In-Hand Manipulation with Soft Fingertips

Soheil Sarabandi*, Qiujie Lu*, Genliang Chen, and Nicolas Rojas

Abstract— **This paper introduces an approach for solving the in-hand manipulation problem, that is, the change of a grasped object pose from an initial configuration to a final one without breaking contact, with robot fingers having out-of-plane motion, redundancy, and equipped with soft fingertips. The proposed technique is based on keeping the initial grasp equilibrium condition as a constraint to resolve finger redundancy. Two important aspects of in-hand manipulation with soft fingertips are then studied; namely: i) the modeling of soft fingertip contacts between fingers and 3D objects, and ii) an efficient method for computing joint angles to move a grasped object between different poses without losing grasp equilibrium. Numerical and empirical experiments using soft fingertips with different shore hardnesses with a two-fingered robot hand, composed of four-degree-of-freedom fingers with out-of-plane motion, are conducted. Results successfully validate the introduced strategy and its components.**

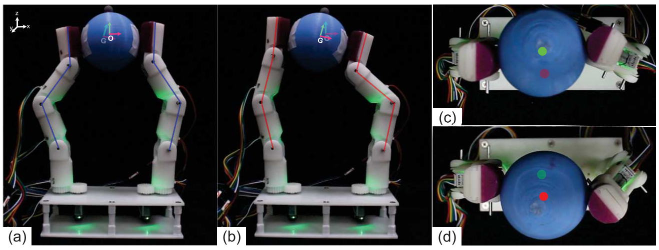

Fig. 1. In-hand rotation of a 70mm sphere along the y-axis for 15 degrees using a two-fingered hand with 4-DOF fingers and soft fingertips while keeping the initial grasping equilibrium condition (**a** and **b**). In-hand translation of the same object along the y-axis for 15mm while also keeping the original grasp equilibrium condition (**c** and **d**).

I. Introduction

While in-hand manipulation of objects is a fundamental everyday task for humans, it is still challenging for robotic hands. Among all robot hands, those with high-degree-of-freedom (high-DOF) fingers are particularly useful for getting accurate, versatile manipulations of grasped objects [1], [2]. However, high-DOF robot fingers with rigid fingertips have lower grip stability due to a smaller contact area with the grasped object, an area that is theoretically idealised as a single-contact point. This realisation has led to the investigation of robotic manipulation with soft fingertips. For example, Lu and Rojas [3], Khurshid and Ghafoor [4], and Shimoga and Goldenberg [5] reported on experiments in which soft fingertips successfully enhanced dexterous capability. Moreover, Brockett [6] and Shimoga and Goldenberg [7] proposed several types of soft and compliant fingertips that successfully enhanced dexterous capability experimentally. Despite these advantages, soft fingertips also introduce extra complexity when modelling the hand-object system, and indeed the relation between soft fingertips and in-hand manipulation is certainly not well defined as yet, as studies have traditionally focused on using the *soft finger* contact model [8] which is an extreme simplification of the finger-object interaction, although recent progress has been made for developing alternatives for in-hand manipulation that reflect a more accurate representation of the resulting contact, while being tractable [3].

In-hand manipulation is the ability to move a grasped object from an initial position to a desired one relying only on the coordination of fingers, as shown in Fig. 1. This is a challenging task, in particular with robot fingers of more than 3-DOF, herein called high-DOF fingers, such as those with four joints in each finger (e.g., [9], [10]), since due to position redundancy there exist multiple joint configurations for each contact location providing sufficient internal forces to prevent object falling. This is even more challenging when considering soft fingertips due to the uncertainties of using soft materials (e.g., rolling, deformation).

As aforementioned, in-hand manipulation with soft fingertips has been widely studied over the past several decades. Chang and Cutkosky [11] determined the kinematic effects of soft fingertips during manipulation with rolling. Doulgeri et al. proposed a method for in-hand manipulation using an adaptive controller for the position and force regulation of a soft fingertip with dynamic and kinematic parameter uncertainties [12], this approach was later extended and applied to a two-fingered hand [13]. A feedback controller for the manipulation of a rectangular object by a two-fingered hand with soft fingertips was presented in [14], [15]. Inoue and Hirai proposed a method for the in-hand manipulation problem of a two-fingered soft robotic hand with 1-DOF fingers [16]; their method is based on the local minimum elastic energy and the intrinsic characteristic of a hemispherical soft fingertip, the approach was later extended to a two-fingered hand with 2-DOF fingers [17]. Most recently, Rodriguez et al. proposed a passivity-based controller to manipulate

S. Sarabandi and Q. Lu contributed equally to this paper.

S. Sarabandi is with the Institut de Robòtica i Informàtica Industrial (CSIC-UPC), Llorens Artigas 4-6, 08028 Barcelona, Spain. (e-mail: soheil.sarabandi@gmail.com)

Q. Lu and N. Rojas are with the REDS Lab, Dyson School of Design Engineering, Imperial College London, 25 Exhibition Road, London SW7 2DB, UK. (e-mail: {q.lu17, n.rojas}@imperial.ac.uk)

G. Chen is with the State Key Laboratory of Mechanical Systems and Vibration and the Shanghai Key Laboratory of Digital Manufacture for Thin Walled Structures, Shanghai Jiao Tong University, Shanghai 200240 China. (e-mail: leungchen@sjtu.edu.cn)

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circular dynamic objects with two soft fingertips [18]. To the best of our knowledge, however, previous works have ignored how the grasp equilibrium condition evolves while the object moves, which is an important consideration to keep the object secured. This is in part because of defining a grasp equilibrium condition with soft fingertips goes beyond the limits of the traditional definition of force closure grasps [19] as it is unknown, due to compliance and closed-loop constraints, where the actual contact points occur.

In this paper, we propose solving the spatial in-hand manipulation problem, meaning that the object can be manipulated in 3D space, with high-DOF fingers having soft fingertips. This is done by keeping the initial grasping equilibrium condition during the manipulation, which in turn is achieved thanks to a tractable soft fingertip model based on spherical joints with clearances. This model leads to the development of a discrete grasp equilibrium condition, which makes use of several friction cones but avoids the need of knowