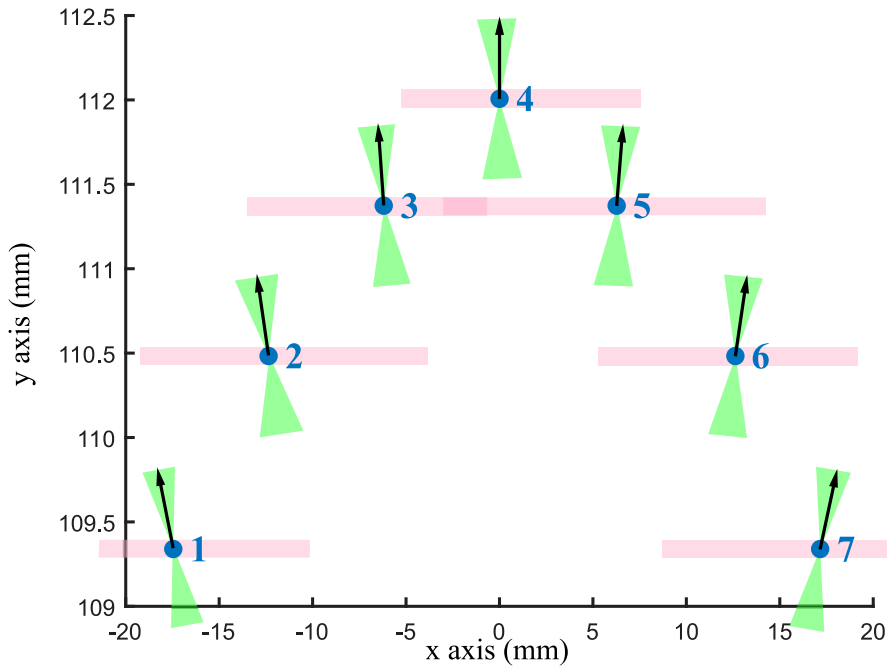


Figure 3.18: The 7 different positions evaluated under rotation and translation: blue dots indicate the center point of the 30mm soft square. Black arrows show the object initial rotation due to gripper design and rolling. Green and pink shaded area indicates the rotation range and translation range, respectively. ©2020 IEEE. Reprinted, with permission, from [LHNR20]

Table 3.3: Dual fingertips in-hand manipulation capability

Position No.	1		2		3		4		5		6		7	
Init. Rot. Angle °	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
	-11.21	1.09	-8.21	0.56	-3.98	0.18	0.11	0.12	4.48	0.81	8.29	0.54	12.09	1.17
Rot. Range °	23.16		28.08		29.62		29.89		29.31		27.43		24.88	
Trans. Range mm	11.45		15.31		12.76		12.72		17.24		13.87		12.49	

Similar phenomenon appears in translation tasks (pink shaded area) as well.

Although the rotation angle and translation distance in left and right direction are not similar, the total rotation range and translation range of those symmetrical points are similar in Table 3.3. It shows the precise in-hand manipulation capability of the gripper is reliable. There are some variation in translation range, which may occur because the relative position between the fingertip and the object may have slightly differences for each test due to placing the object manually. This may result in different inflating position and sensing position which will affect the sensing capability. The size and shape of the object is also an aspect to consider, if the object does not touch the sensing air cavity properly, the sensing capability will decrease and the feasible manipulation range will decrease as well. Additionally, the testing soft square is hollow, the edge of the object is harder than the center,

the inflated air cavities have chances to contact either the object edge or softer object body. As the gripper presents better manipulation capability on harder material, where soft material absorb forces and energy during manipulation. When the inflated air cavity touches to the soft object, if the object is softer than the air cavity, the object may deform at the contact point first and then transfer the force to the rest of the object.

Nonetheless, results show that the approach enlarges the dexterity of simple grippers and the information about grasping state can be obtained by other means (*e.g.*, vision). The air cavity tactile sensors show acceptable sensitivity for soft objects, increasing the sensing area and sensor number may improve the manipulation performance of soft objects.

Simulation shows the gripper with the novel design fingertips can translate object in 17 mm and rotate object in 36 degrees. The average experimental translation range is 14 mm and rotation angle is 28 degrees, which is 17% and 22% less than the simulation results, respectively. The proposed simulation model of the dual purpose fingertip gives satisfactory results on estimating the gripper manipulation capability of a square object. The model can be improved by adding the initial rotation angle condition and considering the deformation of the inflated air cavities. A further extension to this simulation would involve the addition of object shape and material. This would allow the simulation to predict the motion of the object precisely.

3.2.6 Conclusion

In this section, a novel dual-purpose soft fingertip design was proposed and evaluated, presenting a new way to precisely in-hand manipulate soft objects without damaging. This approach is based on enhancing the dexterity of robot hands via soft fingertips with tactile sensing and active shape-changing. With active shape-changing of the embedded air cavities, the fingertip has proved its ability to in-hand manipulate soft objects prehensilely with pressure feedback control. The proposed simulation model gives an evaluation of the manipulation ability of the enhanced gripper, which can be improved by taking the initial rotation angle and deformation of the fingertips into account. The limited dexterity gripper used in this study only has specific object positions for each grasp configuration

when equipped with typical soft fingertips. With the proposed closed-loop control approach and the novel dual-purpose fingertips, the object position can be adjusted at each grasp configuration, increasing the gripper's dexterity vastly. The control algorithm can be developed further in future works for more complex prehensile in-hand manipulations that combine translation and rotation with irregular objects. Moreover, the performance of the dual purpose fingertip could be improved to sense force via the inflated air cavities as well.

3.3 Chapter Conclusion

This chapter includes two types of active surfaces for in-hand manipulation enhancement, which are actuated by different methods. In Section 3.1 the origami-inspired variable friction surface is proposed. The surface can switch the friction condition (high/low) by a single DC motor. This proposed design is parametric, flexible and compact; with high-level manufacturing skill, ideally, it can become as a variable friction skin. The variable friction surface was assembled to a simple two-fingered two-degree of freedom robotic gripper, capable of achieving translation and rotation object manipulation. Compare to a normal two-fingered two-degree of freedom robotic gripper; the results show that the proposed surface provides an obvious enhancement on the capability for in-hand manipulation. The other very important feature for human hands is the sensing capability. In Section 3.2 the proposed active surface is a soft fingertip with air cavities inside. The pneumatic actuation system benefits from the special designed soft fingertip with dual-functionality - tactile sensing and active shape-changing. By detecting the internal pressure of the air cavity, the fingertip can work as a tactile sensor. By increasing the internal pressure of the air cavity, the fingertip can have active shape-changing to manipulate or protect grasped soft objects. With the dual-functionality of the fingertip, a two-fingered two-degree-of-freedom robotic gripper showed the ability to in-hand manipulate soft objects prehensilely with pressure feedback control. The air cavities inside the fingertip can be optimised to enhance the in-hand manipulation performance in terms of size, shape, position, and number. To sum up, both sections show that the proposed active surfaces can enhance in-hand manipulation performance for simple robotic gripper without increasing the control complexity significantly and have a large potential to be optimised in future work.

Chapter 4

The Topology of the Hand-Object System

This chapter is adapted via ©2020 IEEE. Reprinted, with permission, from [Q. Lu, N. Baron, G. Bai, and N. Rojas, "Mechanical Intelligence for Adaptive Precision Grasp". Proceedings of the 2021 IEEE International Conference on Robotics and Automation (ICRA).]

Abstract

The literature review in Chapter 1 has shown that with a very complex mechanical design and a considerable number of actuators and sensors, only software enhancement (control) cannot achieve reliable dexterous manipulation operations under both shape diversity and shape uncertainty. In the last two decades, a principle called mechanical intelligence has been proposed, which can be defined as the use of mechanical and other physical properties to create robotic systems adaptable to new external situations using simple control schemes. Robot hand designs have been successfully developed and optimised following this principle to produce self-adaptive and versatile power grasps via implementations based on underactuated fingers, elastic components, and open-loop motor control. However, these characteristics, and mechanical-intelligent strategies in general, have been seldom leveraged for precision grasping and their success when applied to dexterous manipulation have been remarkably very limited. The hand-object system formed during in-hand manipulation operations constantly generates multiple closed-loop kinematic chains that inherently impose constraints that modify the feasible movements of both the hand and the object. Therefore, in this chapter, a mechanical intelligence strategy based on exploiting the hand topology to achieve predictable behaviours of the object

manipulated, using low-level, simple non-position control schemes with a minimum number of actuators, has been studied. This approach is exemplified by the rigorous analysis, development, and testing of a novel three-fingered two-actuator underactuated robot hand, called the helical hand, which is capable of self-adaptive precision grasping, and of generating helical prehensile in-hand motions of unknown objects by simply setting both actuators at a constant speed.

4.1 Introduction

Mechanical intelligence can be defined as the use of mechanical and other physical properties to create robotic systems adaptable to new external situations using simple control schemes. Principles of mechanical intelligence have been well developed in underactuated hands for grasping tasks, incorporating elastic and passive elements to generate self-adaptation for dealing with uncertainties [BLG07]. Multiple hand designs have certainly been designed and implemented following these principles. Ma et al. [MOD13] proposed an open source, low-cost, single-actuator, 3D-printed underactuated hand with four adaptive fingers. This hand shows the capability of grasping with compliant flexure joints, following ideas previously presented in [Dol06]. An alternative to creating compliant underactuated hands is to use joints with locking mechanisms. Aukes et al. [AHU⁺14] proposed a hand design which is capable to lock individual joints. Then, by locking and unlocking, the hand can adopt grasp capabilities and configurations similar to a fully actuated hand. Moving away from traditional flexure joints, Bai and Rojas [BR18] presented a self-adaptive one-step 3D printed robotic gripper, where the joints are based on a teeth-guided compliant cross-four-bar linkage. This basic single-material, additive manufactured, underactuated hand increases the precision of robotic fingers by removing nonlinear characteristics of flexures. The Ocean One hand [SWKC17] is a tendon-driven robotic hand for deep-sea exploration. In this case, elastic finger joints and a spring transmission are leveraged to achieve a variety of adaptive power grasps. This last research is an example that shows why underactuated hands, with their simpler control and reduced hardware complexity, have become of great use for the robotics community and for diverse robotics applications.

For robotic hands, there are two major types of grasps: power grasp and precision grasp. The precision grasp is associated with the handling of objects between the fingertips, also called the pinch grasp.

The research mentioned above are mainly focus on the power grasp. The ability of underactuated hands to perform precision grasps on objects is very limited, because the precision grasp is normally unstable. Kragten et al. [KBGH11] improved the underactuated hand precision grasp performance by simple design modification by reshaping the distal phalanges of the fingers into a curve surface. Teeple et al. [TKGW20] designed a two-segment fluid-driven soft finger for pinch grasping. The Velo gripper can perform both parallel and fingertip grasps with a single actuator [CHH⁺14], being able to pick up small objects off of a flat surface. Due to a limited number of contact points, 2-fingered grippers struggle to precision grasp the object with additional dynamic forces from the robot arm. 3-fingered grippers show better stability under dynamic forces but still not enough. To provide equal contact forces, traditional 3-fingered grippers positions their fingers in a trigonal way during pinch grasp [TTS15, Rob16, OJC⁺14]. This finger position is normally restricted to pinch grasp regular objects with normal fingers. To improve the grasping capability for irregular objects, additional DOF is added at the base of the fingers for rotation or abduction to achieve different grasping configurations [Rob16, OJC⁺14]. However, with a single motor actuation, the self-adaptability for all three fingers is limited.

Apart from the grasping, in-hand manipulation under simple control scheme is also an active research problem. Dexterous in-hand manipulation broadens the utility of the hand for not only acquiring and maintaining grasps but also for allowing fine adjustments to the position and orientation of the grasped object. This re-positioning is called precision in-hand manipulation when it occurs without breaking or changing the contact between each fingertip and the object [RD16b], but the notion of in-hand manipulation is certainly broader [BMD12]. Some robotic hands exploiting mechanical intelligence have been developed to facilitate in-hand manipulation. For example, the GR2 gripper [RMD16] is a two-fingered hand that introduces an elastic pivot joint between the fingers to enlarge the range of planar reorientation. [DSPG⁺18] designed an intelligent embodied tendon-driven mechanism based on turning transmission friction from a disturbance into a design tool to perform a variety of grasping and manipulation tasks. [LZZX18] proposed a three-fingered gripper that is actuated by a single motor and is able to grasp objects and perform rolling manipulation with a working mode switching mechanism. [MRD16b, MRD16a] proposed a specific hand topology to do spherical motion without relying on object geometry size and grasp location, but the coordinated control of fingers to perform

the spherical manipulation was not simple. However, these two previous works on the spherical hands along with the GR2 gripper constitute the seed of the mechanical-intelligent strategy for in-hand manipulation herein discussed.

Since the hand-object system formed during in-hand manipulation operations constantly generates multiple closed-loop kinematic chains that inherently impose constraints that modify the feasible movements of both the hand and the object, I consider that the design of robot hands for dexterous manipulation must depart from the traditional hand-centered approach to embrace a holistic view that takes into account the manipulated bodies without losing generality. Following this approach, it is then possible to talk about predictable behaviors of the hand-object system to be controlled using low-level, simple non-position schemes with the minimum number of actuators. These behaviors refer to particular compositions of displacements of the object respect to the palm resulting from in-hand prehensile manipulations. Position control of actuators is not desirable as the resulting coordination of fingers for in-hand manipulation may be complex, what jeopardises the control simplicity sought in this work.

A prehensile in-hand helical manipulation trajectory was chosen because its efficient control remains an open problem in the dexterous manipulation literature. For instance, unscrewing and screwing objects is an important ability for humans but reproducing it has normally required detailed knowledge about the object position and contact location with sensor feedback, as well as redundant control systems. Examples of these approaches are [KKE14] and [KKE12], where bioinspired sinusoidal finger joint synergies and electrocardiogram synergy control of an anthropomorphic artificial hand were used. Shih et al. [SDC⁺17] proposed a simpler solution based on a soft robotic gripper that can twist objects but it requires 3 pneumatic chambers per each finger. [ZGR⁺19] recently developed a deep reinforcement learning algorithm for some related everyday hand manipulations such as valve rotation, box flipping, and opening a door with flexible handle using a three-fingered simple hand, but these operations, as set by the authors, do not require prehensile motions.

In this chapter, the mechanical intelligence strategies based on the hand topology design has been developed to achieve not only the precision grasping but also the dexterous in-hand manipulation under low-level control scheme. Here, we are particularly interested in behaviours of manipulation

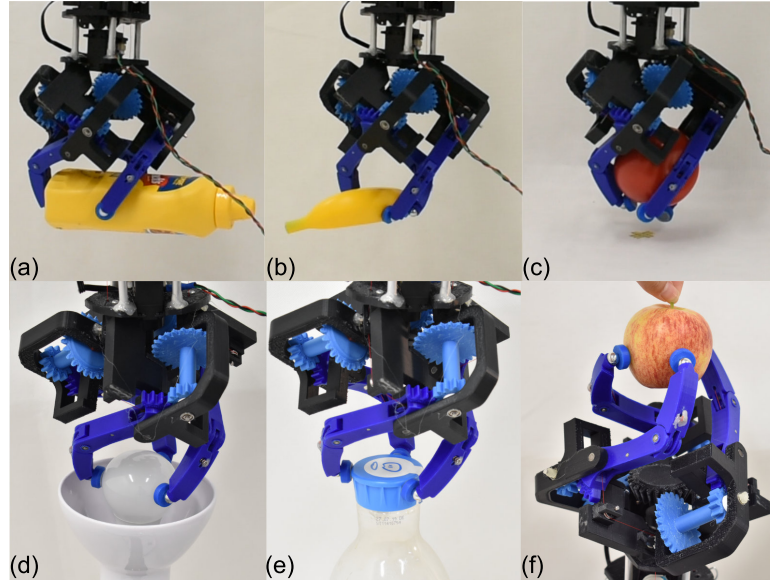


Figure 4.1: Examples of the proposed hand performing adaptive precision grasps (a, b), spiral power grasps (c) and helical prehensile in-hand manipulations (d-f) are shown above.

that go beyond simple rotations and translations along the robot hand coordinate axes to include spatial trajectories (e.g., a helix). A novel three-fingered two-actuator underactuated robot hand, called *the helical hand* (see Fig. 4.1) has been developed based on the hand topology principle which capable of self-adaptive precision grasping, and of generating helical prehensile in-hand motions of unknown objects by simply setting both actuators at a constant speed.

In the following sections, In Section 4.2 I describe the topology of the underactuated hand-object system of the helical hand and the prototype design. Later, the feasible grasping workspace of the helical hand is established based on the kinematic and kinetostatic analysis in Section 4.3. Then the helical in-hand manipulation is thoroughly analysed in Section 4.4 using a mathematical model to gain insight into this type of manipulation. From this model, a low-level control scheme (Section 4.5) is presented and its practical control algorithm based on the differential system is detailed. Both grasping (Section 4.6) and helical motion (Section 4.7) performance have been evaluated via five different tests. Then the results from the experiments are discussed with limitations as well as future developments in Section 4.8. Lastly, the conclusion is made in Section 4.9 .

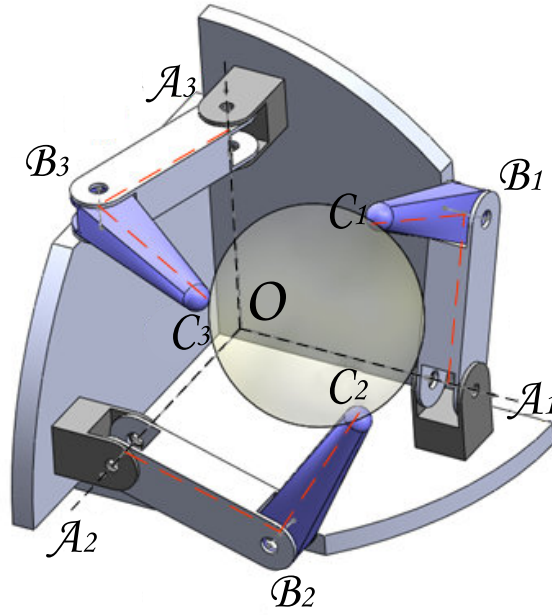


Figure 4.2: Kinematic structure of the helical hand: three fingers attached to three orthogonal planes.

4.2 The Helical Hand

4.2.1 Topology of the Helical Hand

Figure 4.2 shows the kinematic structure of the helical hand. The robotic hand consists of three fingers, each finger is composed of two parallel revolute joints. The fingers are attached to three orthogonal planes, where the proximal joint axes, defined by points O and A_i , are perpendicular to each other. The lengths of segments $\overline{OA_i}$ determine the hand's capacity (volume).

During in-hand manipulation, the contact model between the fingertips and the object is assumed as point contact with friction, the kinematic equivalent of which is a spherical joint [RD16a]. Therefore, the hand-object system, regardless of the object's particularities, is equivalent to a closed kinematic chain composed of 8 links with 3 branches of serial limbs. Each branch is formed by two revolute joints R and one spherical joint S , the resulting kinematic model corresponds then to a rotational cubic parallel manipulator [CLH10].

It is widely known that the generic mobility M of a closed kinematic chain can be characterised by its structural factors; namely, total number of degrees of freedom (DOF) F of the joints, number of

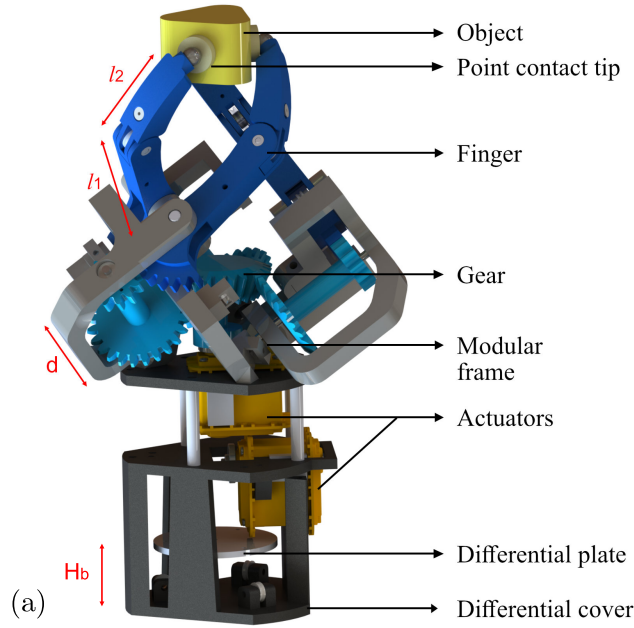


Figure 4.3: CAD model of the proposed helical hand

joints J , and number of links L [RD16b]. Then, according to the extended Chebychev-Kutzbach-Grübler criterion, for the hand-object system of the helical hand we have $M = F - \sum_{i=1}^{\lambda} t_i = 3$, where $\lambda = J - L + 1 = 2$ is the number of independent loops of the kinematic chain and t_i is the motion type of the i th independent loop. $t_i = 6$ in the helical hand.

Since the mobility of the hand-object system for the helical hand (under the point contact with friction assumption) is 3, the feasible movements of a manipulated object correspond to a three-manifold. If as many motors as the computed mobility are used, the hand-object system is fully-actuated. However, herein, the helical hand consists of two actuators for grasping and manipulation. One actuator for the three proximal joints and one actuator for the three distal joints. This makes the hand-object system underactuated.

4.2.2 Hand Design

Figure 4.3 shows the CAD view of the helical hand which is designed based on the topology of the underactuated hand-object system and the static and kinematic model analysis. All three fingers are identical and attached to three orthogonal planes, the proximal joints are gear actuated and the distal joints are driven by tendons. In the model, d determines the hand base palm size, the length of the

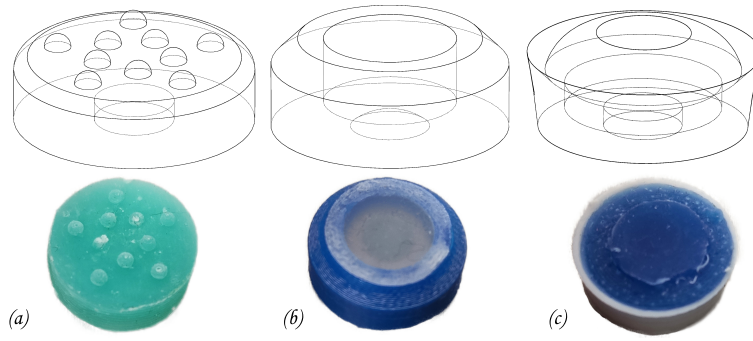


Figure 4.4: Multiple fingertip designs: (a) fully soft design, (b) dual design with soft and rigid, and (c) nail design

fingers l_i determines the grasping height and position. The H_b is the height between the differential plate to the base. With larger H_b , distal links can have larger adaptation. There is an offset between the size of H_b , the distal actuation range and the hand height. The detailed working principles can be found in control scheme section. Fig. 4.3 shows the name of each part. The hand is mainly divided into two parts: the top part is a cubic structure based finger system and the bottom part is the actuation and the differential system.

Following the topology of the hand, the helical hand is designed to use only two motors, one for the proximal links and the other one for the distal links. In order to actuate the proximal links in three different orientations by only using one motor, a specifically arranged and designed bevel gear transformation system was used. The centre motor needs to produce enough torque to actuate the centre bevel gear, since this bevel gear actuates three other bevel gears which are related to the three proximal links respectively. The gear ratio is set as one to keep the control simple.

The distal links are driven by a single motor via a tendon with a differential system in it. This differential system is designed for passively adapting to the shape of the object. For instance, once two fingers are stopped by an object, the third finger is able to adapt the object passively through the differential plate. Each distal joint has a torsional spring in it to pull the distal link towards to its initial position when the tendon is loose. The detailed control scheme can be found in Section 4.5 with the illustration (Fig. 4.14 and Fig. 4.15) of the tendon routing and differential plate working principle.

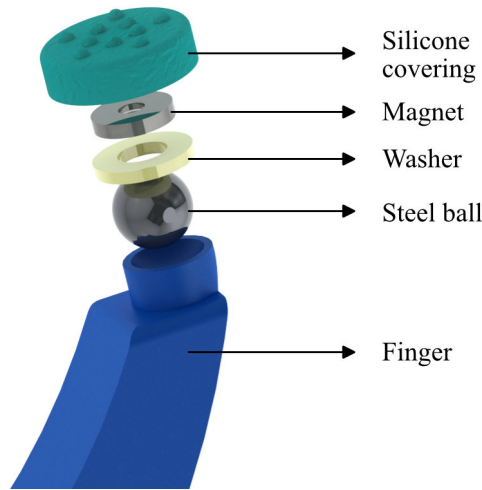


Figure 4.5: The rotary fingertip consists of a silicone cover, a magnet with a space washer and a steel ball embedded in the fingertip.

4.2.3 Rotary Fingertip Design

This hand object model is assumed as a point contact with friction model as discussed in the previous section. However, in practice, it is hard to maintain a point contact with friction in physical systems. The kinematic equivalent of a point contact with friction is a spherical joint, so we introduce the passive, rotary fingertip design to generate a stable contact. This design used magnets and steel balls to produce smooth passive rotary joints.

To achieve a stable grasp, the contact area between fingertips and object needs to increase. Therefore, a disk design is better than a ball design. According to [LR19], the fingertip should be thin and soft to have a good operability which means the disk should be soft and thin. However, making the entire disk from soft material (Fig. 4.4 (a)) is not the best way. It may work perfectly when grasping large objects in the space without touching the ground surface. When picking up small objects or flat objects, the fingertips need to touch the ground and slide underneath the object. The high friction between the soft material and the ground will prevent the sliding motion and if the friction force is too large, the rotary fingertip will drop off from the steel ball.

A dual design (Fig. 4.4 (b)) of a soft material that is surrounded by a rigid material can decrease the friction force when touching the ground. However, the chamfer design around the edge of the rotary disk will create a gap when touching an object. More concretely, when two human fingertips touch together, there is a gap between two end tips. A human will then operate their distal phalanges to

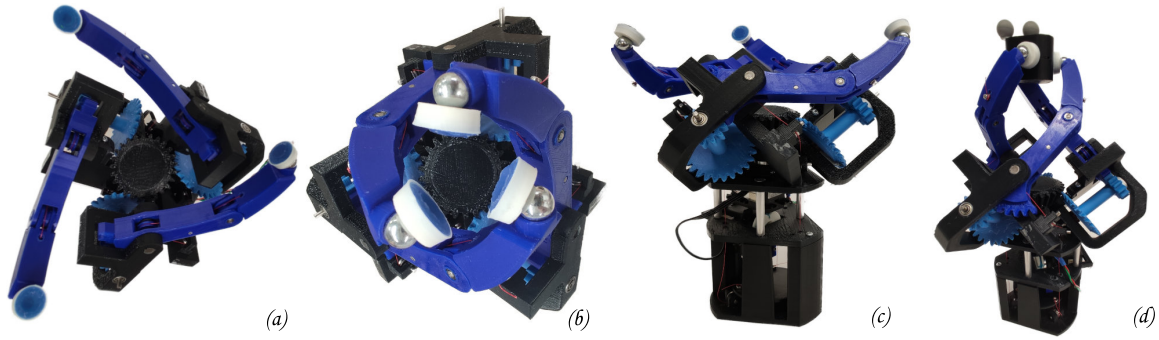


Figure 4.6: Multiple views of the prototype of the helical hand. (a) and (b) are top views of the hand. (a) is the open position and (b) is the grasping position. (c) and (d) are side views of the hand. (c) is the open position and in (d) the hand is grasping a 30mm triangular object. ©2021 IEEE. Reprinted, with permission, from [LBBR]

perform the pinch motion, but for this helical hand the fingertips are passive adaptive to the external forces, it will not be able to pick up flat objects from the ground.

An optimised nail design inspired by [BG18] (Fig. 4.4(c)) has added on the disk to solve the issue. A thin outer layer decreases the friction between contacts effectively which allows the disk to perform a scooping motion. In addition, the inner soft design can hold the object properly. This design increases the hand grasping and pinching capabilities. Fig. 4.5 shows the basic component of the rotary fingertip. A washer, added between the magnet and the steel ball, serving as the low friction sliding surface of the joint. The thickness of the washer can be varied by the strength of the magnet. For the other two fingertip designs, washers are not needed. The thickness of the outer layer case is doing the same job as a washer.

4.2.4 Prototype Design

Figure 4.6 shows the multiple views of the prototype. The maximum height of the hand is about 30cm when in the closed position (Fig. 4.6 d) and the minimum height is around 25cm when in the opened position (Fig. 4.6 c). The maximum width of the helical hand is around 20cm. The length of the proximal links and the distal links are the same around 5.5cm. The weight of the prototype in total is 570g. The prototype was constructed mostly from 3D printed parts on a single nozzle desktop 3D printer. Acrylonitrile butadiene styrene (ABS) are used for all 3D printed parts which included the fingers, modular cases, bevel gears and differential system. Two FeeTech servos (SCS115) are

used to control the helical hand through gears and tendons. The soft part of the rotary fingertips is moulded by silicone Ecoflex-10 and the rigid case is 3D printed by ABS. The thickness of the nail design fingertip is 6mm and the hardness is about Shore $C - 17$. The actuation range of the proximal joints and distal joints are from -48° to 7° and 75° to 107° respectively.

4.3 Static Modelling of Object Configuration Workspace

In this section, the grasping capability of the helical hand is shown by computing the set of feasible configurations in which the object can be grasped or moved into; referred to as the feasible grasping workspace. The workspace is determined by performing the kinetostatics of the helical hand by modelling the hand-object system using a parallel robots framework. A hand-object system, using the point contact with friction assumption, can be analysed as a parallel robot as long as the contact force at each fingertip is within its respective friction cone [BD14], as this maintains the spherical joint kinematic equivalence. The computed workspace shows that the hand is capable of achieving stable grasps for many different configurations and orientations of the object, and therefore complex spatial trajectories, such as helical motion, can be performed.

4.3.1 Kinematic Analysis of the Helical Hand

The kinematic analysis describes the relationship between the grasping object and the hand configuration. The schematic view of the hand-object system is shown in Fig. 4.7. The global coordinate system $O - XYZ$ fixed to the base O is defined as $\{B\}$, and the three revolute joint axes of the hand are coaxial with the three coordinate axes of $\{B\}$. The coordinate system $o - xyz$ fixed on the moving object o is defined as $\{m\}$, which is also located on the centre of the triangle defined by the contact points C_1 , C_2 , and C_3 . In addition, without loss of generality, the y -axis of $\{m\}$ is parallel to the line defined by C_2 and C_3 , and the z -axis is perpendicular to the plane defined by C_1 , C_2 , and C_3 .

The configuration of the hand is determined by the coordinates of B_i and C_i . Here we are using the object size a, b, c and other hand parameters to define the hand configuration. The length of the base

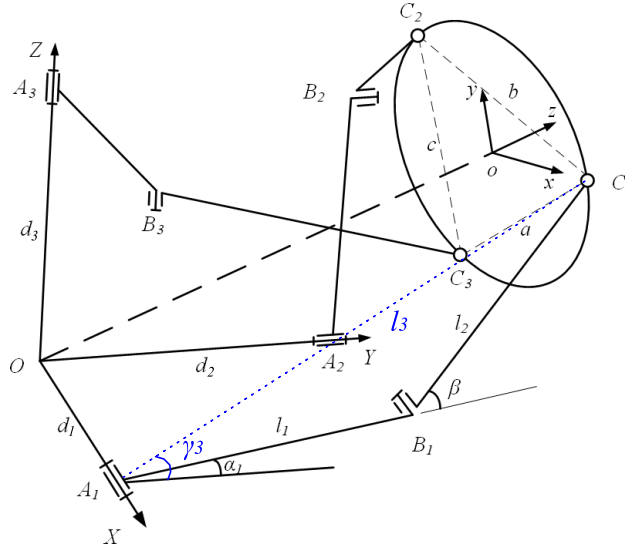


Figure 4.7: Schematic view of the hand-object system with global coordinate systems O-XYZ and object coordinate system o-xyz. Blue references show the case when β_i is fixed during grasping.

side OA_i is denoted by d_i . The coordinates of the fixed point A_i in $\{B\}$ are then $A_1 = [d_1, 0, 0]^T$, $A_2 = [0, d_2, 0]^T$, and $A_3 = [0, 0, d_3]^T$, and based on the forward kinematics, the coordinates of the distal joints B_i in $\{B\}$ are

$$B_1 = \begin{bmatrix} d_1 \\ l_1 \cos \alpha_1 \\ l_1 \sin \alpha_1 \end{bmatrix}, B_2 = \begin{bmatrix} l_1 \sin \alpha_2 \\ d_2 \\ l_1 \cos \alpha_2 \end{bmatrix}, B_3 = \begin{bmatrix} l_1 \cos \alpha_3 \\ l_1 \sin \alpha_2 \\ d_3 \end{bmatrix}. \quad (4.1)$$

Similarly, the coordinates of the contact points C_i in $\{B\}$ ($O-XYZ$) are then

$$C_1 = \begin{bmatrix} d_1 \\ l_1 \cos \alpha_1 + l_2 \cos(\alpha_1 + \beta_1) \\ l_1 \sin \alpha_1 + l_2 \sin(\alpha_1 + \beta_1) \end{bmatrix},$$

$$C_2 = \begin{bmatrix} l_1 \sin \alpha_2 + l_2 \sin(\alpha_2 + \beta_2) \\ d_2 \\ l_1 \cos \alpha_2 + l_2 \cos(\alpha_2 + \beta_2) \end{bmatrix}, \quad (4.2)$$

$$C_3 = \begin{bmatrix} l_1 \cos \alpha_3 + l_2 \cos(\alpha_3 + \beta_3) \\ l_1 \sin \alpha_3 + l_2 \sin(\alpha_3 + \beta_3) \\ d_3 \end{bmatrix}, \quad (4.3)$$

where α_i is the angle between the proximal link and its reference line, and β_i is the angle between the distal link and the proximal link, as shown in Fig. 4.7.

In order to compute the initial grasp configuration based on the object size, the compliant adaptive characteristic of the distal link is disregarded and the initial rest angle β_i is set to 45° . Therefore, the length of $A_i C_i$ (say l_3) is fixed. The angle between $A_i C_i$ and its reference line is called γ_i shown in Fig. 4.7 as blue. Equation (4.2) is then simplified as

$$C_1 = \begin{bmatrix} d_1 \\ l_3 \cos \gamma_1 \\ l_3 \sin \gamma_1 \end{bmatrix}, C_2 = \begin{bmatrix} l_3 \sin \gamma_2 \\ d_2 \\ l_3 \cos \gamma_2 \end{bmatrix}, C_3 = \begin{bmatrix} l_3 \cos \gamma_3 \\ l_3 \sin \gamma_3 \\ d_3 \end{bmatrix}. \quad (4.4)$$

Considering the size of the manipulated object, C_i should satisfy the following system of equations:

$$\begin{aligned} |C_1 C_2| &= \sqrt{(L_3 s \gamma_2 - d_1)^2 + (d_2 - L_3 c \gamma_1)^2 + (L_3 c \gamma_2 - L_3 s \gamma_1)^2} = a \\ |C_2 C_3| &= \sqrt{(L_3 c \gamma_3 - L_3 s \gamma_2)^2 + (L_3 s \gamma_3 - d_2)^2 + (d_3 - L_3 c \gamma_2)^2} = b, \\ |C_3 C_1| &= \sqrt{(d_1 - L_3 c \gamma_3)^2 + (L_3 c \gamma_1 - L_3 s \gamma_3)^2 + (L_3 s \gamma_1 - d_3)^2} = c \end{aligned} \quad (4.5)$$

where s^* and c^* mean $\sin(*)$ and $\cos(*)$. When the size of the manipulated object is given, γ_i can be obtained by solving the above equations. Then, the corresponding coordinates of the three contact points C_i and the orientation of the object can be found out. Those equations define the grasping configuration of the hand based on the grasped object size.

4.3.2 Kinetostatic Analysis

During the grasp phase, the tendon which actuates the distal link remains locked. This means, at the point of grasping, the force transmitted through each fingertip is induced entirely by the actuator

connected to the proximal joint. As the distal joint is locked at the point of grasping, the finger can be modelled as a single link, with an actuated revolute joint connecting it to the base, and three coincident revolute joints whose axes are orthogonal to each other at the contact point.

Here we use the theory of reciprocal screws to determine the matrix which relates the input actuator torques to the wrench exerted onto the grasped object [MD85]. A twist induced by a revolute joint is described by the following 6-dimensional vector

$$\$_r = (\mathbf{s}, \mathbf{p} \times \mathbf{s})^T, \quad (4.6)$$

where $\mathbf{s}$ is the axis of rotation of the joint and $\mathbf{p}$ is its position [JT02, Mer06]. The twist, $\mathbf{T}$, transmitted to the grasped object by each finger is equal to the sum of the twists induced by each joint [MD85], written as

$$\mathbf{T} = \sum_{j=1}^4 \dot{\theta}_{i,j} \$_{i,j}, \quad (4.7)$$

where $i = 1, 2, 3$ denotes the finger number, $j = 1, 2, 3, 4$ denotes the joint number, $\dot{\theta}_{i,j}$ denotes the angular velocity of the j^{th} joint of the i^{th} finger and $\$_{i,j}$ denotes its screw axis. Joint $j = 1$ denotes the proximal joint and joints $j = 2, 3, 4$ denote the three coincident revolute joints (spherical joint) at the contact point.

The aim is to eliminate all of the screws which correspond to the passive joints of the finger; i.e. the three passive joints which represent the contact point. This is achieved by finding the screws which are reciprocal to all of the passive joints in the finger. Two screws, $\$_1 = (\mathbf{s}_1, \mathbf{p}_1 \times \mathbf{s}_1)^T$ and $\$_2 = (\mathbf{s}_2, \mathbf{p}_2 \times \mathbf{s}_2)^T$, are reciprocal to one another if their reciprocal product is zero, such that

$$\$_1 * \$_2 = \$_1^T \Delta \$_2 = (\mathbf{p}_1 \times \mathbf{s}_1) \cdot \mathbf{s}_2 + (\mathbf{p}_2 \times \mathbf{s}_2) \cdot \mathbf{s}_1 = 0, \quad (4.8)$$

where

$$\Delta = \begin{bmatrix} \mathbf{0} & \mathbf{I}_3 \\ \mathbf{I}_3 & \mathbf{0} \end{bmatrix}, \quad (4.9)$$

with $\mathbf{0}$ and $\mathbf{I}_3$ being 3×3 zero and identity matrices, respectively. Physically speaking, two screws are reciprocal to one another if every wrench along $\$_1$ does zero work on a rigid body constrained to

move only along a twist $\$2$ [MA11].

In [JT02], two separate Jacobian matrices are formed; the *Jacobian of constraints* and the *Jacobian of actuations*. The Jacobian of constraints is formed by determining the system of reciprocal screws that are reciprocal to all joints in the chain; for the i^{th} chain of the mechanism which has a connectivity of g_i , the reciprocal screws form a $(6 - g_i)$ system. The Jacobian of actuations is formed by locking the actuated joint in the chain, and determining the system of screws reciprocal to all joints except the actuated one, forming a $(6 - g_i + 1)$ system. We only require to form the Jacobian of actuations for our analysis, as it is this matrix which relates the input joint velocities/torques to the twist/wrench of the grasped object.

Firstly, the reciprocal screw for each finger is identified, such that

$$\$_{ri}\Delta\mathbf{T} = \$_{ri}^T\Delta\$_i\dot{\theta}_i \quad i = 1, 2, 3, \quad (4.10)$$

where $\$_{ri}$ is the reciprocal screw of the i^{th} finger and $\$_i\dot{\theta}_i$ is the twist of the proximal joint of that finger. This system of three equations forms the matrix relation

$$\mathbf{J}_p\mathbf{T} = \mathbf{J}_\theta\dot{\boldsymbol{\theta}}, \quad (4.11)$$

where

$$\mathbf{J}_p = \begin{pmatrix} \$_{r1}^T\Delta \\ \$_{r2}^T\Delta \\ \$_{r3}^T\Delta \end{pmatrix}, \quad (4.12)$$

$$\mathbf{J}_\theta = \begin{pmatrix} \$_{r1}^T\Delta\$_1 & 0 & 0 \\ 0 & \$_{r2}^T\Delta\$_2 & 0 \\ 0 & 0 & \$_{r3}^T\Delta\$_3 \end{pmatrix}, \quad (4.13)$$

and $\dot{\boldsymbol{\theta}} = (\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3)^T$. The screws of the proximal joints of the three fingers are given by

$$\$_1 = \begin{pmatrix} (1, 0, 0)^T \\ \mathbf{a}_1 \times (1, 0, 0)^T \end{pmatrix}, \quad (4.14)$$

$$\$_2 = \begin{pmatrix} (0, 1, 0)^T \\ \mathbf{a}_2 \times (0, 1, 0)^T \end{pmatrix}, \quad (4.15)$$

$$\$_3 = \begin{pmatrix} (0, 0, 1)^T \\ \mathbf{a}_3 \times (0, 0, 1)^T \end{pmatrix}, \quad (4.16)$$

and the reciprocal screws are given by

$$\$_{r1} = \begin{pmatrix} (\mathbf{c}_1 - \mathbf{a}_1) \times (1, 0, 0)^T \\ \mathbf{c}_1 \times ((\mathbf{c}_1 - \mathbf{a}_1) \times (1, 0, 0)^T) \end{pmatrix}, \quad (4.17)$$

$$\$_{r2} = \begin{pmatrix} (\mathbf{c}_2 - \mathbf{a}_2) \times (0, 1, 0)^T \\ \mathbf{c}_2 \times ((\mathbf{c}_2 - \mathbf{a}_2) \times (0, 1, 0)^T) \end{pmatrix}, \quad (4.18)$$

$$\$_{r3} = \begin{pmatrix} (\mathbf{c}_3 - \mathbf{a}_3) \times (0, 0, 1)^T \\ \mathbf{c}_3 \times ((\mathbf{c}_3 - \mathbf{a}_3) \times (0, 0, 1)^T) \end{pmatrix}. \quad (4.19)$$

Matrices $\mathbf{J}_p$ and $\mathbf{J}_\theta$ are then used to formulate the static equilibrium equation via the principle of virtual work [Tsa99], such that

$$-\mathbf{W} = \mathbf{J}_p^T \mathbf{J}_\theta^{-T} \boldsymbol{\tau}, \quad (4.20)$$

where $\mathbf{W}$ is the total wrench exerted on the grasped object, and $\boldsymbol{\tau}$ is the vector of torques applied to the actuated joints. As all of the proximal joints are actuated by a single motor, this vector is written as

$$\boldsymbol{\tau} = \begin{pmatrix} k_1 \\ k_2 \\ k_3 \end{pmatrix} \tau, \quad (4.21)$$

where k_i is the transmission ratio between the actuator and the proximal joint of the i^{th} finger, and τ

is the torque applied by the actuator. By writing

$$\mathbf{J}^T = \mathbf{J}_p^T \mathbf{J}_\theta^{-T}, \quad (4.22)$$

each column of $\mathbf{J}^T$, denoted as $\mathbf{s}_i$, corresponds to the vector of forces and moments transmitted by the actuator to the i^{th} fingertip, such that $\mathbf{s}_i = (\mathbf{f}_i, \mathbf{m}_i)^T$.

Assuming that the grasped object is spherical and the contact points are well distributed, we can define the centre of the object, $\mathbf{p}$, as the mean of the contact points and then define the unit vector from each contact point to the centre of the object as $\hat{\mathbf{n}}_i$. Following this, the fingertip force can be split into the component projected along $\hat{\mathbf{n}}_i$, given by ${}^n f_i = \mathbf{n}_i^T \mathbf{f}_i$, and the component projected along the normal plane, given by ${}^\perp f_i = \|\mathbf{f}_i - {}^n f_i \mathbf{n}_i\|$. The fingertip is inside the friction cone as long as

$${}^\perp f_i \leq \mu {}^n f_i, \quad (4.23)$$

where μ is the coefficient of friction.

4.3.3 Workspace Determination

The workspace of feasible grasps of the object is the set of positions and orientations of the object for which equation (4.23) holds. A representation of the workspace can then be obtained by sweeping through the 6-dimensional space which represents the position and orientation of the object, and a point is included in the workspace if equation (4.23) holds and is excluded if not. A numerical representation of the feasible grasp workspace for the helical hand, displayed in Fig. 4.8, is obtained for a gripper with the following dimensions: $d_1 = d_2 = d_3 = l_1 = l_2 = 55mm$, according to the notation of Fig. 4.7. The object to be grasped has the shape of an equilateral triangle, and the contact points are assumed to be located at the mid-point of each side of the triangle, such that the separation between each contact point is $50mm$.

The workspace is obtained by sweeping through a set of possible contact point positions and using the method described above to determine whether the fingertip is inside the friction cone for each

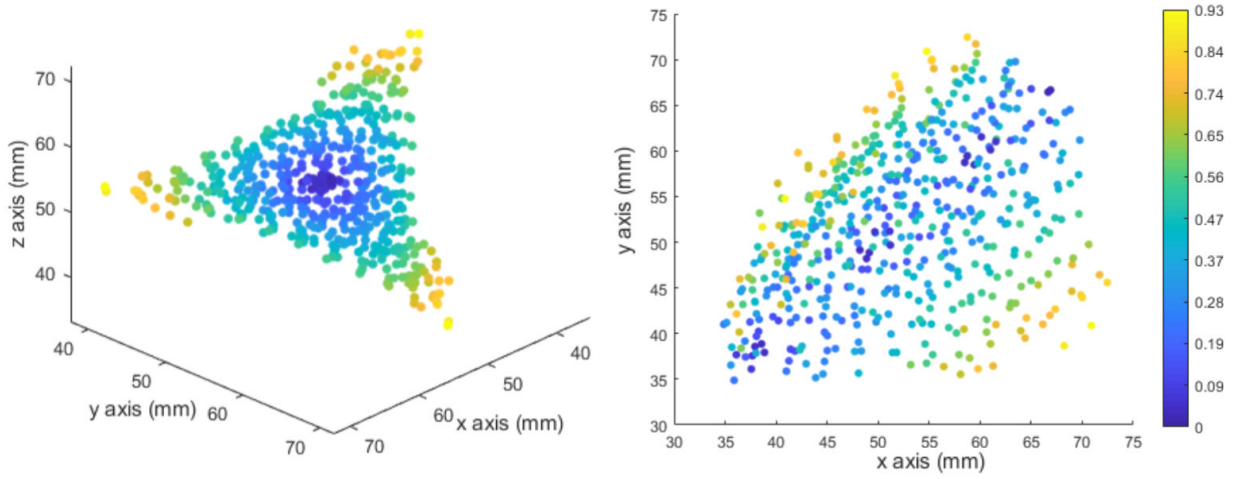


Figure 4.8: **Left:** Top view of the simulated feasible grasping workspace representing jointly position and orientation. Each point represents the centre position of the object, with yellowish coloring denoting a greater tilt of the object with respect to the diagonal axis. See text for further details. **Right:** X-Y plane view. Legend unit in radian.

position. Firstly, the y and z coordinates of $\mathbf{C}_1$, denoted by C_{1y} and C_{1z} , are swept through for values between 0 and 100 (all values are given in mm); recall that C_{1x} always equals d_1 . For each position of $\mathbf{C}_1$, $\mathbf{C}_2$ must be positioned upon the circle which lies in the $y = d_2$ -plane, centred around (d_1, C_{1z}) with a radius of $r_a = \sqrt{d_{1,2}^2 - (d_2 - C_{1y})^2}$, where $d_{1,2}$ denotes the distance between contact points $\mathbf{C}_1$ and $\mathbf{C}_2$, which has been set as 50mm . For each position of $\mathbf{C}_2$ along this circle, there are two possible positions of $\mathbf{C}_3$; these are given by the points of intersection between the circles which lie in the $z = d_3$ -plane, centered around (d_1, C_{1y}) and $(C_{2,x}, d_2)$, with radii of $r_b = \sqrt{d_{1,3}^2 - (d_3 - C_{1z})^2}$ and $r_c = \sqrt{d_{2,3}^2 - (d_3 - C_{2z})^2}$, respectively.

For each contact point, the position of the corresponding distal joint, B_i , is computed to check if the distance constraints are satisfied. If so, equations (4.11)-(4.23) are used to assess if the forces are within the friction cones; if they are, the point $\mathbf{p}$, the mean of the contact points, is added to the feasible workspace. The full workspace is obtained by repeating this method and changing the order in which the the contact points are swept through/computed in order to ensure each part of the workspace has been swept through equally.

The workspace depicted in Fig. 4.8 shows the set of feasible positions of the grasped object and the tilt of the object with respect to the diagonal axis (axis defined by points O and o in Fig. 4.7), whose magnitude is represented according to the color bar on the right-hand side. The tilt angle is obtained

by determining the normal vector to the plane defined by the three contact points, and computing the angle between it and the diagonal axis. Fig. 4.8 shows that the tilt angle is zero along the diagonal axis in the center of the workspace and approaches its maximum value, 0.93 radians (53.3°), at the edges of the workspace.

4.4 In-Hand Motion Analysis of Grasped Objects

4.4.1 Kinematic Analysis of Manipulation Phase

Based on the kinematic analysis of the grasping phase in Section 4.3.1, the following kinematic analysis is used to find the manipulation trajectory of the grasped objects. The orientation of the object with respect to the base frame $\{B\}$ is given by the orientation matrix R .

$$R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, \quad (4.24)$$

where r_{ij} are the elements of the orientation matrix at the i -th row and the j -th column. For the analysed hand dimensions ($d_1 = d_2 = d_3 = l_1 = l_2 = 55mm$), the $\{m\}$ coordinate system $o-xyz$ needs to rotate three times to fit the global coordinate system $O-XYZ$. Firstly, a rotation along the Z -axis of $\theta_1=45^\circ$. Then, a rotation along the X -axis of $\theta_2=54.736^\circ$. Finally, a rotation along the Z -axis of $\theta_3 = \delta+60^\circ$, where δ is the rotational angle between the Y -axis and y -axis (the orientation of the object) as shown in Fig. 4.9. Therefore, the corresponding orientation matrix R with $r_{i,j}$ components is:

$$\begin{aligned}
R &= R_Z R_X R_Z \\
&= \begin{bmatrix} c\theta_1 & s\theta_1 & 0 \\ -s\theta_1 & c\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\theta_2 & s\theta_2 \\ 0 & -s\theta_2 & c\theta_2 \end{bmatrix} \begin{bmatrix} c\theta_3 & s\theta_3 & 0 \\ -s\theta_3 & c\theta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4.25)
\end{aligned}$$

In our analysis, continuing with the grasping kinematic model assumptions, the manipulated body is an equilateral triangular object, where the edge lengths are the same, so the coordinates of the points C_i in $\{m\}$ can be simplified as $C'_1 = [\frac{\sqrt{3}}{3}a, 0, 0]^T$, $C'_2 = [-\frac{\sqrt{3}}{6}a, a/2, 0]^T$, and $C'_3 = [-\frac{\sqrt{3}}{6}a, -a/2, 0]^T$.

The origin coordinates of $\{m\}$ in $\{B\}$ are $\mathbf{o} = [o_x, o_y, o_z]^T$, and then $C_i = \mathbf{o} + RC'_i$ in $\{B\}$, such that

$$\begin{aligned}
C_1 &= \begin{bmatrix} o_x + \frac{\sqrt{3}}{3}ar_{11} \\ o_y + \frac{\sqrt{3}}{3}ar_{21} \\ o_z + \frac{\sqrt{3}}{3}ar_{31} \end{bmatrix}, \\
C_2 &= \begin{bmatrix} o_x - \frac{\sqrt{3}}{6}ar_{11} + \frac{1}{2}ar_{12} \\ o_y - \frac{\sqrt{3}}{6}ar_{21} + \frac{1}{2}ar_{22} \\ o_z - \frac{\sqrt{3}}{6}ar_{31} + \frac{1}{2}ar_{32} \end{bmatrix}, \\
C_3 &= \begin{bmatrix} o_x - \frac{\sqrt{3}}{6}ar_{11} - \frac{1}{2}ar_{12} \\ o_y - \frac{\sqrt{3}}{6}ar_{21} - \frac{1}{2}ar_{22} \\ o_z - \frac{\sqrt{3}}{6}ar_{31} - \frac{1}{2}ar_{32} \end{bmatrix}. \quad (4.26)
\end{aligned}$$

As the actuated joints of the helical hand are all revolute joints, the axis of rotation of the segment C_iA_i is in the direction of OA_i at A_i , which makes the x -coordinate of the point C_1 is always equal to d , and similarly for the y -coordinate of the point C_2 and the z -coordinate of the point C_3 as also shown

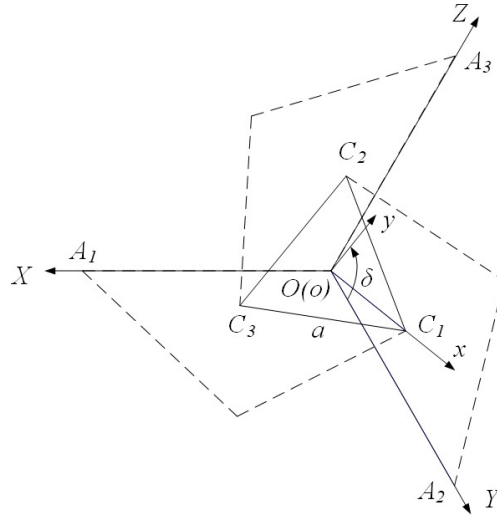


Figure 4.9: Top view of the hand-object system. δ is the rotation angle between the reference frames $\{m\}$ and $\{B\}$.

in equation (4.2). Then, we have

$$\begin{cases} C_{1x} = o_x + \frac{\sqrt{3}}{3}ar_{11} = d \\ C_{2y} = o_y - \frac{\sqrt{3}}{6}ar_{21} + \frac{1}{2}ar_{22} = d \\ C_{3z} = o_z - \frac{\sqrt{3}}{6}ar_{31} - \frac{1}{2}ar_{32} = d \end{cases}, \quad (4.27)$$

by rearranging, the relationship between the object coordinates and the object orientation is given by

$$\mathbf{o} = \begin{bmatrix} o_x \\ o_y \\ o_z \end{bmatrix} = \begin{bmatrix} d - \frac{\sqrt{3}}{3}ar_{11} \\ d + \frac{\sqrt{3}}{6}ar_{21} - \frac{1}{2}ar_{22} \\ d + \frac{\sqrt{3}}{6}ar_{31} + \frac{1}{2}ar_{32} \end{bmatrix}. \quad (4.28)$$

Finally, from the component r_{32} of the orientation matrix R , the relationship between the size of the object a and the orientation of the object δ can be found, namely

$$-\sin(\theta_2)\cos(\delta + \pi/3) = \frac{C_{2z} - C_{3z}}{a}. \quad (4.29)$$

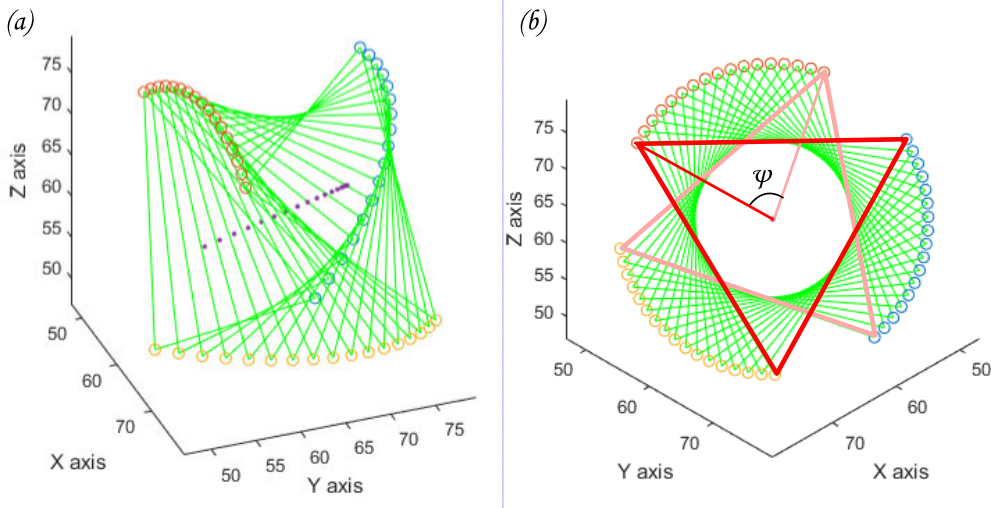


Figure 4.10: Simulation of the helical motion trajectory of a triangular object of size 30 mm. The coloured circles are the contact point positions of each finger, the purple dots indicate the centre point of the equilateral triangle. ψ indicates the object rotation range from the starting to the end position.

4.4.2 Helical Motion Determination

Based on the kinematic model of the manipulation phase, the trajectory of the grasped object can be worked out. I found out the grasped object has a coupled rotation and translation movement when actuating the hand. Figure 4.9 shows when the object rotates clockwise, the orientation δ decreases. For each δ , by using equation (4.25), the orientation matrix R can be worked out. Then the coordinates of $\mathbf{o}$ can be calculated by equation (4.28).

For helical motion, the characteristic is that the centre of the object will move along the rotation axis while performing rotation. In this case, for different δ , the coordinates of those different $\mathbf{o}$ should follow along the rotation axis. It has been verified via numerical simulation in MATLAB that when all the three fingers' movements are identical, for different δ , the position of $\mathbf{o}$ moves along the vector $\vec{v} = [1 \ 1 \ 1]$, where the value of o_x , o_y , and o_z are all equal for each $\mathbf{o}$. In addition, the direction vector of the centre line (diagonal axis) of the hand is $\vec{v} = [1 \ 1 \ 1]$ as well in spatial frame. This result shows that the hand is able to manipulate an object under a helical motion along its diagonal axis.

Figure 4.10 illustrates the helical motion of a equilateral triangular object in two views. ψ indicates the object rotation range, the coloured circles denote the contact point positions, and the purple dots denote the centre points of the object. This figure shows that when the orientation of the ob-

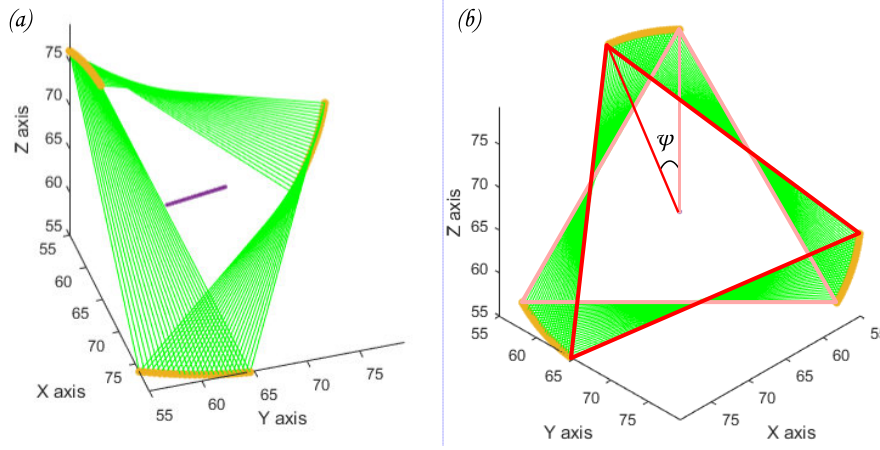


Figure 4.11: The constrained helical motion trajectory of a triangular object of size 30 mm based on the actual prototype's actuation range. Refer to Fig. 4.10

ject changes linearly, the translation distance $\|o\|$ is not linear in which objects have less translation variation when approaching to their maximum translation distance. In simulation, when plotted the translation distance vs time, the line is an approximately sine wave. In terms of the translation speed, it means objects will reach their maximum and minimum translation distances slowly and move relatively fast during the helical motion without considering the finger constraints.

4.4.3 Two-Motor Control

Since the translation matrix and orientation matrix can be used to calculate the contact point coordinates, see equations (4.26) and (4.28), the hand configuration can be defined through the inverse kinematics. If the coordinates of C_i are known, equation (4.2) can be solved for α_i and β_i . For example, see equation (4.30), by knowing the coordinates of point C_1 , there will be only two sets of α_1 and β_1 values, which means each finger will have two configurations to grasp the object at the same position

$$\begin{cases} C_{1y} = l_1 \cos \alpha_1 + l_2 \cos(\alpha_1 + \beta_1) \\ C_{1z} = l_1 \sin \alpha_1 + l_2 \sin(\alpha_1 + \beta_1) \end{cases} \quad (4.30)$$

Following these steps, given the moving trajectory of the object, when we keep $\alpha_1 = \alpha_2 = \alpha_3$, if the results of β_i are the same ie. $\beta_1 = \beta_2 = \beta_3$, then we can say this hand mechanism can perform the motion by using two motors, one for α joints, the other for β joints. Additionally, it can be shown using

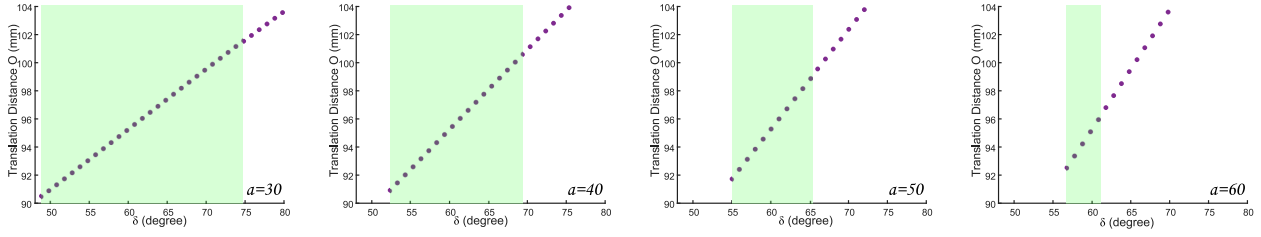


Figure 4.12: The relationship between the translation distance o and the orientation δ with different object sizes. Green areas indicate the feasible rotation range of each object.

numerical simulation that when β_i are constrained to be equal, α_i can be the same to produce a helical motion along the object z axis based on the equation. This shows that the hand has the ability to perform the helical motion along the object z axis by only using two motors.

4.5 Control via Mechanical Intelligence

Based on the actuation range of the prototype determined in Section 4.2.4, the proposed kinematic model and the performance of the grasped object are changing with those constraints. Fig. 4.11 shows the constrained motion trajectory of a triangular object of size 30mm, compared to Fig. 4.10, it is obvious that under the actuation constraints, the rotation and translation range of the grasped object decreases.

From equation (4.28) and (4.29), it can be seen that the object size is one of the factors that effects the manipulation range and the grasping configuration of the helical hand. Fig. 4.13 illustrates the relationship amongst the object size, the hand configuration (α & β), and the object orientation (δ). It shows for a z axis helical motion controlled by two motors, when the object rotates anti-clockwise (δ increases), the proximal joints α_i will increase and the distal joints β_i will decrease. Green areas are the feasible rotation ranges for each size of object when actuation angle constraints are applied. Here the constraints are based on the helical hand design. The proximal joints α_i range of the helical hand is between -48° and 7° and the distal joints β_i range is between 75° and 107° . The feasible rotation range (green shaded area) decreases significantly when the object size increases. Similarly, the translation distance o has been plotted with the object orientation δ in 4 different object sizes (Fig. 4.12).

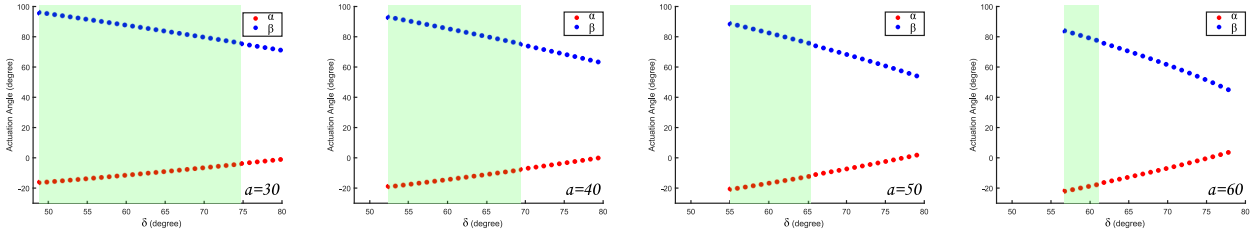


Figure 4.13: The relationship between the actuation angle α, β and the orientation δ with different object sizes (a). Green areas indicate the feasible rotation range of each object.

Table 4.1: Control relationship between proximal joints and distal joints

object size	δ range	α initial	α final	$\Delta\alpha$	β initial	β final	$\Delta\beta$	$\Delta\beta/\Delta\alpha$	new $\Delta\beta$	new β final
30 mm	48° -76°	-16.1°	-3.2°	12.9°	95.5°	74.5°	21°	1.6279	18.9°	76.6°
40 mm	52° -70°	-18.8°	-7.5°	11.3°	92.6°	74.9°	17.7°	1.5663	16.6°	76.0°
50 mm	55° -66°	-20.5°	-11.1°	9.4°	88.4°	74.1°	14.3°	1.5212	13.8°	74.6°
60 mm	56° -63°	-21.6°	-15.2°	6.4°	83.5°	74.1°	9.4°	1.4687	10.4°	74.1°

4.5.1 Control scheme

Both α_i and β_i in the green areas of Fig. 4.13 are approaching a linear trend for all sizes of objects. We analysed the variation of α_i and β_i inside of the green shaded area in Table 4.1 to see how the changing rate of α_i and β_i varies with the object size. For different sizes of objects, the table shows the ratio between the $\Delta\beta$ (distal joints variation) and the $\Delta\alpha$ (proximal joints variation) are similar. The results show that the hand has potential to use the same speed control scheme to manipulate different sizes of objects. Higher ratio indicates greater change in the distal joints when changing the proximal joints. For instance, for this prototype, if α_i are fixed, larger β_i provide smaller distances between contact points. Also, the β_i decreases when the α_i increases. Therefore, in order to choose a suitable $\Delta\beta/\Delta\alpha$ ratio for a secure grasp during manipulation, the change in distal joints ($\Delta\beta$) can only be smaller than required. In this case, we chose the minimum $\Delta\beta/\Delta\alpha$ ratio which is the 60 mm object (1.4687) to calculate the new $\Delta\beta$. According to the results, the maximum difference between the $\Delta\beta$ and the new $\Delta\beta$ is 2.1°. Broadly speaking, the difference is not obvious in terms of the prototype, we can establish a hypothesis that this mechanical design is capable to perform a predictable in-hand helical motion of various object sizes at a constant speed (velocity regulation). The performance of the helical hand with velocity regulation by applying the new β final has been evaluated in the next section.

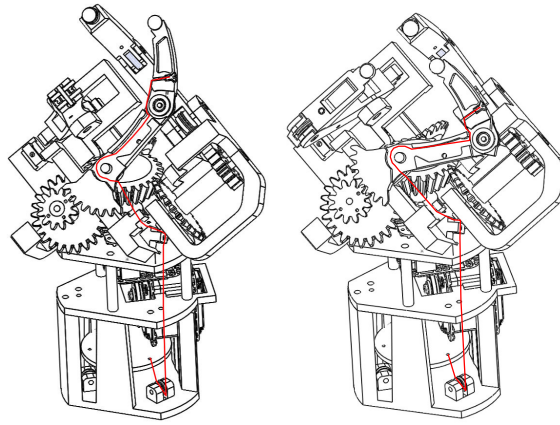


Figure 4.14: Section view of the tendon routing structure of the Helical Hand. Left: the hand is in a closed position. Right: the hand is in an open position.

4.5.2 Practical control algorithm

For the practical case, due to the prototype design, the conversion between the joint angles (α_i, β_i) and the actuation motor positions is not straightforward. Fig. 4.14 shows the tendon routing structure of one finger. The tendon starts from the back of the distal link, goes around the proximal joint and finishes at the differential plate. Given this routing method, those distal links are compliant adaptive to the proximal links. It means when the tendon is tightened in the close hand position shown in Fig. 4.14 (left), during the opening process, the distal link will move with the proximal link simultaneously without controlling the tendon. Since the change in joint angles will put the tendon in tension when approaching to the open hand position Fig. 4.14 (right).

This compliant adaptive characteristic is beneficial to the grasping stage, which provides the hand with possibilities to grasp irregular objects by only operating the proximal joints. Since for the differential system, the distal joints need space to perform the adaptation. When the distal joint is in its maximum or minimum position, the adaptation is not available because the distal link has no space to adapt when at the joint limit. As there is a differential system connected to the distal links, the distal links have compliant and adaptive characteristic when just control the proximal links (single motor) at a constant speed. This characteristic provides the hand with possibilities to grasp regular and simple irregular objects by only operating the proximal joints. However, this tendon changing differences due to the mechanical design may not enough for some special or complex objects, the additional actuator for the differential plate can be set at a constant speed to provide large compliant adaptability

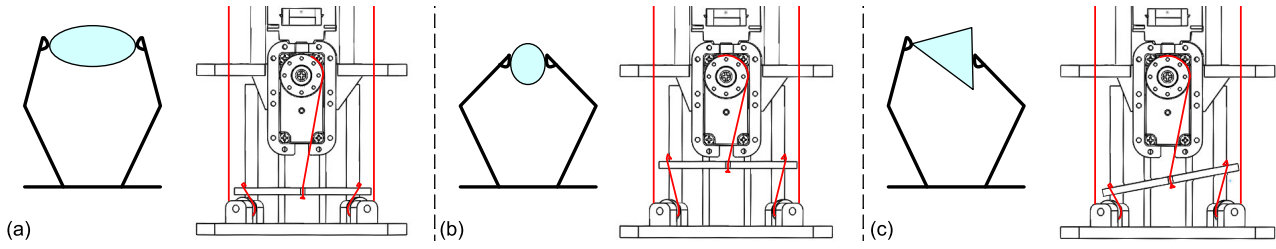


Figure 4.15: The differential plate inside the differential base. (a): for large regular objects, the helical hand can grasp the object without actuating the differential motor. (b): for small regular objects, the differential motor is actuated to close the distal links. (c): for small irregular objects, the differential plate is self-tilted to achieve the self-adaptable grasping.

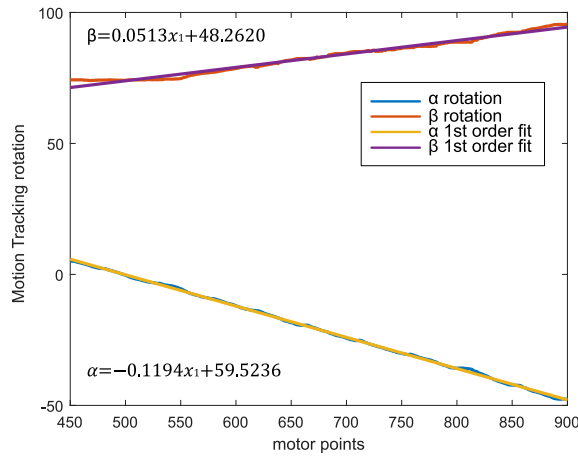


Figure 4.16: Motion tracking joint rotation results vs the actuation points of motor 1 in blue and red for α and β . The yellow and the purple lines are the best fit for the actual α and β rotation in first order.

and strong grasp (Fig. 4.15). In terms of force transmission, the distal link's force is exerted by the tendon, but when it is approaching the maximum joint limit, the distal link force is exerted by the hand structure and the gear.

A motion tracking analysis has been operated to find out how this compliant adaptive characteristic is affected by the motor control. By just actuating the proximal joint motor (No.1) and leaving the distal joint motor (No.2) at its starting position (780), the relationship between the joint angles (α_i, β_i) and the actuation motor 1's points are shown in Fig. 4.16. Four markers were attached to the frame, the proximal joint, the distal joint and and the fingertip to record the variation of the joint angles (α_i, β_i) by actuating motor 1 linearly. It is shown that within motor 1's point range (450-900), the proximal joint angle α_i (blue) decreases from 7° to -48° and the distal joint angle β_i (red) increases from 74° to 96° in an approximately linear way. By using the first order best fit function in MATLAB, *polyfit*, the

Algorithm 1 Motor points calculation

-
- 1: **procedure** (REQUIRED JOINT ANGLES α, β)
 - 2: Compute Motor 1's point $\mathbf{x}_1$ using equation (4.31)
 - 3: Compute the compliant adaptive β_0 angle using equation (4.32) at $\mathbf{x}_1$
 - 4: **if** $\beta_0 < \beta$ **then**
 - 5: $\beta^+ = \beta - \beta_0$
 - 6: Compute Motor 2's point increment $\mathbf{x}'_2$ using equation (4.33)
 - 7: Motor 2's point $\mathbf{x}_2 = \mathbf{x}'_2 + 780$
 - 8: **else**
 - 9: Motor 2's point $\mathbf{x}_2$ remains at 780
-

Algorithm 2 Manipulation Control Scheme

-
- 1: **procedure** (OBJECT SIZE $\mathbf{a}$, DESIRE ROTATION ANGLE δ OR TRANSLATION DISTANCE $\mathbf{o}$)
 - 2: Compute the initial grasping configuration $\alpha_{initial}, \beta_{initial}$ (joint angles) and $\mathbf{o}_{initial}$ (grasping height) based on the input object size $\mathbf{a}$ using equations (4.2), (4.5), (4.28), and (4.29)
 - 3: Compute the initial motor points of both motor using Algorithm 1
 - 4: Move both motor to the calculated initial positions
 - 5: Compute the final grasping configuration $\alpha_{end}, \beta_{end}$ based on the input desire manipulation δ or $\mathbf{o}$ using equations (4.25) - (4.30)
 - 6: Compute the final motor points of both motor using Algorithm 1
 - 7: Move both motor to the desired positions linearly to perform the manipulation
-

function of joint angles (α_i, β_i) in terms of motor 1's actuation points x_1 are

$$\alpha_i = -0.1194x_1 + 59.5236, \quad (4.31)$$

$$\beta_i = 0.0513x_1 + 48.2620, \quad (4.32)$$

where x_1 is between 450 and 900.

For in-hand manipulation or grasping complicated objects, the distal joints need extra actuation to perform that by controlling motor No.2. A similar motion tracking test was performed for motor 2 which actuates the distal links via tendons. The motor range of motor 2 is from 780 to 1000, where the difference is 220. The first order best fit line is also calculated for the β increment (β^+) with the motor points increment (x'_2)

$$\beta^+ = 0.1403x'_2 + 3.6448, \quad (4.33)$$

where x'_2 is between 0 and 220.

Algorithm 1 describes the method of computing the motor points by inputting the required joint angles

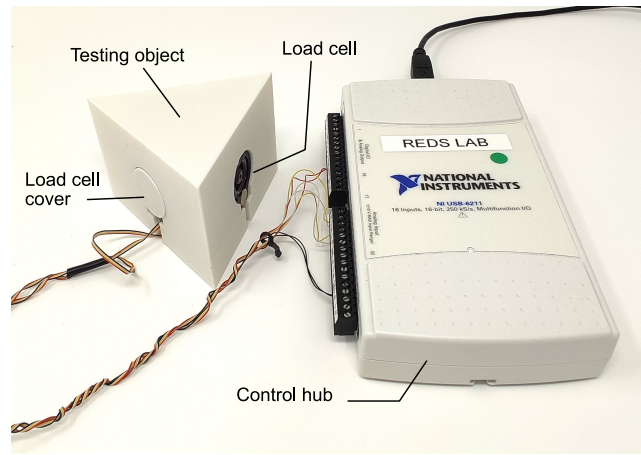


Figure 4.17: Grasping strength test setup. Two compression load cells are attached to the testing object to investigate the grasping forces.

α and β based on the motion tracking's output equations. Algorithm 2, the manipulation control scheme, utilises the above motor points calculation to perform the helical or grasping manipulation.

4.6 Grasping Performance Evaluation

Grasping performance is an important function to evaluate the general capability of the hand. Good grasping performance shows that the hand is not designed only for helical motion but also for general purpose, e.g working like a normal gripper. In order to evaluate the grasping performance of the helical hand, three individual tests were conducted which including the pinch grasping strength, the grasping tolerance of the positioning errors, and the grasping capabilities.

4.6.1 Grasping Strength

The first test was to measure the grasping strength of the helical hand, which was inspired by the NIST grasp strength test [FVWM18]. However, their testing object is not suitable for precision grasping, we designed a new testing object to measure the object pinch force shown in Fig. 4.17. The compression load cells (FX1901) are installed in the testing object to detect the grasping forces. To test the grasping strength, the hand was placed on a desk and the object was suspended right above the hand. As the hand was performing the precision grasp, the fingertip should be able to contact at the same position

on the object. The object was centred in the hand and hanging up at the right height. The test was terminated when the hand grasped the object ten times at maximum torque. The mean and standard deviations of the grasping forces are reported.

A data plot of voltages for two load cells throughout the 10 grasp cycles is shown in Fig. 4.18. The data sample rate is 62.5kHz. The grasping forces can be calculated via Eq. (4.34), where the nominal output of the load cell is 20mV/V and the full scale range is 10lbf. The input voltage is 5V in this case. For each cycle, the peaks indicate dynamic forces and the approximate stationary sections are quasi-static grasping forces.

$$\frac{\text{Nominal output}}{\text{Full scale range}} * \text{Input voltage} = \frac{\text{Reading}}{\text{Force}} \quad (4.34)$$

The mean quasi-static grasp forces were extracted for each data set. For load cell 1, the mean quasi-static grasp force is around 3.8N with 0.307 standard deviation. For load cell 2, the mean quasi-static grasp force is around 3.4N with 0.370 standard deviation. Due to the limitation on the number of sensors, we assume the total grasping force of this helical hand is three times the mean of these two load cells' mean quasi-static grasp forces, which is around 10.8N with a standard deviation of 0.33. According to the Mathiowetz's study [MKV⁺85], the average performance of all subjects for fingertip pinching is around 61N with a standard deviation of 15N and the minimum pinch force is around 25N. The result of the helical hand shows it can produce almost half of the minimum human pinch force. Also Ma et al. [MOD13] presents the Yale open hand Model T and Model T42 have similar grasp forces around 10N. In comparison, the helical hand performs well on pinch grasping strength, it certainly can enlarge the force by improving the prototype with less manufacturing errors.

Additionally, Fig. 4.18 shows the fingertip force of both sensors are similar most of the time, a few of them have around 0.5mV differences. Those differences may because of the rotary fingertips. Those fingertips cannot guarantee the contact location always in the same position. As this setup is to measure the pinch force, the contact location is important in this test. The force reaches maximum when the contact location is at the centre of the load cell.

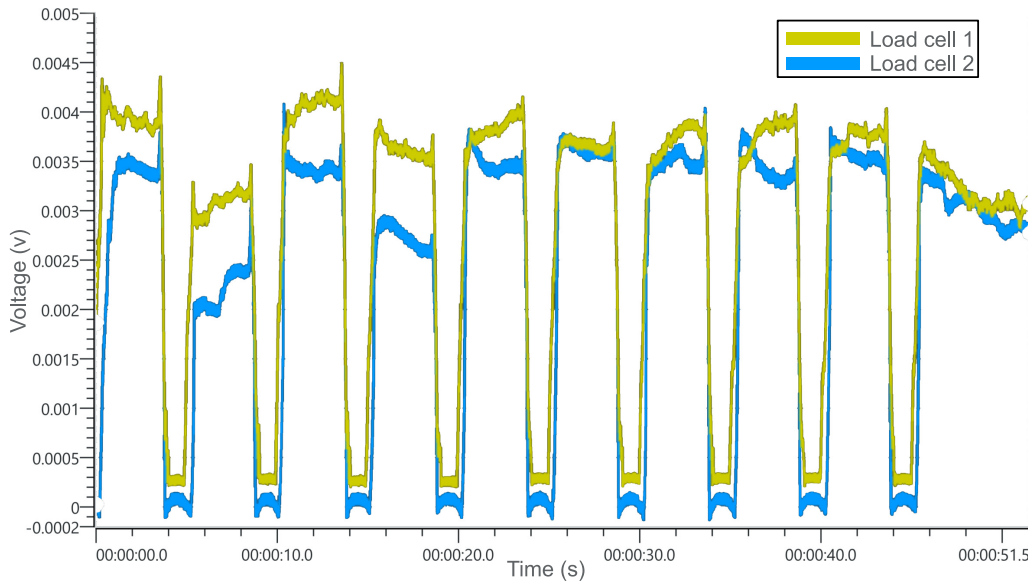


Figure 4.18: The load cell voltages for the helical hand precision grasping the 50mm triangle for ten times. Two different colour indicates two load cells' reading separately.

4.6.2 Grasping Tolerance

The second test tested the hand tolerance of positioning errors by moving objects offset in the x , y , and z direction along the diagonal axis. In general, a larger grasping region makes the hand more tolerant to the positioning errors. Three markers were positioned at each proximal joint to define the coordinate frame of the hand. A 50 mm triangular object with tracking markers was grasped by the hand at several positions. Then motion tracking cameras (OptiTrack Flex3) record the position of the objects and the orientation of the object is post processed in MATLAB and the grasping tolerance results of the hand are plotted in Fig. 4.19.

Figure 4.19 shows the experimental grasping tolerance results for a 50 cm triangular object. It presents the position and orientation of those feasible testing points. Colour indicates the orientation of the object, yellow means greater rotation at this point. The self defined middle position is defined as the home position where the rotation is equal to zero radians. The orientation are mostly distributed from 0 to 0.36 radians. The feasible grasping positions are distributed along the diagonal axis, points close to the diagonal axis show less orientation. For this certain size and shape object, the helical hand performed well on grasping tolerance with an alpha volume around $1.84 \times 10^4 \text{ mm}^3$. Compare to the simulation manipulation map (Fig. 4.8), the simulation alpha volume is around 1.29×10^4 which is

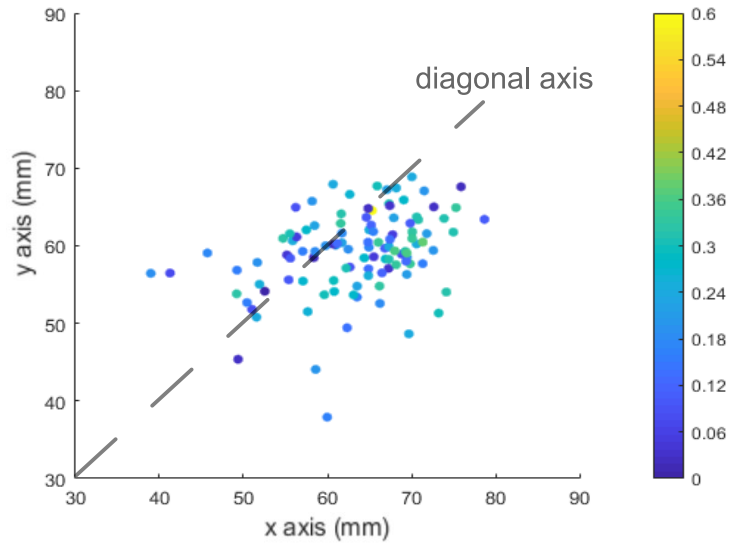


Figure 4.19: x-y plane view of the experimental grasping tolerance result represents position and orientation. The dotted axis is the diagonal axis of 3 reference axes. 'Home' position of the object is self defined and yellow points indicate greater rotation at those points. Legend unit in radian.

30% less than the experimental results. The differential system in the distal links provides the high tolerance of positioning errors to the helical hand.

Moreover, both simulations of the feasible workspace and the experimental grasping results show that the hand is capable of grasping an object with a high tolerance of positioning errors. Simulation shows the object has greater rotation near the edge of the workspace and less rotation along the centre axis of the hand. The experimental rotation range is slightly less than the simulation results due to the fact that the rotary fingertips may come off at the extreme boundary grasping position. The Alpha Volume for the experimental result is greater than the simulation which may be because, in the simulation, the contact points are assumed to be distributed evenly on the object and the distal joints are fixed. However, in the experiments, when the differential system is actuated, the contact points will not be distributed evenly anymore.

4.6.3 Grasping Capability

The grasping capabilities of the helical hand was also quantified by evaluating the hand according to the gripper assessment protocol described by [CWS⁺15] partially. During the test, the helical hand was attached to the UR5 and picked up each object from a smooth workbench (Fig. 4.20). The

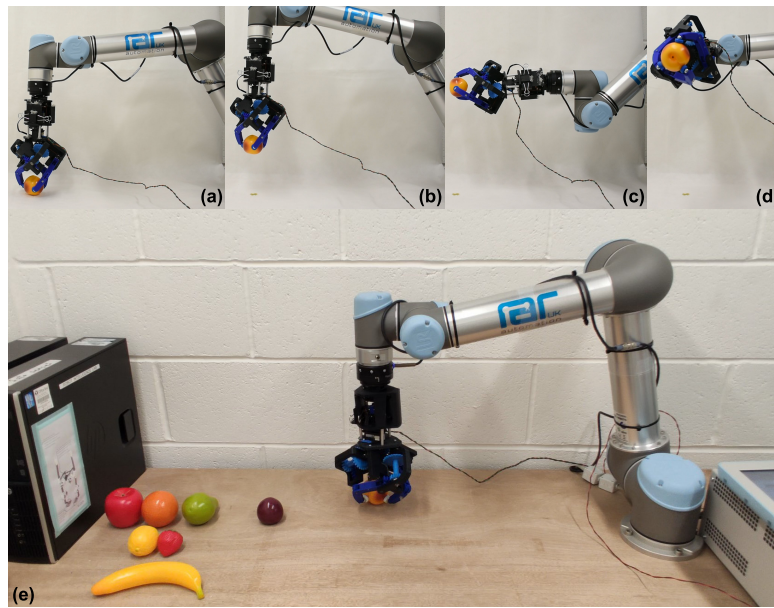


Figure 4.20: The hand is attached on a UR5 robot arm grasping a set of YCB objects **(e)**. This setup is testing the grasping capability. The hand is grasping a nectarine **(a&b)** and rotating about x **(d)** and y **(e)** axes.

gripper assessment involved the grasps of the objects listed in Table 4.2 including a set of round objects ranging in size from $35.2mm$ to $145mm$, a set of food items in box and can shapes, a set of fruits ranging in size from $36mm$ to $75mm$, and a number of kitchen items. For each object, the test started by finding a grasping strategy which persistently grasps the object within the target position. The hand was then scored based on its performance to grasp each object from a workbench from the target position and move by $10mm$ in x, y, z direction without adjusting the grasping trajectory. The score is out of 4 possible points: one point each is allocated if the object is successfully grasped, if it does not drift in the hand, if it remains in the grasp when the hand is rotated 90° about both x and y axes, and if it does not move after those rotations.

Table 4.2 shows the results from the gripper assessment to assess the hand grasping capability. As can be seen from the sub-scores for each class of object, the helical hand performed well overall on the grasping with a score of 318 points out of 400 points. The distal links can self adapt to the shape of an object via the differential system. It showed a strong adaptability of positioning errors and it worked very well on the cylindrical and regular objects. However, the hand showed difficulties on grasping small objects (less than $\varnothing 35mm$) and flat objects because of the large fingertip size. Additionally, the soccer ball is larger than the maximum open size of the hand, the hand could still grasp it by

Table 4.2: Scoring table for gripper assessment

Class	Object	Size (mm)	Mass (g)	Target position	x offset	y offset	z offset
Round Objects	Soccer Ball	Ø145	191	2	2	2	2
	Softball	Ø96	175	3	3	3	3
	Baseball	Ø70	143	3	3	3	3
	Tennis ball	Ø64.7	58	2	2	2	2
	Racquetball	Ø55.3	41	4	4	4	3
	Golf ball	Ø42.7	46	2	2	2	2
	Marble XL	Ø35.2	59	2	2	2	2
Food Items	Cracker Box	60 x 160 x 230	54	2	2	2	2
	Sugar Box	38 x 89 x 175	25	2	2	2	2
	Pudding Box	35 x 110 x 89	64	4	4	4	4
	Gelatin Box	28 x 85 x 73	60	4	4	4	4
	Potted Meat Can	50 x 97 x 82	23	2	2	2	2
	Master Chef Can	Ø102 x 139	93	2	2	2	2
	Tuna fish can	Ø85 x 33	30	4	4	4	4
	Chips Can	Ø76 x 86	75	4	4	4	4
	Mustard Bottle	50 x 85 x 175	43	4	4	4	4
	Tomato Soup Can	Ø66 x 101	37	4	4	4	4
Fruits	Banana	Ø36 x 190	66	2	2	1	2
	Strawberry	Ø43.8 x 55	18	4	4	4	4
	Apple	Ø75	68	4	4	4	4
	Lemon	Ø54 x 68	29	4	4	4	4
	Peach	Ø59	33	4	4	4	4
	Pear	Ø66.2 x 100	49	4	4	4	4
	Orange	Ø73	47	4	4	4	4
	Plum	Ø52	25	4	4	4	4
Score	Round objects:			71/112			
	Food items:			128/160			
	Fruits:			119/128			
	Total:			318/400			

pushing the hand into the object and closing the fingers which is deforming the object to achieve the successful grasping. However, the magnetic fingertips sometimes came off when the pushing force was too large.

The hand performed very well on the fruits class. The rotary fingertip contributed a lot when overcoming the offset. The offset scores are similar to the target position scores apart from the banana, while the hand was struggled on those long, thin and heavy objects. The sub-scores for round objects are relatively low due to three reasons. One is the contact area with a spherical object is limited, when the contact surface is smooth, like the marble or the golf ball, slipping can easily occur. The second reason is some of the balls are pretty heavy compared to the hand strength, with additional dynamic forces from robot arm, heavy objects may escape easily. Lastly, during the reorientation to the x

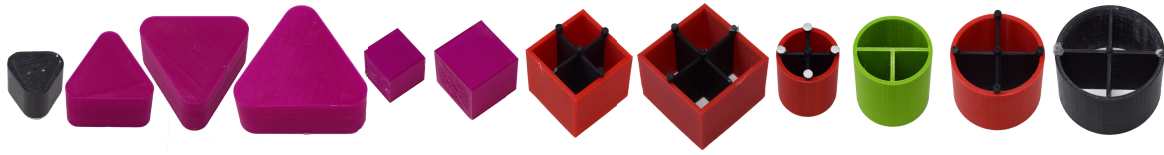


Figure 4.21: 16 different testing objects for helical motion test: four triangles (30mm-60mm), four squares (30mm-60mm), and four cylinders (40mm-70mm).

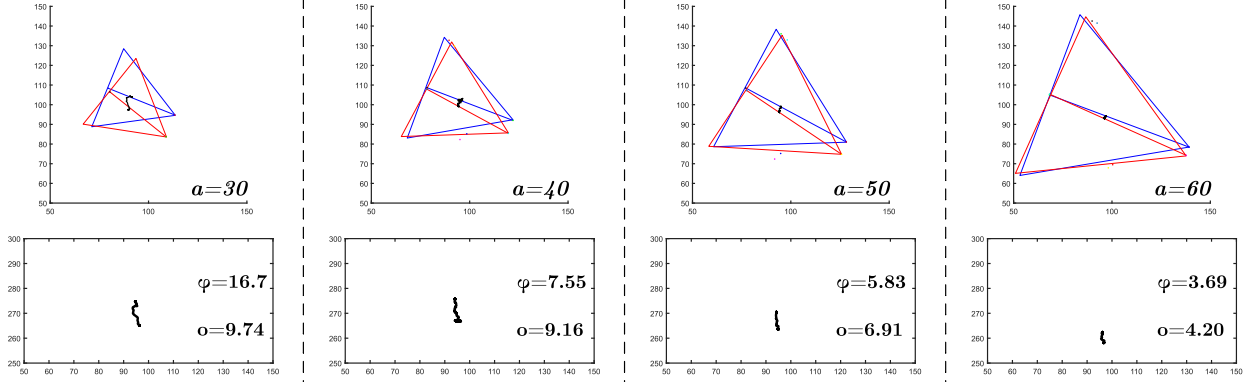
and y axes, the hand may have the chance to change the precision grasping to power grasping. If the object is smaller than the closing hand geometry, it will shift in the hand or escape between the finger gaps. Only the racquetball scored 4 for the target position because that is the only one made of rubber which provides a high friction force between the fingertip and the object. This makes the hand capable of precision grasping all the time. It got one mark down with the z offset due to the effect on the precision grasping by the offset.

For food items, the hand had high capability to grasp small boxes and cans. Weaknesses happened when reorienting the large objects. As the grasping strength and the grasping location of the hand are limited, a large object may rotate around its centre of mass due to the large mass inertia. Tests showed that the hand performed better when the grasping plane is close to the centre of mass plane. For fruits, the hand almost got full marks except for the banana. The banana is thin and long compared to other fruits, so the grasping strategy was complicated. During the attempts, the hand easily ended up just using two fingers to grip the banana, where the third finger was just touched the object. This was fine to lift the object vertically, but when starting to reorientate the banana, it slipped out of the hand.

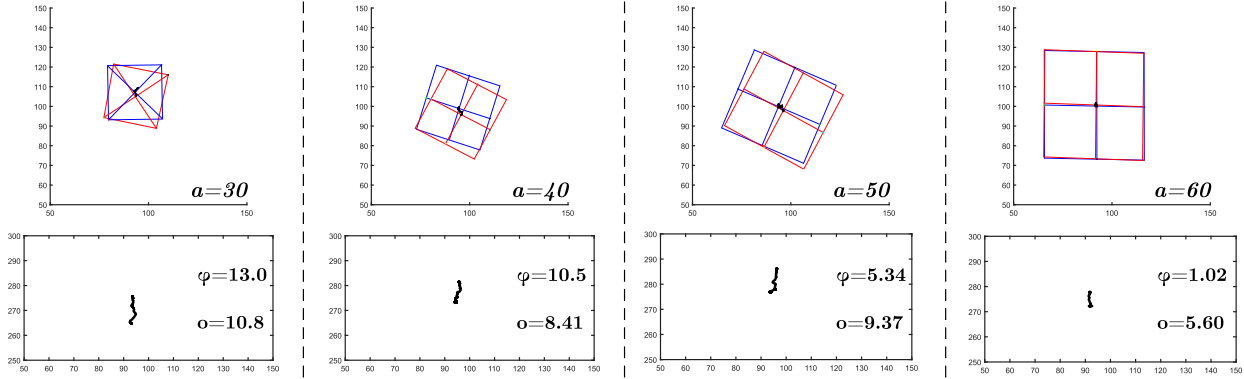
4.7 Helical Motion Performance Evaluation

To evaluate the proposed control scheme of the helical hand, 12 different objects were manipulated by the helical hand (Fig. 4.21) with velocity regulation of actuators. The hand is facing up and holding the object firmly like Fig. 4.6(d). This setup configuration enables the cameras to record the markers properly. Each object has 4 tracking markers to define the centre and the edge of the object. Motion tracking cameras (OptiTrack Flex 3) were used to record the object trajectory. According to the new β_{final} from Table 4.1 and based on the control algorithms, the motors of the helical hand were set at

I: Triangle



II: Square



III: Circle

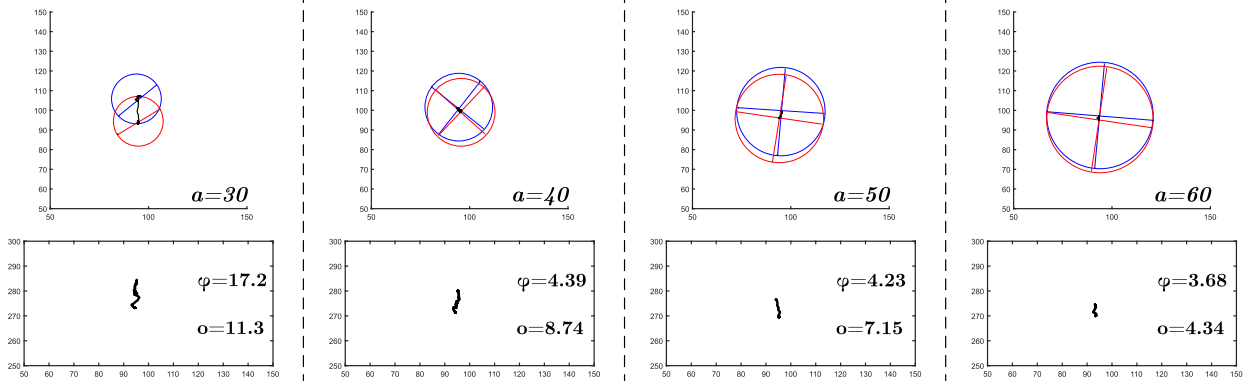


Figure 4.22: Helical motion trajectory of different triangles (I.), squares (II.), and cylinders (III.) in 4 different sizes in the X-Z (rotation) and the X-Y (translation) plane: a is the size of the object in mm , ψ is the rotation angle in degrees and o is the translation distance of the object. Blue and red indicates the starting position and ending position respectively.

the same speed to manipulate those 12 objects, size varies from 30mm to 60mm, in two conditions: direct and offset.

Table 4.3: Simulation and experimental results of 3 object shapes on various sizes with velocity regulation control

object size	Sim: $\Delta\delta$	Sim: Δo	Exp: $\bar{\psi}$	Exp: $\bar{o}$
30 mm	27°	11.4 mm	15.6°	10.6 mm
40 mm	17°	9.7 mm	7.48°	8.77 mm
50 mm	11°	7.8 mm	5.13°	7.81 mm
60 mm	6°	5.1 mm	2.79°	4.71 mm

4.7.1 Helical Motion from Target Position

First condition is grasping the object at the centre of the hand and perform the manipulation with the constant velocity ratio followed by the control scheme. Fig. 4.22 illustrates the helical motion, which presents the rotation in the X-Z plane and the translation in the X-Y plane. Those figures include the size of the objects, the starting (blue) and ending (red) position, the rotation angles and the translation distances of the manipulated objects. There were 4 markers on each object and the motion tracking data was post-processed in MATLAB to illustrate the motion clearly. In Fig. 4.22, the black lines are the trajectory of the object centre. The lines connected with those markers are used to calculate the rotation angle. The rotational range is the included angle between the start and end position. The translation distance is the average of the differences between the start and end position of those four markers.

Figure 4.22 shows smaller objects have larger offsets during the in-hand manipulation. For objects in size 30 mm, all the shapes show obvious offsets along z-axis. Table 4.3 shows the comparison of the simulation and the experimental rotation angle ψ and the translation distance o . Here, the simulation results are summarised from Table 4.1 and Fig. 4.12 and the experimental results are the average of all three object shapes. It is shown that, with the proposed velocity regulation control scheme, the helical hand can rotate and translate different objects at the same time. The experimental translation results are very close to the simulation range with error less than 1 mm. However, the experimental rotation results are less than the simulation results at around half of them.

Figure 4.23 illustrates the variation in rotation and translation of all triangular, square and cylinder objects in 4 different sizes. Due to the limitation on the rotation results, the experimental results are not quite match with the simulation trend. However, there are some objects follow the trend,

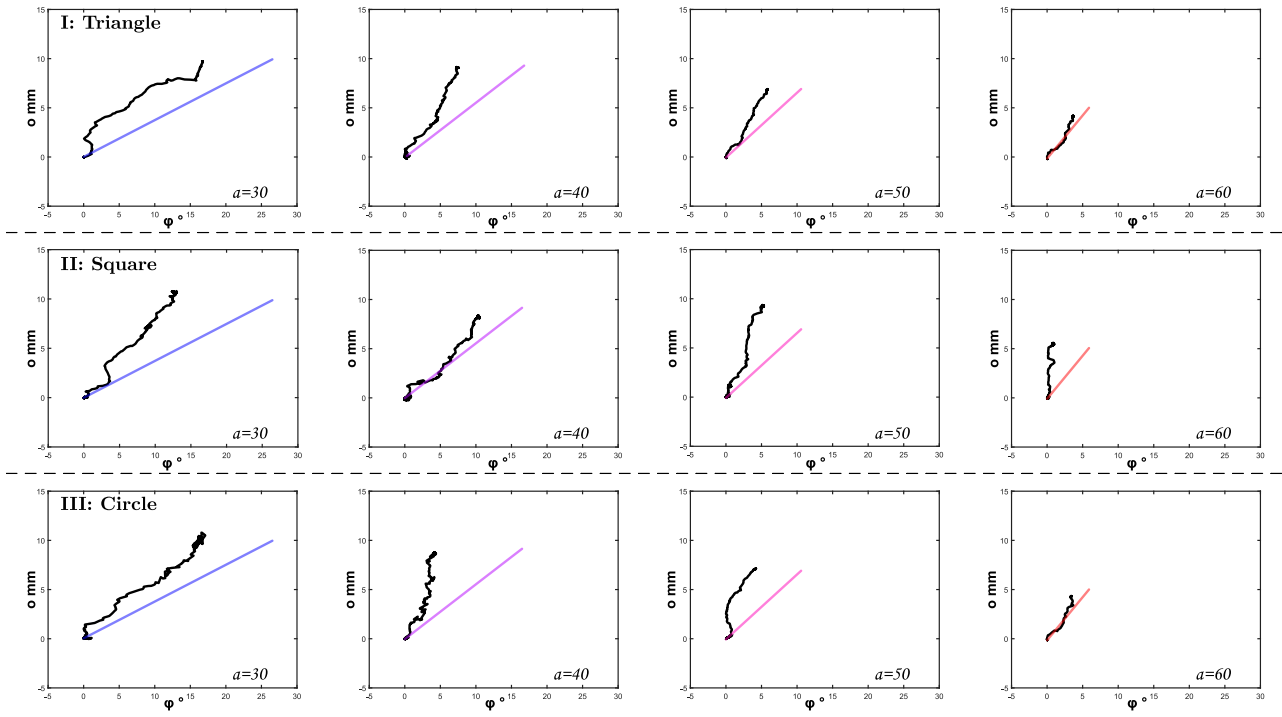


Figure 4.23: The relationship between the translation distance o and the rotation ψ with different object sizes on 3 different object shapes: triangles (I.), squares (II.), and circles (III.). a is the size of the triangle in mm , ψ is the rotation angle in degrees and o is the translation distance of the object in mm . The black lines are the experimental results and the rest coloured lines are the simulation relationship between the translation distance o and the rotation ψ .

e.g. the 60 mm triangle and circle etc. In summary, the triangular objects perform better than the others. This may be because of the differences in grasping strategy for those three types of shapes. The contact locations are slightly different from these three shapes. Triangular objects have the best contact strategy as the hand topology is orthogonal. The hand grasps the cylinder in a similar strategy, but the contact condition is changing from a flat-to-flat contact to a flat-to-curved contact, the stability of the hand decreases. This may lead to tilting and slipping during the manipulation. For square objects, the grasping condition is different, the hand is incapable of holding the object evenly. So the hand is primarily using two fingers to grip the object and the rest finger for guiding the object or even providing a push out force towards to the fourth edge. This special grasping strategy limits the translation distance of the square objects.

To improve the rotation range of the hand, another experiment has been conducted to manipulate the same 12 objects but without using the velocity regulation control scheme. The control scheme is straightforward that controlling both motors to their maximum positions but this also has a drawback

Table 4.4: Simulation and experimental translation results of 3 object shapes on various sizes with maximum control scheme

object size	Sim: $\Delta\delta$	Sim: Δo	Exp: $\bar{\psi}$	Exp: $\bar{o}$
30 mm	27°	11.4 mm	20.7°	12.3 mm
40 mm	17°	9.7 mm	20.5°	14.7 mm
50 mm	11°	7.8 mm	10.6°	14.3 mm
60 mm	6°	5.1 mm	5.86°	14.4 mm

that the overload force may break the fingers. Table 4.4 shows the comparison of the simulation and the experimental rotation angle ψ and the translation distance o under this control scheme. The rotation ranges improved a lot on all object sizes where the differences are decreasing from average 7.5° to less than 1°, but the translation range became worse. The translation ranges have little changes among different sizes of objects, especially from size 40 mm to 60 mm, the average translation range are almost identical.

4.7.2 Helical Motion with Offset

Apart from grasping the object at the centre of the hand, we also tested the manipulation tolerance of the helical hand by placing the object at three offset positions. The offset positions are the positions of each fingertips at the opening stage. We labelled the first fingertip position as offset X, the second fingertip position as offset Y, and the third fingertip position as offset Z. The distal link adaptive feature are utilised in this experiments by grasping the object in offset positions. The helical hand was controlled under the velocity regulation control scheme for this experiments.

Figure 4.24 shows the rotation and translation range of both simulation and experimental results on all tested objects. The performance of each offset for different objects are not steady with the circle in offset Y position is the largest rotation of size 30 mm, and the square in offset Z position is the largest rotation of size 40 mm and 50 mm, but the average of all three offsets results are close to the direct grasping results. For object size 30 mm to 50 mm, the largest experimental rotation ranges are larger than the simulation results, but all experimental results for 60 mm objects are less than the simulation results. In summary, the rotation ranges are following the trend that when the size of the object increases, the rotation range decreases.

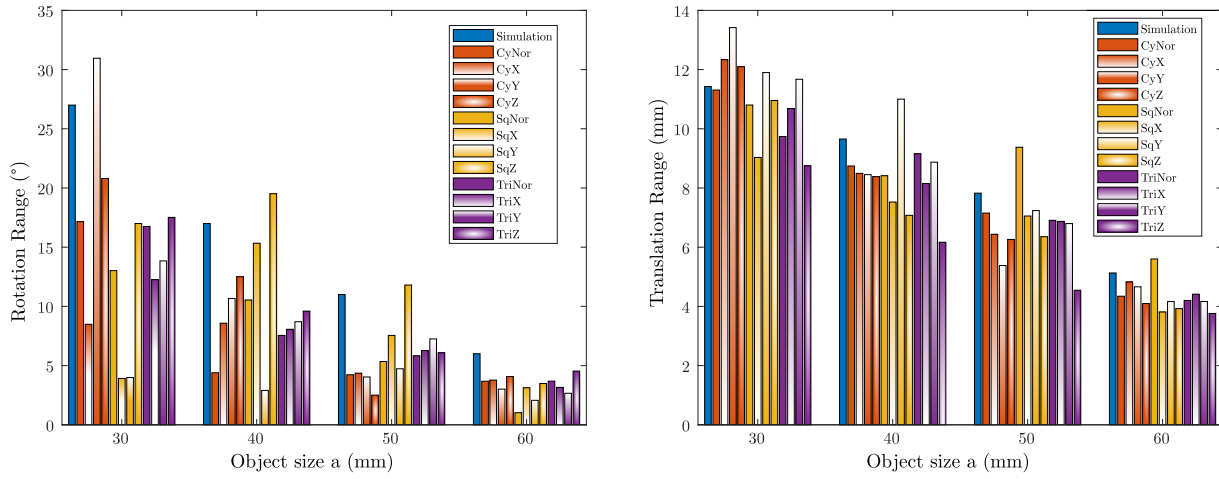


Figure 4.24: Rotation and translation range of the experimental results for each object under direct and offset grasping. Different colours indicate different shapes and different infills indicate different grasping conditions. Blue denotes the simulation results, orange denotes the experimental results of circles, yellow for squares, and purple for triangles.

The experimental results of translation ranges are more consistent and close to the simulation results. Fig. 4.24 shows for objects of size 30 mm, the translation ranges of offset Y position are the highest ones among other offset conditions. The translation ranges of offset Z position of triangular objects are the least for all sizes. Overall, the translation range differences among all three shapes at the same size are not obvious, the helical hand showed high manipulation capability and tolerance on translating objects regardless shape. However, there is a clear trend that when the size of the object increase, the translation range decreases, which is the same as the rotation range. Furthermore, the experimental results are following this trend obviously.

4.8 Discussion

Following the performance evaluation of the helical hand, it shows that the hand can manipulate objects in a helical motion with speed control and still keep the general grasping capabilities. The proposed hand performs well enough for the grasping performance tests. It is able to pick up the testing objects with offsets, while some objects dropped out during reorientation along x and y axes. Due to the special topology of the hand, three fingers are orthogonal to each other, the grasping location is limited to the hand. It is a big challenge to locate the object's centre of mass on the contact

centre plane when using the underactuated hand. Especially for round surfaces, the pinch force is limited as well, objects will have a high probability of slipping.

The passive rotary fingertip is another unstable factor. This design is good at adapting to different object shapes especially for this hand topology. However, it reduces the pinch force at the same time and the stability can become a problem in a dynamic environment. Additionally, the fingertip is passive, when sliding the hand on the table surface for grasping thin objects, the fingertip has a high chance of flipping over if the friction force is too large or if the grasping position is bad. The fingertip design will be optimised such that it can no longer come off in future work for better grasping and manipulation performance.

The helical motion results verified the hand can rotate and translate an object at the same time with the simple speed control. Under the velocity regulation control scheme, for different object sizes and shapes, the velocities of both motors are always based on the same speed ratio. Due to the motor limitation, there is no torque control, the motors are position controlled which are calculated from the simulation. As there is a reality gap and the manufacturing errors, the hand did not grasp the objects tight enough by using the calculated motor points. Shown in Table 4.3 the rotation ranges are unsatisfactory due to the loose contact conditions and the backlash of the actuation gears. Manipulating objects with offset grasping conditions were also evaluated to test the helical performance. Although the rotation and the translation ranges are small, the hand performed consistent with offset conditions. The trend of the manipulation capability are clear which is the rotation and the translation ranges decrease when the manipulated object sizes increase.

Moreover, we control the hand with the maximum control scheme which is actuating the motors to their maximum positions which will produce a very tight grasp during the manipulation. It is fine for this hand design and rigid objects, delicate force may required for soft objects. Table 4.4 shows that the rotation ranges improve a lot compared to the previous method, but the translation ranges are unusual. As the motors are reaching to their maximum positions, the ended positions of the helical hand for most cases are similar, that is why the differences of the average translation ranges amongst various object sizes are close to each other. Furthermore, under the high grasping force, the proximal gears may jump over teeth when motors trying to reach their maximum positions. In real life, humans

usually use more forces than required to guarantee grasping, which is known as the safety buffer. Although torque control or force sensors are helpful during grasping without doubt, it may not be necessary during the in-hand manipulation. It is shown that the maximum control scheme is not suitable for the helical hand.

Additionally, the hand has been asked to perform some daily activities to approve its versatility. The first is to screw a light bulb. The hand is attached on UR5 facing down to the light bulb (Fig. 4.1) to screw the light bulb in the socket. Second is to screw a lid on a water bottle. The setup is similar as the one for the light bulb. The last one is twisting and pulling an apple at same time to remove the stem. The stem is hold by human during the test and the hand is facing up to the apple. This is to mimic the situation when the hand can be used to pick apples from trees. The dimension of the light bulb, bottle lid, and apple is $60mm$, $52mm$, and $63mm$, respectively. The weight of them are $36g$, $8g$, and $121g$, respectively.

One of the main issues during the potential application tests is the variation of the helical pitch for different tasks. With the same speed ratio control, the hand is only able to produce a certain type of helical motion which may not be the suitable one for all tasks. The rotary fingertip is using magnetic attraction to keep itself on the end of distal link. The magnetic attraction force needs to be low enough to mimic a smooth spherical joint. However, this will also lead the rotary fingertip to easily disconnect from the distal link. This phenomenon will become a big barrier when screwing an object with friction. We used an alternative way to perform the tasks by putting silicone tape directly on the end of the distal link. This method changed the contact model from surface contact to point contact which increases the uncertainties. Therefore, there is a trade off between the range of rotation and the performance stability when designing a rotary fingertip. Nevertheless, the hand shows the capability to perform helical motion on different type of objects.

4.9 Conclusion

The mechanical intelligence strategy based on the hand topology design herein proposed has been proved by the introduced prototype for self-adaptive precision grasping and helical prehensile in-

hand motions. However, this prototype still has some aspects that can be improved. Maintaining stable and robust contact conditions during the in-hand manipulation for irregular object remains a considerable challenge. Slip and rolling during in-hand manipulation was expected due to the insufficient pinch forces despite the application of the passive rotary fingertips to maintain point contact constraints. The differential distal link system can help the hand adapt to the shape of the object automatically. However, those designs influenced the grasping strength negatively as well. Experimental tests of the helical hand discovered some opportunities for future work. For instance, the hand dimension and the joint limitation could increase, improving the capability of the hand grasping and the performance of the helical motion. The rotary fingertip attachment design could be improved to minimise the pinch force loss. Each proximal finger could be actuated separately to have different in-hand manipulation behaviours; it would be helpful to extend the grasping ability and the potential applications as well. Overall, this hand topology idea shows limited potential in improving the in-hand manipulation capabilities of simple robot hands. This hand topology may achieve all 6-DOF manipulation when actuating all the fingers, but the design and the control scheme will become more complex. If control simplicity is chosen, it may result that a new hand topology has to be designed to satisfy the purpose for a different type of in-hand manipulation trajectory. Therefore, this mechanical design idea to enhance the in-hand manipulation capability of robot hands is not encouraged.

Chapter 5

Decoupling Grasping and In-hand Manipulation

This chapter is adapted via ©2020 RSS. Reprinted, with permission, from [Q. Lu, N. Baron, A. Clark, and N. Rojas, "The RUTH Gripper: Systematic Object-Invariant Prehensile In-Hand Manipulation via Reconfigurable Underactuation," Proceedings of the 2020 Robotics: Science and Systems (RSS).]

Abstract

With the help of the extra degree of freedom of the palm and the adduction/abduction capability of the base joint for each finger, human hands can achieve various grasping types. Humans can then choose different strategies to grasp the object with the best performance. In this chapter, a reconfigurable underactuated robot hand has been developed to achieve different grasping types. The hand utilises a two-degree-of-freedom five-bar linkage as the palm of the gripper, with three three-phalanx underactuated fingers—jointly controlled by a single actuator—connected to the mobile revolute joints of the palm. Additionally, this hand is able to perform systematic prehensile in-hand manipulations regardless of object size or shape. Three actuators are used in the robot hand system in total, one for controlling the force exerted on objects by the fingers through an underactuated tendon system, and two for changing the configuration of the palm and thus the positioning of the fingers. This novel layout allows then decoupling grasping and manipulation, facilitating the planning and execution of in-hand manipulation operations. The reconfigurable palm provides the hand with a large grasping

versatility. It allows easy computation of a map between task space and joint space for manipulation based on distance-based linkage kinematics. The motion of objects of different sizes and shapes from one pose to another is then straightforward and systematic, provided the objects are kept grasped. This is guaranteed independently and passively by the underactuated fingers using a custom tendon routing method, which allows no tendon length variation when the relative finger base positions change with palm reconfigurations. The theoretical grasping workspace and grasping and manipulation capability of the hand have been analysed. The algorithms for computing the manipulation map and in-hand manipulation planning are presented and evaluated experimentally. Numerical and empirical results of several manipulation trajectories with objects of different size and shape clearly demonstrate the viability of the proposed concept.

5.1 Introduction

Prehensile in-hand manipulation involves manipulating a grasped object by a robot hand's fingers without losing contact with it. With the rising interest in robot hands, as an approach to achieve task versatility in robotic systems, not only robust grasping, but also in-hand manipulation has become an important and essential ability to improve dexterity. Several highly articulated anthropomorphic hands, with high number of degrees of freedom, have been indeed developed to achieve grasping and manipulation tasks [SC82, JIK⁺86]. These robot hands are usually redundant by having actuators at each joint of the fingers, making them well suited to perform hand gestures but not necessarily reliable for prehensile in-hand manipulation as they become prone to error because of the large number of actuators. By introducing tendon driven and joint coupling design [Wal04, SPN⁺10], robot hands have been undergoing continuous improvements in performance and durability to mitigate these issues. Regarding state-of-the-art control strategies, deep reinforcement learning has been recently used to perform successfully complex manipulation tasks with multifingered robot hands [OAA⁺19b, ABC⁺20], but the method has shown to require huge amounts of feedback data, and enormous time and energy consumption to achieve goals—with a relative low success rate and no fingertip force modulation. Indeed, performing reliable prehensile in-hand manipulation under both shape diversity and shape uncertainty with a robot hand is still an open problem [BK19].

Underactuated robot hands, by actuating multiple finger phalanges with a single actuator through a carefully designed transmission mechanism, have less actuators and are simpler to control while being able to grasp diverse objects [DH11, BR18]. For example, the Velo gripper [CHH⁺14] can perform both parallel and fingertip grasps with a single actuator, being able to pick up small objects off a flat surface. The Ocean One hand [SWKC17] achieves a variety of pinch and power grasps via elastic finger joints and a spring transmission. Catalano *et al.* [CGF⁺14] proposed an adaptive synergy that allows the 19-joint hand to accommodate an arbitrary number of grasp postures using only one actuator. In general, underactuated hands, by incorporating elastic and passive elements to generate self adaptation for dealing with uncertainties, have been well developed for grasping tasks. However, these characteristics and hands have been seldom leveraged for achieving dexterous manipulation while keeping control complexity low.

Several robotic hands have been developed by modifying existing underactuated designs in different ways to achieve translation and rotation of objects. Chavan-Dafle *et al.* [CDLR18] designed a pneumatic shape-shifting fingertip to enable a simple parallel jaw gripper to reorient and grasp objects by changing the contact type between the fingertips and objects. This method takes advantage of gravity to reorient the object, which makes the direction and range of rotation limited. For increasing rotation capabilities, elastic pivot joints between the fingers can be implemented [RMD16] or soft fingertips can be used as it has been shown that, when compare to rigid fingertips, they generate a larger manipulation workspace for a given gripper [LR19]. Indeed, by adding inflatable air cavities in soft fingertips [LHNR20], simple grippers can in-hand manipulate (soft and delicate) objects against gravity. Alternatively, by dynamically varying the surface material of fingers both translation and rotation can be achieved [LCSR20].

Adding an extra degree of freedom on the proximal joints of an underactuated robotic hand is also a popular method to increase hand dexterity, without increasing the actuator space excessively [OJC⁺14, Rob16, Rig19]. For instance, the iHY Hand [OJC⁺14] is a three-fingered underactuated hand driven by 5 actuators in which two of the fingers have a coupled adduction/abduction motion at the proximal joints to perform different grasps and simple re-position tasks. Another alternative is to change the morphology of the fingers to achieve a particular motion characteristic. Ma *et al.* [MRD16a] proposed a curved finger design to a three-fingered underactuated hand for objects to follow a sphere

surface, regardless of the object size and grasping location. However, in all these cases, the control simplicity that underactuation gives to grasping is not inherited or maintained when performing in-hand manipulation operations.

There is another approach to enlarge the grasping capabilities of robot hands based on changing the relevant position of the proximal joints of the hand, which is equivalent to equip it with a reconfigurable palm [Tow00, DWC09, SMM18, HJI⁺05]. For instance, two of the articulated fingers of the BarrettHand [Tow00] can rotate 180° around the central axis of the palm to adapt various grasping configurations. This design approach is adopted in [SMM18] and [HJI⁺05] to achieve some particular manipulation tasks. Regarding reconfigurable palms, Dai *et al.* proposed the Metahand [DWC09] which uses a spherical mechanism as a palm, proposing later a design based on a planar linkage [CSZ⁺18]. These works are the closest to our approach, which is also based on incorporating a reconfigurable palm in the robot hand system. However, while the hardware may seem similar, our ethos and objectives are completely different, as rather than interested in presenting the versatility of a new hand, our focus is on investigating how robot hand hardware characteristics, such as a reconfigurable palm, can be leveraged to devise simple algorithms for planning and control of in-hand manipulation operations with arbitrary objects.

In this chapter, a Reconfigurable Underactuated constant-Tendon Hand (RUTH) gripper is introduced. It is a three-fingered self-adaptive reconfigurable underactuated hand which decouples grasping and manipulation to achieve systematic prehensile in-hand manipulations regardless of object size or shape. The hand utilises a two-degree-of-freedom five-bar linkage as the palm of the gripper, having a total of three actuators—two for controlling the reconfiguration of the palm and one for controlling the underactuated fingers, which are connected to the mobile revolute joints of the palm. The reconfigurable palm provides the hand with large grasping versatility, while allowing the easy computation of an object-invariant map between task space and joint space for manipulation. Using this map, the in-hand manipulation of objects of different sizes and shapes from one pose to another is straightforward and systematic, provided the objects are kept grasped. This step is guaranteed independently by the actuator that controls the underactuated fingers using a novel tendon routing that eliminates tendon length variations when the palm reconfigures.

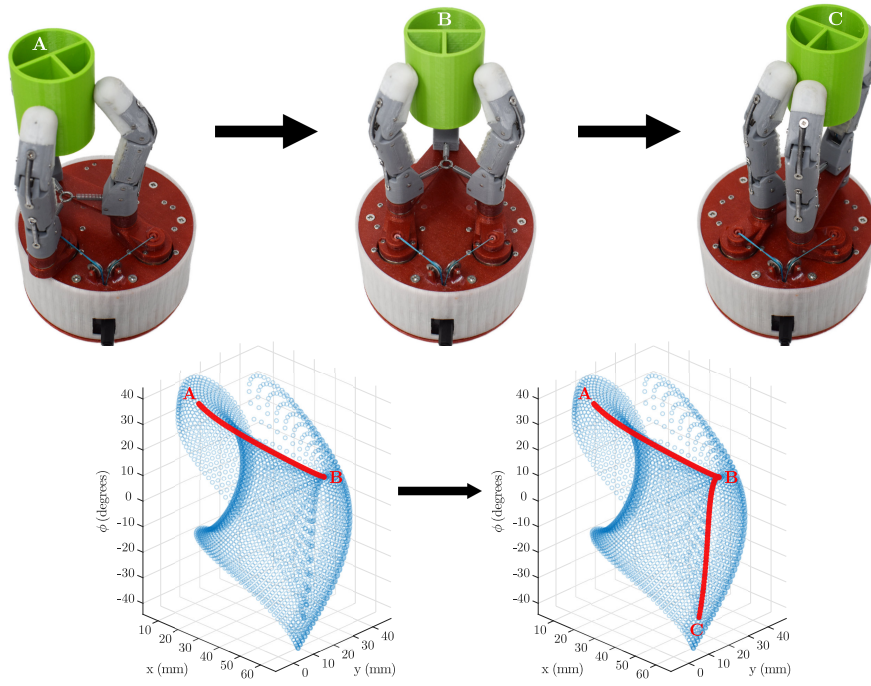


Figure 5.1: **Top:** The RUTH gripper manipulating a cylindrical object from pose A to poses B and C. **Bottom:** The manipulation map with the numerical object trajectory from A to B to C.

In what follows, Section 5.2 introduces the design and prototype of the RUTH gripper. Then its grasping and manipulation characteristics is analysed in Section 5.3, presenting algorithms for computing the mapping between object manipulation workspace and active joint space, and for computing the shortest distance in joint space to move a grasped object from its current pose to a desired one. Next the gripper performance on both grasping and in-hand manipulation tasks has been evaluated in Section 5.4. Section 5.5 discusses the comparison between the simulation and the gripper performance. Lastly, the conclusion has been made in Section 5.6.

5.2 Design of the Reconfigurable Palm Gripper

The RUTH gripper shown in Fig. 5.1 was designed to facilitate the planning and control of prehensile in-hand manipulation by the repositioning of underactuated fingers. The RUTH gripper decouples grasping and in-hand manipulation by exploiting palm reconfiguration and self-adaptiveness of underactuated fingers. With this gripper the motion of grasped objects of different sizes and shapes from one pose to another is straightforward and systematic, since an object-invariant map between

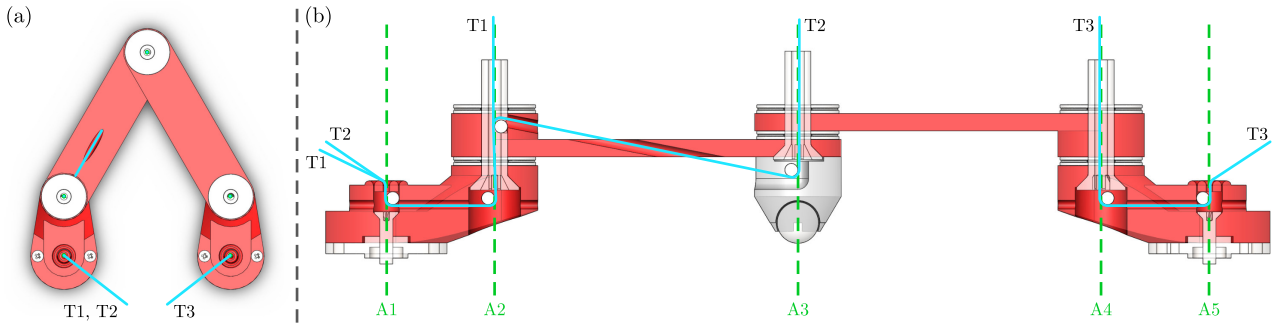


Figure 5.2: CAD model showing the five-bar linkage design and configuration-independent tendon routing (blue lines, T1, T2, and T3), achieved by aligning tendon routing with the 5 axes of rotation (green lines, A1-5): **(a)** Top-view showing five-bar initial configuration and **(b)** Unwrapped section-view showing tendon routing.

task space and joint space can be easily pre-computed. The developed three-fingered gripper is a completely self-contained unit, with all actuators and electronics packaged inside the gripper base, and only 3 actuators are needed for the co-planar in-hand manipulation. The design of the working mechanism and overall system are discussed next.

5.2.1 Five-Bar Reconfigurable Palm

A five-bar linkage was selected for reshaping the gripper palm as it allowed 3 specific points, namely five-bar joints 2, 3, and 4, to be repositioned in the x-y plane through the control of only two motors, located at joints 1 and 5. When selecting dimensions for the five-bar linkage, a symmetrical structure (link 1 = link 4, link 2 = link 3) was chosen to ease manufacturing, and further to allow for the five-bar to form an equilateral triangle. This was achieved by distancing the motors axes (axes 1 and 5) at the same distance as between the five-bar joint axes 2 and 3 (link 2 = link 3 = link 5). The isolated five-bar linkage in its equilateral triangle configuration can be seen in Fig.5.2(a). To ensure the free-floating five-bar was supported throughout its manipulation and grasping, and ensuring minimal translation of the 5-bar system in the Z-Axis (away from the top plate of the gripper), a caster wheel was placed under joint 3. As the caster wheel required a surface to translate on, the magnitude of the 5-bar was limited by the size of the gripper housing, which was limited by the size of the motors used. Through careful positioning of the 3 servo motors (Dynamixel MX64s), a compact housing size of 140 mm $\varnothing$ (by 66 mm tall) was developed. From this size, links 2, 3, and the motor distance (link 5) were set

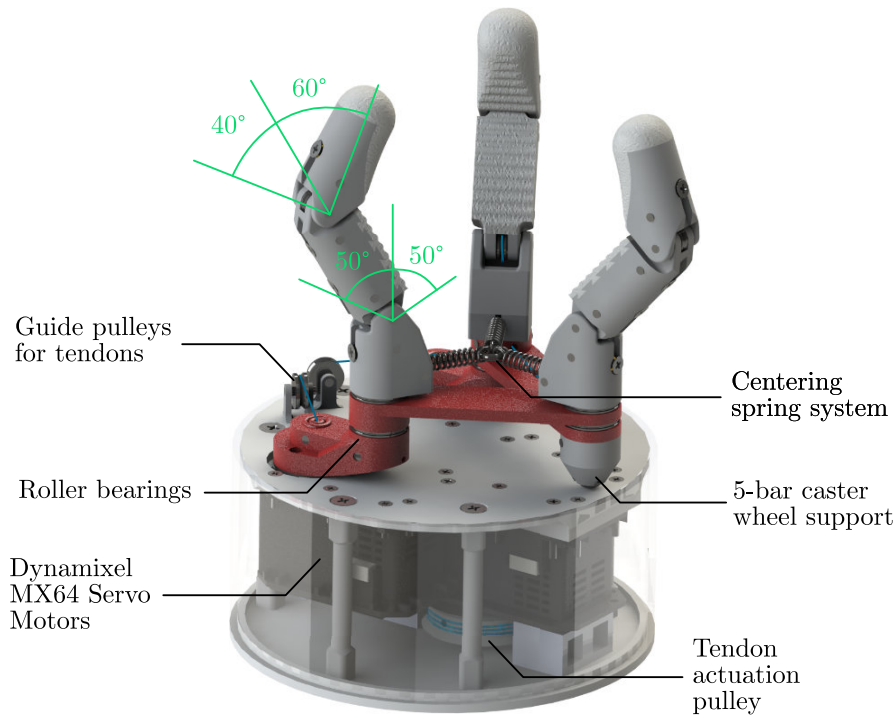


Figure 5.3: CAD model showing the overall gripper structure and components. Finger joint angle limits are also shown.

as 70 mm. To provide structural rigidity the links were given cross-sectional dimensions of 20 mm x 4 mm (minimum). Shorter links 1 and 4 were dimensioned such that each motor could theoretically achieve full 360° motion without collisions with the other, and with a link width of 20 mm this gave a resulting length of 25 mm. The links of the 5-bar system were connected using bolts, and between each of the contacting faces of the links needle thrust bearings (20 mm $\varnothing$) were used to reduce the friction of the system.

To actuate the fingers of the underactuated gripper, a tendon-based method was implemented as this allowed all 3 fingers to be controlled using a single motor. However, one of the unique features this gripper presents is the variation in distance between the fingers and actuation motor as the five-bar linkage changes configuration. In typical underactuated grippers, the tendon exits the base of each finger and connects directly to the actuation motor. If this were to be implemented with the RUTH gripper, as the five-bar changes its configuration the finger tendons would vary in length relative to each other, and grasping would fail, as has been shown in previous research [WLCR20].

To overcome this issue, a constant-tendon system was implemented, where the length of each finger tendon was independent of the five-bar configuration. Each of the 3 tendons were passed through

the five-bar mechanism, ensuring no horizontal translation occurred across the five-bar joint axes. Instead, each tendon was constrained to only vertical translation across joint axes through the use of 3 mm steel pins as reduced-friction guide pulleys positioned tangentially to the 5-bar axes. This also presented a problem at joints 2, 3, and 4, where the desired route for the tendon, along the axis, was already occupied by the bolts fixing the 5-bar system together. To allow the tendons to pass along the axes, the bolts were hollowed out, and in the case of tendon routing 2 a secondary cavity was created in the side of the bolt tangential to axes 2, allowing for a steel pin to be inserted and tendon 2 to continue to its finger. On exiting the 5-bar system, the tendons needed to converge to a single point (the motor), however a dual pin arrangement, as used on axes 2 for tendon 2, could not be used without restricting the movement of the 5-bar system. Instead, a free-rotating ring was placed at axes 1 and 5, that allowed the tendons to converge without introducing collisions and maintaining the independent length system. A cross section of the expanded 5-bar linkage showing the tendon routing for the 3 individual tendons can be seen in Fig.5.2 (b). Once the tendons exited the five-bar linkage at joints 1 and 5, they were routed to the inverted actuation motor in the beneath housing using guide pulleys. These guide pulleys and other components of the gripper can be seen in Fig. 5.3. The tendon routing in the base of the hand connected to the actuation motor, and the routing inside of the fingers, can be seen in Fig. 5.4.

5.2.2 Underactuated Fingers

To affix the fingers to the five-bar linkage, while also allowing rotation of the fingers, a 6 mm machine screw was threaded through the joint axis of each finger. The machine screw was also hollowed out to allow the tendon to pass directly through the axes, with the aforementioned no horizontal translation. The three fingers followed an identical design, with 2 flanges providing $\pm 50^\circ$ motion for the proximal flange and $+60^\circ/-40^\circ$ motion for distal flange, shown in Fig. 5.3. Guide pulleys were placed inside the fingers at the joints to further reduce friction. To increase the grasping ability, the surfaces of the fingers were coated in textured silicone (SmoothOn Eco-Flex 00-10). To return the fingers on the release of a grasp, springs were placed in channels on the back of the fingers for each joint.

To maintain the grasping capability as the five-bar configuration changes, the fingers actuation motion

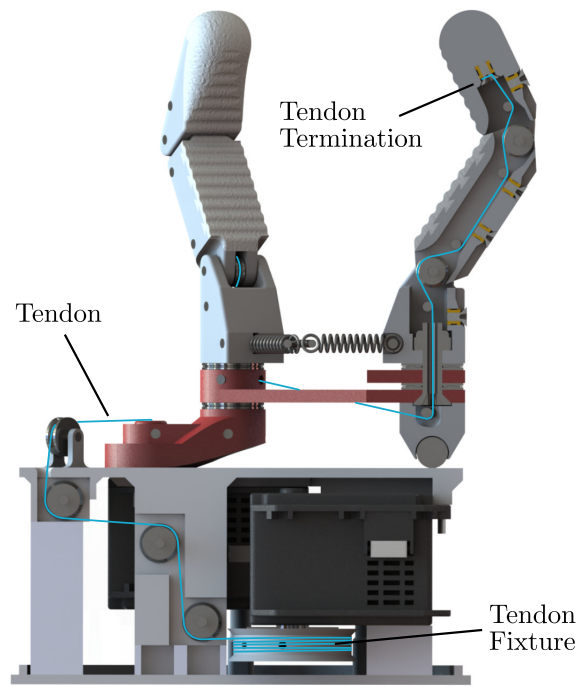


Figure 5.4: Section view of the RUTH gripper, showing tendon routing in the base of the hand and in the fingers.

should be towards the centre of the triangle formed by the three finger base positions (five-bar axes 2, 3, and 4). To achieve this, the direction of each finger was controlled by a high stiffness spring attached at the base of each finger to a central ring. The central ring is held in the triangle centre by the three finger springs, and the ring design allows each of the finger springs to rotate around the centre without experiencing the torsion expected with fixed springs. Conversely, the spring is fixed in position where it connects to the base of each finger, ensuring the spring and finger rotate towards the triangle centre as one system. This spring system can be seen in Fig. 5.3.

5.2.3 Design of the Prototype

The prototype was constructed mostly from 3D printed parts on a single nozzle desktop 3D printer. The fingers were printed out of Polylactic Acid (PLA), while the five-bar was printed out of Polyethylene Terephthalate Glycol (PETG) for increased rigidity. This was advantageous due to the high number of complex cavities in both. The housing for gripper was constructed from a combination of PLA and PETG printed parts. To ensure a uniform surface on the top of the housing for the caster wheel, all surface fixtures were countersunk then filled with hot glue and smoothed till flat. An Ar-

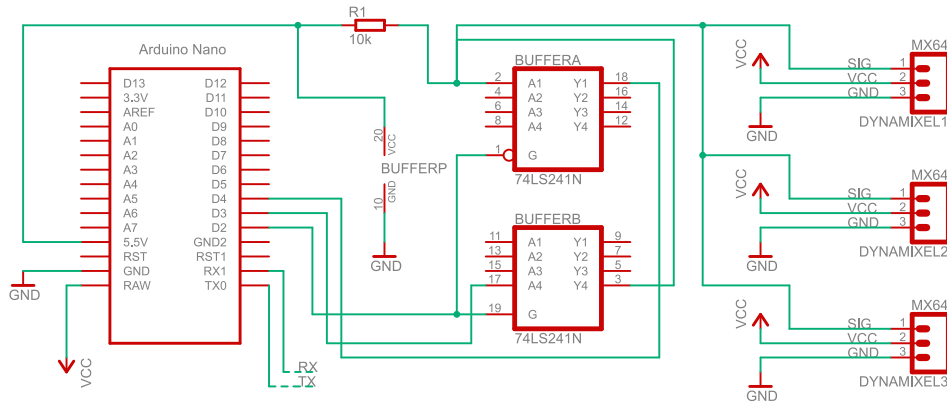


Figure 5.5: Electrical schematic for controlling the RUTH gripper motors using software serial with a tristate buffer, freeing the hardware serial to enable real-time monitoring and control of the gripper.

duino Nano microcontroller was used to control the hand, utilising a software serial connected tristate buffer (74LS241N) to communicate using half-duplex UART protocol with the Dynamixel MX64 servo motors. This allows for real-time control of all motors, as well as provides a communications channel back from the motors to the control system (whilst receiving commands) and from the control system (in this case the Arduino) to a desktop computer through a hardware serial, allowing for real-time monitoring and control. This provides a significant advantage of previous proposed solutions, which typically directly connect the motors to the microcontroller. The electrical schematic can be seen in Fig. 5.5. Thanks to the small size of the electronics they were contained within the gripper housing, with a USB socket and barrel power jack accessible on the side on the housing.

5.3 Grasping and Manipulation Analysis of the Gripper

5.3.1 Grasping Configuration

I first explore the different grasping capabilities of the RUTH gripper. Using the five-bar structure, the fingers can be re-positioned to allow for a variety of grasps, shown in Fig. 5.6. In its default configuration, an equilateral triangle, the fingers form a trigonal planar grasp, ideal for power grasping spherical objects [Fig. 5.6 (b)]. By rotating the motors inwards, the two short-link fingers come together to form a single ‘finger’, forming a parallel grasp with the long-link finger [Fig. 5.6 (a)]. This grasp is ideal for pinch grasping small objects and planar grasping regular cubic objects. Finally, by

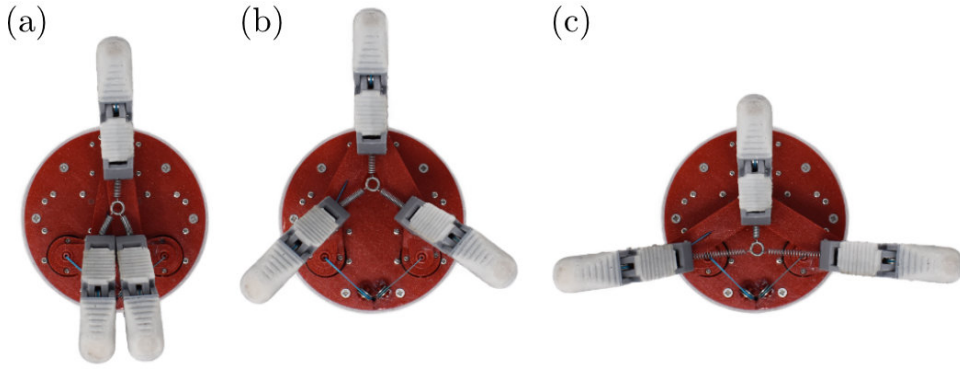


Figure 5.6: Different types of grasp achievable with the RUTH gripper: (a) Parallel, (b) Trigonal planar, and (c) T-shape.

rotating the motors outwards the five-bar expands and the gripper forms a T-shape grasp, where the short-link fingers are parallel and opposite each other, with the long-link finger acting perpendicularly [Fig. 5.6 (c)]. The enlarged reach of this grasp enables the grasping of larger objects, and is a combination of both the parallel and trigonal planar grasp in that it can perform power grasps on the majority of objects, with an increase in performance grasping regular cubic objects over the trigonal planar due to the 90° rotated fingers, rather than 120° .

5.3.2 Feasible Grasping Workspace

The feasible grasping workspace of the gripper is the set of positions in which an object can lie relative to the base of the hand, the palm, and be successfully grasped. It is possible to achieve a range of different grasping positions as the five-bar linkage can be reconfigured such that the centre point of the proximal joints of the fingers is moved underneath the position of the centre of the object. The two-dimensional grasping workspace is therefore given by the set of positions that the centre point of the proximal joints of the fingers, namely $\mathbf{P}_2$, $\mathbf{P}_3$, and $\mathbf{P}_4$, can achieve.

The positions of the palm's base joints, namely $\mathbf{P}_1$ and $\mathbf{P}_5$, are known and the positions of joints $\mathbf{P}_2$ and $\mathbf{P}_4$ are determined by the input angles of the actuators, say θ_1 and θ_2 , such that

$$\mathbf{P}_2 = \mathbf{P}_1 + l_1 [\cos \theta_1 \sin \theta_1]^T \text{ and} \quad (5.1)$$

$$\mathbf{P}_4 = \mathbf{P}_5 + l_1 [\cos \theta_2 \sin \theta_2]^T. \quad (5.2)$$

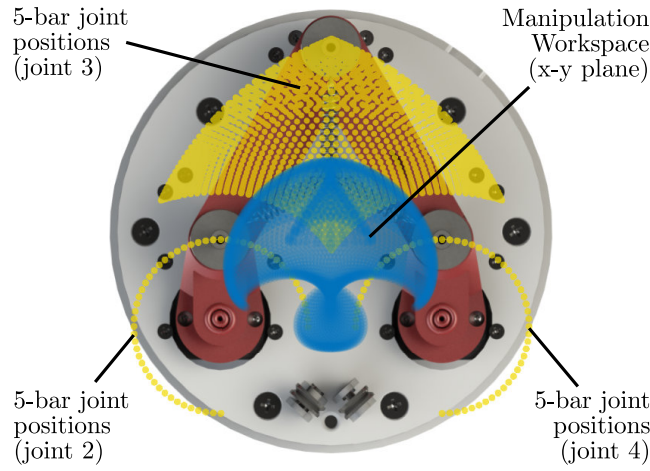


Figure 5.7: X-Y manipulation workspace of the RUTH gripper (blue) in respect to the five-bar mechanism and gripper housing (fingers removed for clarity). Five-bar joint positions for joints 2, 3, and 4 are also shown (yellow).

The position of $\mathbf{P}_3$ can be then obtained using bilateration [BPR19, Roj12] as

$$\mathbf{P}_3 = \mathbf{P}_2 + \mathbf{Z}_{2,4,3}(\mathbf{P}_4 - \mathbf{P}_2), \quad (5.3)$$

where

$$\mathbf{Z}_{2,4,3} = \frac{1}{2d_{2,4}^2} \begin{bmatrix} d_{2,4}^2 & -4A_{2,4,3} \\ 4A_{2,4,3} & d_{2,4}^2 \end{bmatrix},$$

with $A_{2,4,3} = \frac{1}{4} \sqrt{(d_{2,4}^2 + 2l_2^2)^2 - 2(d_{2,4}^4 + 2l_2^4)}$ and $d_{i,j}$ being the distance between $\mathbf{P}_i$ and $\mathbf{P}_j$. The sign of $A_{2,4,3}$ determines whether $\mathbf{P}_3$ lies to the left or the right of the vector from $\mathbf{P}_2$ to $\mathbf{P}_4$; herein, the sign of $A_{2,4,3}$ is positive as it is desired that $\mathbf{P}_3$ lies always to the left.

The centre point, $\mathbf{C}$, of the proximal joints of the fingers is then given by

$$\mathbf{C} = \frac{\mathbf{P}_2 + \mathbf{P}_3 + \mathbf{P}_4}{3}. \quad (5.4)$$

The numerical grasping workspace of the gripper can be obtained by sweeping through the possible input actuator angles, θ_1 and θ_2 , and computing the set of positions of $\mathbf{C}$ using equations (5.1)-(5.4). The only mechanical constraint that needs to be taken into account is the links cannot collide with the tendons passing into the base joints $\mathbf{P}_1$ and $\mathbf{P}_5$. Following this, if θ_1 and θ_2 are defined as the angles taken anti-clockwise from the x -axis to the vectors from $\mathbf{P}_1$ to $\mathbf{P}_2$, and $\mathbf{P}_5$ to $\mathbf{P}_4$, respectively, then the

limits to avoid collisions with the tendons are $0 < \theta_1 < 3\pi/2$ and $-\pi/2 < \theta_2 < \pi$. The computed workspace is shown in Fig. 5.7, where an instance of the five-bar linkage is also given for perspective.

5.3.3 Systematic In-hand Manipulation Map and Planning

In this section, the prehensile in-hand manipulation capabilities of the gripper are demonstrated. Firstly, a manipulation map is generated which relates the planar position of the centre of the object and its orientation to the configuration of the five-bar linkage. Algorithm 3 describes the method of computing the mapping between the object manipulation workspace and the active joint space, which describes the possible combinations of θ_1 and θ_2 . All the feasible combinations of θ_1 and θ_2 are then swept through and the centre of the object, whose coordinates are given by x and y , is determined using the method described in the previous section (5.3.2).

Additionally, the orientation of the object, denoted by ϕ , is given by the anti-clockwise angle from the x -axis to the vector from $\mathbf{P}_2$ to $\mathbf{P}_4$; this is computed using the two-argument inverse tangent function so that the direction of the angle is determined. Each feasible object pose is stored in the k^{th} row of matrix, say $\mathbf{M}_1$, and the corresponding joint angles make up the k^{th} row of another matrix, say $\mathbf{M}_2$. As the units of $\mathbf{M}_1$ are not homogeneous, $\mathbf{M}_1$ is normalised, such that

$$\mathbf{M}_{1,norm,i} = \begin{bmatrix} \frac{x_i - \min(x,y)}{\max(x,y) - \min(x,y)} \\ \frac{y_i - \min(x,y)}{\max(x,y) - \min(x,y)} \\ \frac{\phi_i - \min(\phi)}{\max(\phi) - \min(\phi)} \end{bmatrix}^T \quad (5.5)$$

where $\mathbf{M}_{1,norm,i}$ denotes the i^{th} row of the normalised $\mathbf{M}_1$ matrix, (x_i, y_i, ϕ_i) make up the i^{th} row of $\mathbf{M}_1$, $\min(x,y)/\max(x,y)$ denotes the minimum/maximum of all x and y values, and $\min(\phi)/\max(\phi)$ denotes the minimum/maximum of all ϕ values.

Algorithm 4, the computation of manipulation planning, utilises the above mapping to find the shortest distance in joint space to move from the current pose of the manipulator to the desired pose,

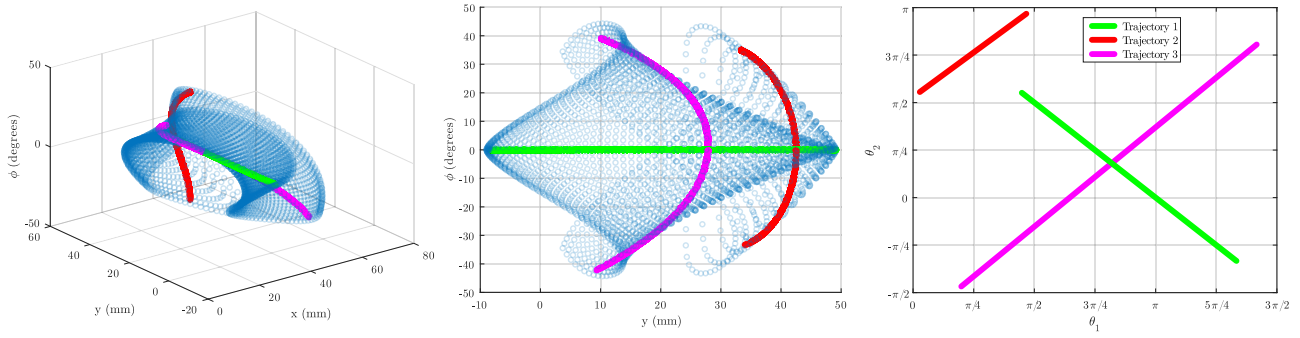


Figure 5.8: The manipulation map with the three tested trajectories of the grasped object. Trajectory 1 is a pure translation, trajectory 2 is a pure rotation, and trajectory 3 is a combined translation and rotation. (a) and (b) show two different views of the object trajectories across the hand workspace, and (c) shows the corresponding joint angle profiles.

$\mathbf{D}=(x_D, y_D, \phi_D)$. $\mathbf{D}$ is normalised in the same manner as $\mathbf{M}_{1,norm}$, such that

$$\mathbf{D}_{norm} = \begin{bmatrix} \frac{x_D - \min(x,y)}{\max(x,y) - \min(x,y)} \\ \frac{y_D - \min(x,y)}{\max(x,y) - \min(x,y)} \\ \frac{\phi_D - \min(\phi)}{\max(\phi) - \min(\phi)} \end{bmatrix}^T. \quad (5.6)$$

Now, in order to find the nearest neighbour in $\mathbf{M}_{1,norm}$ to $\mathbf{D}_{norm}$, a k - d tree is formed from $\mathbf{M}_{1,norm}$. This tree is formed by taking the median of the points in $\mathbf{M}_{1,norm}$ with respect to a particular coordinate (this point is called the root), and splitting the set into two; the subset of points to the left of the root comprise the left side of the tree and the ones to the right comprise the right side of the tree. The median of each of these sets is found with respect to the next coordinate and the tree is formed by continuing to partition all of the points in this fashion. The k - d tree is then used to perform a nearest neighbour search, such that the point in $\mathbf{M}_{1,norm}$ that is the shortest Euclidean distance from $\mathbf{D}_{norm}$ is found. This is performed by starting at the root and moving down the tree depending on whether the coordinate of the desired point corresponding to the current partition is to the left or the right of the partition.

If a point in the tree is reached which is closest so far to the desired point, it is recorded as such. The possibility that there are points on the other side of the partition that are closer is checked by forming a sphere around the desired point with a radius equal to that of the distance between the current closest point and the desired point—if the sphere crosses the partitioning plane, there could be closer points

Algorithm 3 Manipulation Mapping Algorithm

```

1: procedure ( $\mathbf{P}_1, \mathbf{P}_5, l_1, l_2$ )
2:    $\mathbf{M}_1 \in \mathbb{R}^{(n+1)^2 \times 3}$ 
3:    $\mathbf{M}_2 \in \mathbb{R}^{(n+1)^2 \times 2}$ 
4:    $k = 1$ 
5:   for  $i \leftarrow 0$  to  $n$  do
6:      $\theta_1 \leftarrow i3\pi/2n$ 
7:     for  $j \leftarrow 0$  to  $n$  do
8:        $\theta_2 \leftarrow j\pi/n - \pi/2$ 
9:       Compute  $\mathbf{P}_2, \mathbf{P}_3, \mathbf{P}_4$ , and  $\mathbf{C}$  using equations (5.1)-(5.4).
10:       $\phi \leftarrow \text{atan2}(\mathbf{P}_{4,y} - \mathbf{P}_{2,y}, \mathbf{P}_{4,x} - \mathbf{P}_{2,x})$ 
11:       $\mathbf{M}_1[k, :] = (x, y, \phi)$ 
12:       $\mathbf{M}_2[k, :] = (\theta_1, \theta_2)$ 
13:       $k = k + 1$ 
14:   Normalise  $\mathbf{M}_1$  using equation (5.5)

```

Algorithm 4 Manipulation Planning Algorithm

```

1: procedure ( $\mathbf{D}, \mathbf{M}_{1,norm}, \mathbf{M}_2, \theta_{C,1}, \theta_{C,2}, x_D, y_D, \phi_D$ )
2:   Normalise  $\mathbf{D}$  using equation (5.6)
3:   Create  $k$ - $d$  tree from  $\mathbf{M}_{1,norm}$ 
4:   Search tree for nearest neighbour to  $\mathbf{D}_{norm}$ 
5:    $m \leftarrow$  index of nearest neighbour
6:    $(\theta_{F,1}, \theta_{F,2}) \leftarrow m^{th}$  row of  $\mathbf{M}_2$ 
7:   Path from  $(\theta_{C,1}, \theta_{C,2})$  to final  $(\theta_{F,1}, \theta_{F,2})$  is discretised such that the  $\theta_1$  and  $\theta_2$  step sizes are each constant and are equal in number

```

and therefore the opposite branch must be checked, otherwise the opposite branch can be neglected. This algorithm continues until the nearest neighbour is found. The index, m , of this point is taken and the final joint coordinates, $(\theta_{F,1}, \theta_{F,2})$, are given by the m^{th} row of $\mathbf{M}_2$, the matrix of joint angles.

The path from the current pose of the manipulator, defined by the joint angles $(\theta_{C,1}, \theta_{C,2})$, to the final pose is discretised such that the θ_1 and θ_2 step values are constant and equal in number. Fig. 5.8 shows the manipulation map of the gripper with 3 examples trajectories of the object; Fig. 5.8 (a) and Fig. 5.8 (b) show the trajectories of the object from two different views and Fig. 5.8 (c) shows the corresponding joint angle profiles.



Figure 5.9: The YCB Object set, used entirely in the grasping capability evaluation and partially in the in-hand manipulation evaluation of the gripper.

5.4 Performance Evaluation

To show how the five-bar linkage of the RUTH Gripper and proposed manipulation strategy impact the grasping and in-hand manipulation behaviour, a series of objects, including both regular objects (e.g. cylinders, squares) and daily-life objects, were used for assessment. The daily-life objects were taken from the YCB object set [CSW⁺15]. The grasping and in-hand manipulation tasks included picking up and grasping an object from a workbench with the three grasping configurations, and manipulating an object in the air across the gripper workspace. 15 objects of various sizes and shapes were used for in-hand translation and rotation tasks, and 28 objects were grasped as detailed in the YCB Gripper Assessment Benchmark [CSW⁺15]. This section highlights the five-bar reconfigurable palm and other design features illustrated by the experiments.

5.4.1 Experimental Setup

The RUTH Gripper was attached to a Universal Robot Arm (UR5) for performing grasping tests. An Arduino Nano was used to control the movement of the five-bar linkage (reconfigurable palm) and the grasping through the Dynamixel motors. Motion tracking cameras (OptiTrack Flex3) were used to track the testing object trajectories, where all these objects had four tracking markers on them. Each in-hand manipulation test consisted of 5 repeated trials to generate reliable performance results.

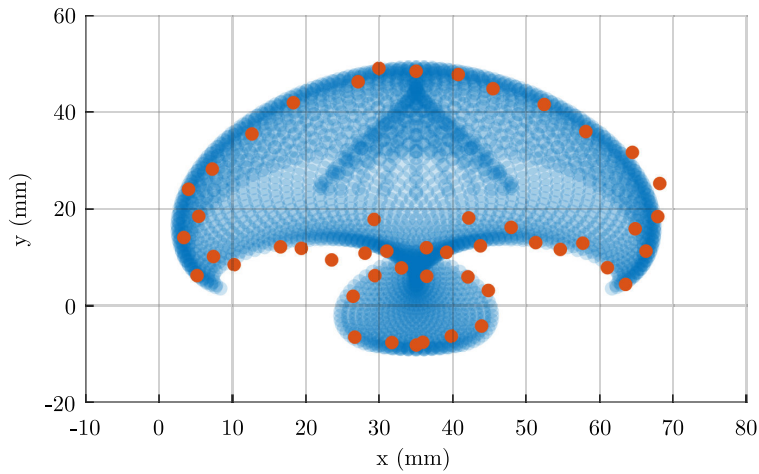


Figure 5.10: Experimental object positions at the RUTH gripper’s configuration boundary (red). Simulation workspace of the RUTH gripper (blue).

5.4.2 Grasping Capability and Workspace

By taking advantage of the five-bar linkage palm, the RUTH gripper is able to grasp various objects in the different grasping configurations shown in Fig. 5.6. The grasping capability of the RUTH gripper was tested by performing the YCB Gripper Assessment Benchmark [CSW⁺15], grasping a range set of YCB objects which include a set of spheres ranging in size from 17.4 mm to 145 mm, a set of tools, flat objects, and articulated objects (see Fig. 5.9).

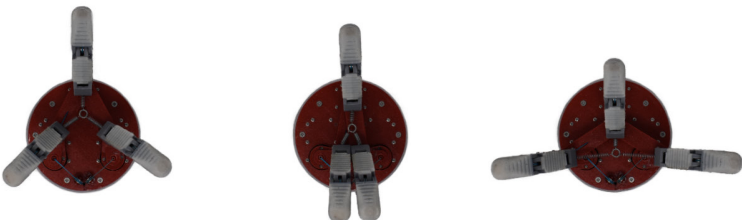
The grasping tests were carried out not only to show the grasping capabilities of the gripper, but additionally to show how the reconfigurability of the gripper increases the number of objects that can be grasped. Firstly, all of the objects were attempted to be grasped using the trigonal planar grasp posture, as shown in Fig. 5.6 (b); this grasp was tested first as its symmetrical nature allows force closure for a greater range of objects compared to the other two grasps. The grasp procedure was carried out for each object (excluding the two articulated objects) as follows. Firstly, the hand was moved into the correct grasping position and the fingers were closed to grasp the object. Then, the gripper was raised by 30cm and would remain in this position for 3 seconds. The gripper would then be rotated about the x -axis, an axis which is parallel to the surface of the table, and then remain in this position for 3 seconds. The grasp was then given a score between zero and four depending on the success of the test. If the initial grasp failed, or if the object was dropped during the raising motion, a score of zero would be awarded. If the object remained in the grasp after being in the raised

position for 3 seconds but had visibly moved within the grasp, a score of one was awarded. If the object remained in the grasp with no visible movement up to this point, a score of two was awarded. Similarly, if the object was dropped after being rotated and held there for 3 seconds, no additional score was awarded. If the object had stayed in the grasp but visibly moved during this process, an additional score of one was awarded (scoring a total of 3). If a secure grasp was maintained during this process, an additional score of two was awarded (scoring a total of 4).

In order to test the robustness to uncertainty in the object's position, the grasping procedure was attempted for each object in four different positions. Firstly, the object was placed onto a flat, 1cm-thick surface which was placed on top of the table, and the grasping procedure described above was performed. Then, the same procedure was performed, with the same initial gripper position, for three other object positions, corresponding to disturbance along the x , y , and z axes. It should be noted that the z axis disturbance is measured for the round objects and the tools, but not the flat objects. The x and y axes correspond to the orthogonal axes which form the plane corresponding to the surface of the table, the z axis is orthogonal to the surface of the table, and the origin is defined by the initial object position. The disturbance along the x and y axes is performed by moving the object 1cm along each of the axes, respectively. The disturbance along the z axis is performed by removing the 1cm-thick surface and placing the object on the table directly below the initial object position. The grasping procedure was carried out, and a score was given, for each of the objects in each of the four positions.

One of the advantages of the RUTH hand is that its reconfigurability allows different grasp postures to be achieved, which increases the potential number of objects that are able to be grasped. After carrying out the grasping procedure using the trigonal planar grasp and collecting the scores for each object in each position, there are some objects which received a maximum score, and some that did not. The grasping procedure was performed again on those objects that did not achieve a maximum score, but this time using the parallel grasp, as shown in Fig.5.6 (a). Similarly, after grasping with the parallel grasp, the grasping procedure was performed again on those objects that still had not achieved a combined maximum score, this time using the T-shape grasp, as shown in Fig.5.6 (c). The results are given in Fig.5.11.

The two articulated objects follow a different grasping procedure and scoring method. The object is



		Trigon-Planar				Parallel				T-Shape			
		SP1	SP2	SP3	SP4	SP1	SP2	SP3	SP4	SP1	SP2	SP3	SP4
		Origin	ΔX	ΔY	ΔZ	Origin	ΔX	ΔY	ΔZ	Origin	ΔX	ΔY	ΔZ
Round Objects	Soccer Ball	4	4	4	4								
	Softball	4	4	4	4								
	Tennis Ball	4	4	4	3	4	4	4	4				
	Racquetball	4	4	4	4								
	Golf Ball	4	4	4	0	4	0	4	4				
	Marble XL	4	4	4	0	4	4	4	4				
	Marble L	4	4	4	0	4	4	4	4				
	Marble M	4	4	4	0	4	0	4	0	0	0	0	0
	Marble S	0	0	0	0	4	0	4	0	0	0	0	0
Flat Objects	Washer M28	0	0	0		0	0	0		0	0	0	
	Washer M20	0	0	0		0	0	0		0	0	0	
	Washer M14	0	0	0		0	0	0		0	0	0	
	Washer M10	0	0	0		0	0	0		0	0	0	
	Washer M7	0	0	0		0	0	0		0	0	0	
	Washer M5	0	0	0		0	0	0		0	0	0	
	Washer M2.5	0	0	0		0	0	0		0	0	0	
	Credit Card	0	0	0		0	0	0		0	0	0	
Tools	Pen	4	4	4	0	4	4	3	0	4	4	0	0
	Scissors	0	0	0	0	0	0	0	0	0	0	0	0
	Hammer	0	0	0	0	0	0	0	0	0	0	0	0
	Screwdriver	1	0	0	0	4	4	0	0	0	0	0	0
	Drill	0	0	0	0	0	0	0	0	0	0	0	0
	Clamp XL	4	4	4	0	4	4	4	4				
	Clamp L	3	3	3	4	4	4	4	0				
	Clamp M	4	4	4	4								
	Clamp S	4	4	4	4								
Articulated	Chain	2				2				0.5			
	Rope	10											

Figure 5.11: Experimental results of the YCB Grasping Benchmark, with failed objects repeated with successive grasp configurations. Repeats are stopped (grey hashed) once the full score for an object can be achieved.

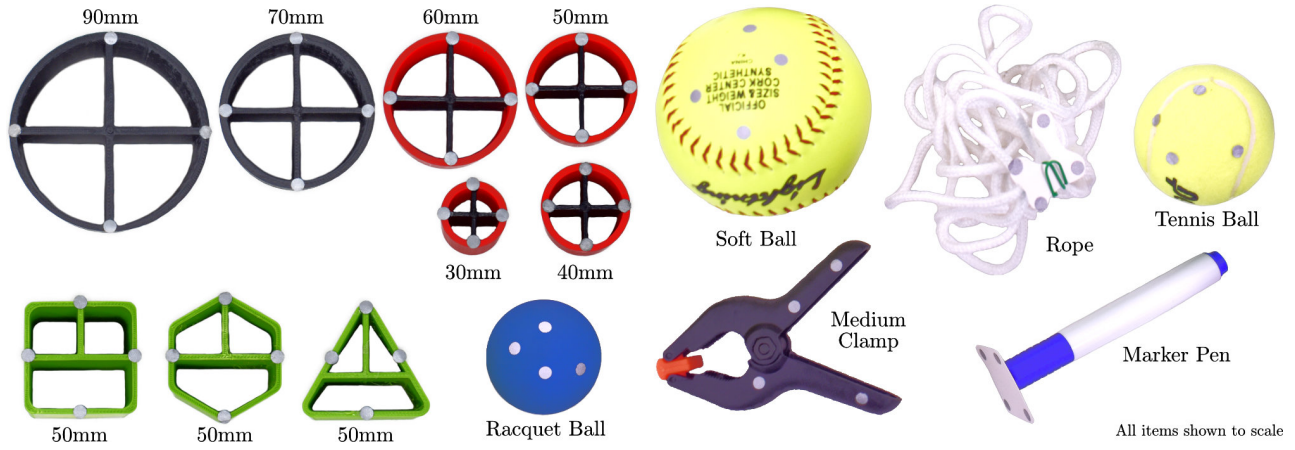


Figure 5.12: Regular objects and a subset of the YCB objects used in the in-hand manipulation evaluation of the gripper, with tracking marker positions shown.

grasped, raised by 30cm, and held there for 3 seconds. If the object remains in the grasp with no part of it touching the ground, 0.5 points is awarded. This is repeated 20 times, giving a total possible score of 10. Similarly to the rigid object, if the articulated object did not receive a perfect score with the trigonal planar grasp, then it was repeated with the planar a grasp, and then the T-shape grasp. The results for the articulated objects are given at the bottom of Fig.5.11.

In addition to the YCB grasping benchmark tests, the grasping workspace was measured by grasping the 50 mm cylindrical object at the boundary case and comparing it to the simulated workspace shown in Fig. 5.10. The blue dots are the feasible manipulation workspace of the RUTH gripper in the X-Y plane produced by MATLAB. The red dots correspond to the motion tracking data of the grasped object centre positions. The experimental data verified the gripper grasping workspace with a little deviation due to the underactuated finger design and inconsistent grasping force.

5.4.3 Systematic Prehensile In-hand Manipulation

As proposed in section III.C, the prehensile in-hand manipulation map of the gripper was generated in terms of x , y and ϕ using Algorithm 1. The grasped object can be moved into a desired pose by using the map to identify the θ_1 and θ_2 values as described in Algorithm 2. Three characteristic trajectories of the object were chosen for the tests. During the tests, the gripper was given the θ_1 and θ_2 values produced by the map by inputting the target x , y and ϕ . The change of θ_1 and θ_2 during the

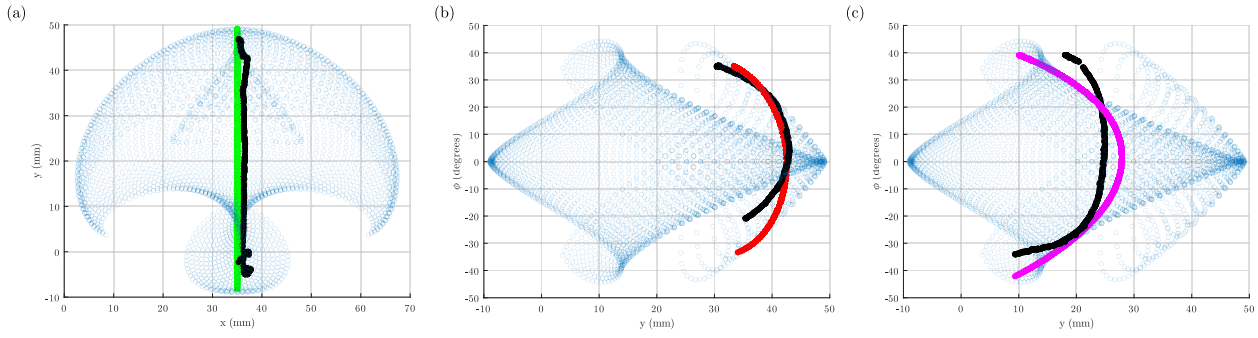


Figure 5.13: Experimental motion tracking object trajectories (black) overlaid on simulated trajectories. (a) Pure translation, (b) pure rotation, and (c) combined translation and rotation.

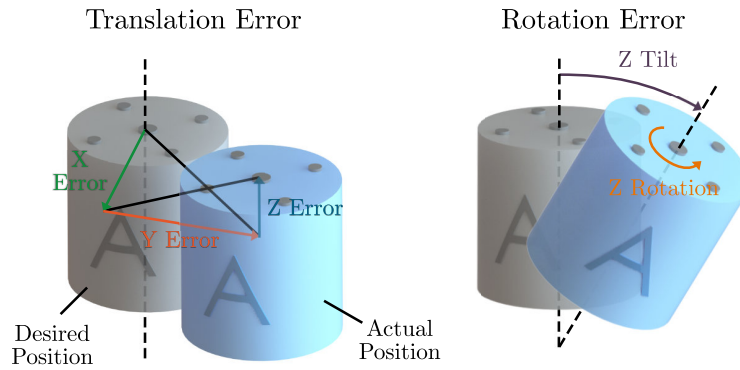


Figure 5.14: Diagram demonstrating how the translation (left) and rotation (right) positioning errors relative to the desired object location are reported.

manipulation are linear as shown in Fig. 5.8(c).

To evaluate the manipulation capability of the hand, multiple objects were tested along each of the three trajectories. For the regular objects, six cylindrical objects varying from 30mm to 90mm along with a cube, a hexagonal prism, and a triangular prism all of size 50mm were used, as well as six objects from the YCB object set (see Fig. 5.12). The three testing trajectories were chosen such that the first trajectory resulted in a pure translation of the object (57.2 mm), the second trajectory resulted in a pure rotation of the object (68.2 °), and the third trajectory resulted in a combined translation and rotation of the object (54.9 mm, 81.2 °). A summary of these values can be seen in Table 5.1. These trajectories can be seen visually in Fig. 5.8. The positions of each of the manipulated objects were tracked using reflective markers placed on each of the objects. The position of the gripper base was also tracked, enabling the mapping of the simulated object trajectory to the tracking coordinate system. The difference between the simulated object trajectory and each experimental object trajectory were measured and reported. The translation error along each axis (X/Y/Z), where Z

Table 5.1: Simulated translation and rotation quantities of the desired 3 trajectories for the in-hand manipulation evaluation.

Trajectory	Simulated Trajectory Motion	
	Translation (mm)	Rotation ($^{\circ}$)
T1	57.2	0°
T2	0.7	68.2°
T3	54.9	81.2°

is the vertical axis and X and Y are the planar axes, and the rotation error around the Z axis and from the Z axis (reported as ‘tilt’), are reported. A diagram demonstrating each of these errors can be seen in Fig. 5.14. These errors are reported as both an average error across the entire trajectory, as well as just at the desired end point of the trajectory. Each trajectory was repeated 5 times for each object, with the average then taken to improve accuracy. Fig. 5.13 shows an example experimental object’s trajectories compared to the simulation trajectories. The translation error results of the manipulation test can be seen in Fig. 5.15, whereas the rotation error results can be seen in Fig. 5.16.

5.5 Discussion

The performance of the RUTH gripper in the YCB Manipulation Benchmark demonstrates how the different grasp configurations are advantageous, as they can achieve a successful grasp where other configurations might not succeed. In the trigonal planar grasp, there is a complete success (that is, full marks achieved in grasping at the object origin, as well as in the X, Y, and Z offsets) in the larger spherical objects, as well as the smaller clamps and rope. The smaller spherical objects fail with the Z offset, which can be explained by the gripper no longer grasping below the centre of the sphere, causing the objects to fall out of the gripper. For the smallest spherical object, it was not possible to grasp below the centre point in any of the object positions. In the case of the articulated objects, the rope shows complete success as it is quite light, and holds its form when grasped, unlike the chain which is significantly heavier and requires a more encapsulating grasp, explaining its limited success. For the tools, results showed success with the majority of the clamps, as well as success with the pen, which showed a similar issue to the spherical objects in the Z offset. The drill and hammer were shown to be too heavy for the RUTH gripper, with the object’s weight causing the object to slide

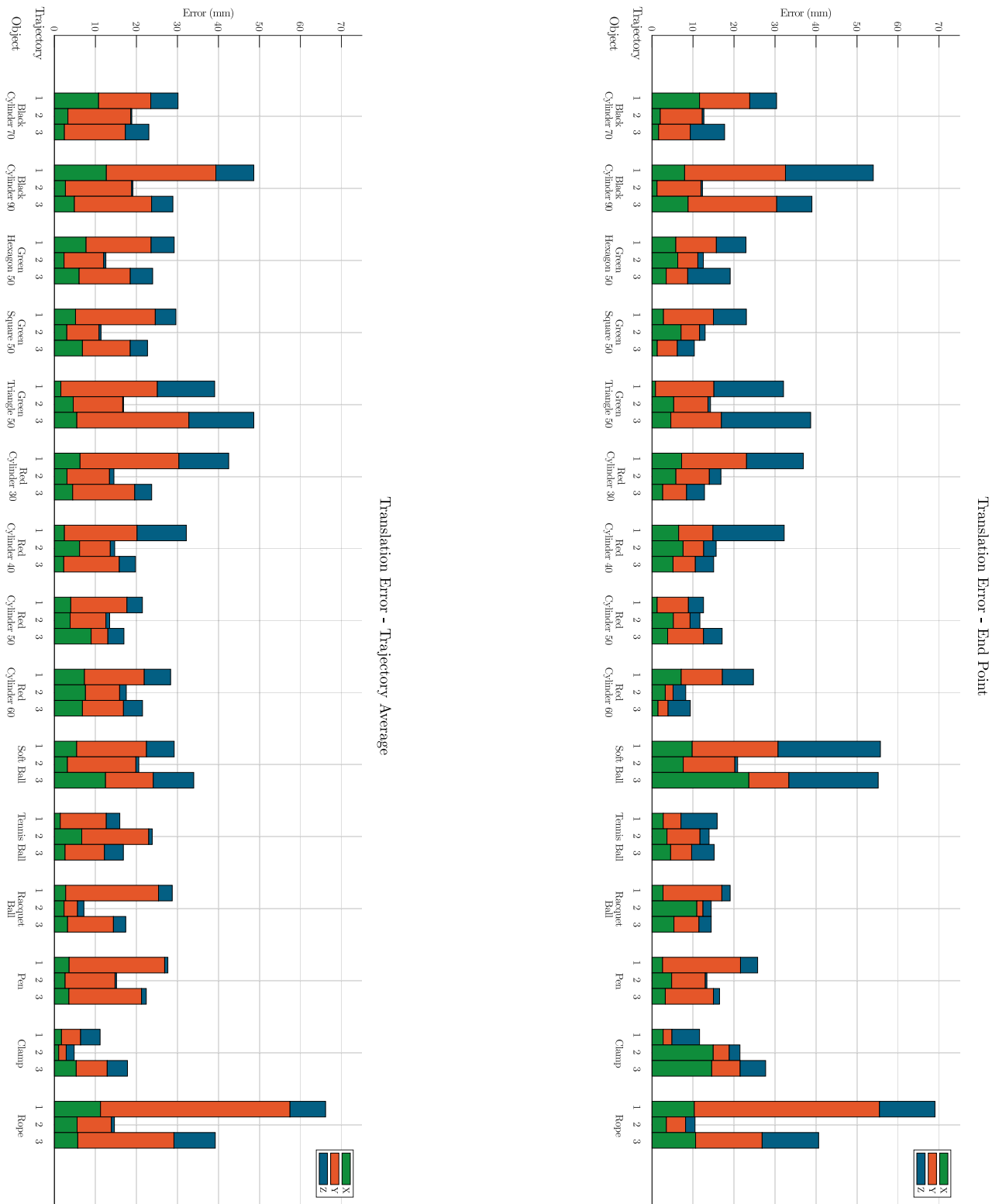


Figure 5.15: **Left:** Translation errors averaged across the entire object trajectory. Translation error is shown in mm in the three (X/Y/Z) axes from the desired object location, for each of the three trajectories for all objects. **Right:** Translation errors at the end point of the object trajectory. Translation error is shown in mm in the three (X/Y/Z) axes from the desired object location, for each of the three trajectories for all objects.



Figure 5.16: **Left:** Rotation errors averaged across the entire object trajectory. Rotation error is shown in degrees, and is represented by rotation around axis Z and from axis Z (tilt), for each of the three trajectories for all objects. **Right:** Rotation errors at the end point of the object trajectory. Rotation error is shown in degrees, and is represented by rotation around axis Z and from axis Z (tilt), for each of the three trajectories for all objects.

out of the grasp. Weight also showed to be an issue for the screwdriver, where the balance of the weight caused the object to rotate out of the grasp. The scissors were not too heavy, however were too flat to be grasped by the gripper. None of the flat objects were successful, and I believe this can be attributed to the underactuated finger design, providing limited control over balancing the bending of the finger phalanges, as well as the fingers lacking optimisation for flat objects, such as not including a fingernail. In all configurations, the gripper was unable to lift the flat objects off of the table, and any recorded movement typically resulted in the object being pushed out of the grasping area. For the purely trigonal planar grasp, a score of 193/404 was achieved, giving a successful percentage of 48%. Removing flat objects from scoring, this scoring is 193/260, with a grasp percentage of 74%.

Objects that did not show complete success were repeated in the parallel grasp, and then again in the T-shape grasp if a complete success had still not been achieved. The parallel grasp showed success in areas where the trigonal planar had failed, such as maintaining a grasp with the Z offset on the medium (tennis ball) and smaller spherical objects. Some success was also shown for the screwdriver and the larger clamps, possibly due to the slightly higher grasp force achievable in the parallel grasp. No additional successes that had not previously been achieved were measured with the T-shape grasp, however this was expected as the main advantage of the T-shape grasp is the increased grasping size, and the largest objects of the YCB set had already shown complete success in the trigonal planar grasp. With the additional scores from the parallel grasp, the total score was increased to 228/404, a percentage of 56%. Removing the flat objects category this scoring is 228/260, a percentage of 88%.

From these results, the grasp configurations do indeed provide an advantage in grasping, allowing an increased number of objects to be successfully grasped. Limitations of the gripper were highlighted, such as the fingertip design and phalange control for flat objects, as well as the force transmission through the tendon routing system restricting the maximum force output making grasping heavy objects difficult. Objects outside of these two categories however showed consistent success.

The overall performance of the RUTH gripper in manipulating an object is predictable with some deviations, especially for non-cylindrical objects. Across all objects, a minimal error in the x axis (<10 mm) is observed, a consistent error of 5–15 mm for the y axis, and either almost no error (<5 mm) or a larger 10–20 mm error in the z axis. For non-cylindrical objects, the distances from

each finger contact point to the centre of the object vary during the manipulation, which is a challenge for an underactuated gripper. The translation errors may occur, at least partly, due to the gripper grasp-pushing the manipulated object away from the centre of the gripper. This is reflected by the greater error in the translation along the y axis, as opposed to the x axis, for most of the trials, as the fingers attached at P_2 and P_4 tend to push the object more toward the finger attached at P_3 . This also explains the consistency across the y axis errors, with the majority of objects showing an error of ~ 10 mm. This may easily affect both the average mean and final position of the object and contribute to the translation error. For the proposed design, in order to have a constant tendon routing design for the five-bar linkage (the reconfigurable palm) the tendon routing, shown in Fig. 5.2, may reduce the force transmission efficiency significantly given the small-radii pulleys that are used, resulting in a limited ability to push the object towards the centre of the gripper.

As discussed above, the translation errors tended to be relatively small for the cylindrical objects, with the exception being the largest of them; the Black Cylinder with a 90mm diameter. However, for the rotational errors the opposite is true, with the smaller cylinders performing worse than the larger cylinders. This is likely to be because for the larger cylinders, there were not only contacts at the fingertips but also at other points on the fingers, which may have helped keep these objects more upright during the manipulation. This was also the case for the pen, the end of which was in contact with the base of the gripper throughout the manipulation, and, as a result, both the mean and final tilting error is quite small.

Another contributing factor to the translation errors is the changing contact points during the prehensile in-hand manipulation. In the simulation, it is assumed that the object is always being grasped at the centre of the hand and the grasping configuration of each finger is identical. However, in reality, there are some aspects that make these assumptions not totally valid. Firstly, the three three-phalanx fingers are actuated by only one motor via tendons. With the same change in the length of the tendon, each finger configuration (the angles between phalanges) may still vary due to other factors, such as the contact force, manufacturing errors, and structural friction. With this uncertainty, each of the three fingers may end up with a slightly different bending height which will cause object translation and rotation errors. Taking into account these considerations into the simulation is still an open research question. In the case of loosely held objects, such as the rope, this change in contact points may also

explain the slippage of the object, resulting in an increased z axis error. The same is true for heavy objects (soft ball, black cylinder 90), and objects that do not adapt well with a change in finger configuration (green triangle 50). This is confirmed by the same objects showing little to no z axis error in the second trajectory, where the finger configuration is constant across the entire trajectory.

To maintain the grasping capability as the five-bar configuration changes, the fingers actuation motion should be towards the centre of the triangle formed by the three finger base positions proposed in section 5.2. To achieve this, the direction of each finger was controlled by a high stiffness spring attached at the base of each finger to a central ring. In some cases, when the gripper grasped an object tightly, the central ring may struggle to pull all the fingers towards the centre of the triangle which may produce the position error adding to the end position.

In terms of the trajectories, it is clear from the results that the displacement error tends to be lower for Trajectory 2. This is likely because the length of the total trajectory is smaller than that of the other two, and additionally the end point position of the object should be equal to its start position. Similarly, the smaller rotational errors for this trajectory can be accounted for by its shorter total length, as well as the previously mentioned lack of gripper configuration change across the trajectory. The rotational errors for Trajectory 1, the straight translation trajectory, are reasonably small, especially the rotational error about the z axis. This is likely due to the fact that the aim for this trajectory does not include a rotation around the z axis, and so the fingers sliding over the surface of the object produced little unwanted rotation. It is expected that Trajectory 3 suffered the highest errors, in both translation and rotation, as it was both the longest trajectory but also included a rotational aspect as well.

5.6 Conclusion

In this chapter, the design, construction, and evaluation of a reconfigurable underactuated constant-tendon hand (the RUTH gripper) is presented, which decouples manipulation and grasping to facilitate the control and implementation of prehensile in-hand manipulation. Using a five-bar linkage as the palm of the gripper, the fingers are capable of repositioning to allow different grasp types and object-invariant in-hand manipulation. The design of the reconfigurable palm is explored, as is the method

of achieving underactuated constant-tendon routing despite the ability of each finger to change its proximal joint position. An algorithm to compute the feasible manipulation map using distance-based kinematics is proposed, as is an algorithm for manipulation planning and control. The hand is experimentally evaluated in both grasping and in-hand manipulation capabilities. A wide range of objects was tested for the grasping capability under different grasping configurations. Nine sample objects of different size and shape and six daily objects were manipulated in three trajectories using the algorithms proposed. From the results, we see that with the proposed mechanical-intelligence design principle, the gripper can achieve precise, systematic in-hand manipulation regardless of the particularities of the object with a simple control scheme.

For future work, force analysis can be performed to calculate the required torque for the constant-tendon routing, and this routing can be optimised to improve the force transmission efficiency. Moreover, the introduced grasping-manipulation decoupling approach can be explored for 6D in-hand manipulation through a novel design of the base linkages or an improved underactuated finger design. Overall, the work in this chapter opens up a new idea on co-designing robot hand and control for dexterous in-hand manipulations.

Chapter 6

Conclusion and Future Work

With the fast technological development in robotics at the beginning of the 21st century, robots are now being used in a wide variety of fields beyond factory settings to free or augment human labour. Robot end effectors, which attempt to match the capabilities of the human hand, are then being required to perform grasping and manipulation tasks of increasing complexity and in dynamic environments prone to uncertainty. Capturing the richness and complexity of the human hand has been an ambition of many fields of human knowledge. Since at least the end of the sixteenth century, researchers have tried to match the sensory and motor functions of the human [ZO14]. This design approach may have the potential to perform complex tasks in real-world scenarios, but evidence shows that this may require the use of even more power-hungry data-driven control techniques than those used in current state-of-the-art solutions for simpler tasks. The resemblance to the human hand in appearance and movement and function might be indeed overly complex for multiple applications from manufacturing to healthcare. Recently, a different design approach has then become popular, which aiming at achieving robust, easily programmable, and economically viable robotic hands capable of performing a valuable subset of the functions of human hands in a variety of domains and conditions [PGCB19].

Following this towards simplification design approach, a vast number of two-fingered and three-fingered robotic grippers have been developed to execute grasping tasks. Underactuation, which refers to controlling the degrees of freedom of a system with fewer actuators than required, is very

popular and useful in gripper design research. Its use can result in self-adaptive efficient systems with simple control schemes. However, robotic research has long been also interested in the ability to in-hand manipulate objects to improve the dexterity and applicability of robots. Further research is indeed needed in the components of a dexterous manipulation robotic system, which are a robotic hand and a control policy, along with the object to be grasped and manipulated by the hand [HT98]. Improving the in-hand manipulation ability of robot grippers without increasing their design and control complexity has then become an active area of research in recent years. Indeed, performing reliable prehensile in-hand manipulation under both shape diversity and shape uncertainty with a robot hand is still an open problem [Bic00, BK19].

Both of the described design approaches have benefits and drawbacks. This thesis, in order to maximise the benefits—such as getting better dexterity with simpler control, integrates the two approaches by taking principles from the superiority of the human hand design and applying them to simple robotic grippers, such that a reliable prehensile in-hand manipulation without increasing the control complexity significantly is achieved. Four mechanical enhancement aspects have been chosen as inspiration from the human hand design: i) soft fingertips, ii) active, changing surfaces in fingers, iii) the exploitation of hand topology for particular tasks, and iv) an active, flexible palm—a reconfigurable palm. This thesis aims to explore and innovate around these mechanical design aspects to deliver a clear understanding of their efficacy and practicality for complex motion, in particular for the in-hand manipulation of a wide range of objects.

The research contents of this thesis are based on the above four mechanical enhancements. In Chapter 2, the role of soft fingertips for in-hand manipulation has been analysed. The reason to analyse the soft fingertips is that high grasping stability arises from the compliance of fingertips in the human hand since the deformation of the soft glabrous fat has an increase in the contact area between fingertips and the grasped object. Thus, soft fingertips have become a suitable approach in robotics to handle excessive contact force in grasping and manipulation tasks. A novel, tractable approach for contact modelling of soft fingertips in within-hand dexterous manipulation settings has been proposed to understand the role of soft fingertips for in-hand manipulation. Numerical and empirical experiments are conducted to analyse the effects of soft fingertips on manipulation operability; results demonstrate the functionality of the proposed approach, as well as a trade-off between hardness

and depth in soft fingertips to achieve better manipulation performance of dexterous robot hands. The fingertips need to be not only soft but also thin (without objects touching the 'robot bones', the links) to increase the robot hand's workspace for in-hand manipulation. Moreover, this proposed model of soft fingertips can give an estimation of the object workspace within a short period of time without special expertise.

The human hand can change its surface condition, i.e. the coefficient of friction and appearance via subcutaneous nerve when the environment condition is changing. Chapter 3 proposes this phenomenon as an example of active surfaces, which refers to changing the robot hand's surface condition via actuators instead of the passive environment changes. Two types of active surfaces of fingers have been proposed to determine their capabilities for both grasping and in-hand manipulation. Firstly, a novel origami-inspired thin surface for robotic fingers, which allows obtaining the benefits of variable friction for dexterity in a more compact setting, has been proposed. The surface can switch the friction condition (high/low) by a single DC motor. This proposed design is parametric, flexible and compact; with high-level manufacturing skill, ideally, it can become as a variable friction skin. The introduced surface was assembled to a simple two-fingered two-degree-of-freedom robotic gripper, capable of achieving translation and rotation of objects with it. Compare to a normal two-fingered two-degree-of-freedom robotic gripper, the results show that the active surface provides a noticeable enhancement on the capability of in-hand manipulation. Additionally, an active soft fingertip has been proposed to enhance the dexterity of robot hands via the dual-functionality of tactile sensing and active shape-changing; such that pressurised air cavities act as soft tactile sensors to provide closed-loop control of fingertip position and avoid object's damage, and pneumatic-tuned positive-pressure deformations act as a localised soft gripper to perform additional translations and rotations. Furthermore, the air cavities inside the fingertip can be optimised to enhance the in-hand manipulation performance using variables such as size, shape, position, and number. To sum up, both active surfaces proposed in Chapter 3 have shown the capability and the great potential to enhance the in-hand manipulation performance for simple robotic grippers, without increasing the control complexity significantly.

Chapter 4 investigates a mechanical intelligence strategy based on using the hand topology to produce complex object in-hand manipulations. There are 24 degrees of freedom in the human hands. This is one of the reasons why they can perform many complex and dexterous in-hand manipulations.

Since the hand-object system formed during in-hand manipulation operations constantly generates multiple closed-loop kinematic chains that inherently impose constraints that modify the feasible movements of both the hand and the object. The idea of using a particular hand topology to perform specific complex in-hand manipulation with a reduced number of actuators has been explored. The proposed hand topology design can achieve self-adaptive precision grasping and generating a complex predictable behaviour, namely, helical prehensile in-hand motions of unknown objects under low-level, simple non-position control schemes with the minimum number of actuators. However, this helical motion shows difficulties in real-world applications because the pitch of the helical motion is not changeable with this hand topology design. This may cause the helical in-hand manipulation to not match particular requirements. Overall, this hand topology idea shows limited potential in improving the in-hand manipulation capabilities of simple robot hands. The proposed hand topology may achieve all 6-DOF manipulations when actuating all the fingers, but the design and control would become more complex. For keeping control simplicity, a new hand topology has to be designed to satisfy the purpose for a different type of in-hand manipulation trajectory, making the approach less tractable.

To achieve human hand versatility, another interesting mechanical design aspect have been developed in Chapter 5 based on a reconfigurable palm. With the help of the extra degree of freedom of the palm and the adduction/abduction capability of the base joint for each finger, human hands can achieve various grasping types. Humans can then choose different strategies to grasp the object with the best performance. The reconfigurable palm idea has been applied to a three-fingered underactuated hand to achieve different grasping types. The hand utilises a two-degree-of-freedom five-bar linkage as the palm of the gripper, with three three-phalanx underactuated fingers—jointly controlled by a single actuator—connected to the mobile revolute joints of the palm. Additionally, with this five-bar linkage palm design and the constant tendon routing method, the hand exhibits the capability to perform systematic prehensile in-hand manipulations regardless of object size or shape. Even more, this novel layout allows decoupling grasping and manipulation control, facilitating the planning and execution of in-hand manipulation operations. The reconfigurable palm provides the hand with a large grasping versatility, while allowing easy computation of a map between task space and joint space for manipulation based on distance-based linkage kinematics. The motion of objects of different sizes

and shapes from one pose to another is then straightforward and systematic, provided the objects are kept grasped. This is guaranteed independently and passively by the underactuated fingers using a custom tendon routing method, which allows no tendon length variation when the relative finger base positions change with palm reconfigurations. Overall, the work in this chapter opens up a new idea on co-designing robot hand and control for dexterous in-hand manipulations.

6.1 Future Work

- **Soft Fingertip Model for Spatial Manipulation.** A limitation of the proposed contact model in Chapter 2 is that it is impossible to simulate different shapes of the fingertip or object geometry as the model is based on point contact with friction that does not consider curvature information. The other limitation of this current model is that only planar manipulation has been studied; indeed, the overall approach can be leveraged to study spatial manipulation by modelling the soft fingertips as spherical joints with clearance and extending the use of affine arithmetic to maintain tractability. Furthermore, the initial grasping condition of the proposed soft fingertip model can be used as a constraint to solve the redundancy of high-DOF robot fingers and obtain exact solutions for in-hand manipulation problems. Additionally, the use of the soft fingertip model for motion planning could be extended by considering the dynamics.
- **Variable Friction Skin for Better In-hand Manipulation Performance.** Chapter 3 results show the unit density is one of the main aspects to improve the gripper performance, showing a higher manipulation magnitude per cycle with a higher reliability. For the objects manipulated, it was also observed that objects with faces parallel to each of the fingers produced a larger manipulation as the contact friction can change, unlike in point contact conditions. For future work, the performance of the proposed surface could be improved to move an object to a target position and orientation via closed-loop control, with the addition of vision or tactile sensors to monitor translation and rotation magnitude. In addition, the size of the proposed surface could be scaled down while increasing the unit density to manufacture an origami soft skin.
- **Soft Fingertip Design for Better Tactile Feedback.** As discussed in Chapter 3, with active

shape-changing of the embedded air cavities, fingertips are able to in-hand manipulate soft objects prehensilely with pressure feedback control. The proposed simulation model gives an evaluation of the manipulation ability of the enhanced gripper, which can be improved by taking the initial rotation angle and deformation of the fingertips into account. The limited dexterity gripper used in this study only has specific object positions for each grasp configuration when equipped with typical soft fingertips. With the proposed closed-loop control approach and the novel dual-purpose fingertips, the object position can be adjusted at each grasp configuration, increasing the gripper's dexterity vastly. The control algorithm can be developed further in future works for more complex prehensile in-hand manipulations that combine translation and rotation with irregular objects. Moreover, the performance of the dual purpose fingertip could be improved to sense force via the inflated air cavities as well.

- **Develop Novel Hand Topology for Various In-hand Manipulation Trajectories.** Experimental tests of the helical hand described in Chapter 4 discovered some opportunities for future work. For instance, the hand dimension and the joint limitation could increase, improving the capability of the hand grasping and the performance of the helical motion. The rotary fingertip attachment design could be improved to minimise the pinch force loss. Each proximal finger could be actuated separately to have different in-hand manipulation behaviours; it would be helpful to extend the grasping ability and the potential applications as well.
- **6D Grasping-Manipulation Decoupling.** For future work, force analysis can be performed to calculate the required torque for the constant-tendon routing, and this routing can be optimised to improve the force transmission efficiency. Moreover, the introduced grasping-manipulation decoupling approach can be explored for 6D in-hand manipulation through a novel design of the base linkages or an improved underactuated finger design.

The design ideas proposed in this thesis can be helpful for future dexterous robot hand development. Hopefully, under the mechanical simplicity principles herein explored and introduced, along with the support of appropriate software and perception development, robot hands could soon match the capabilities of human hands.

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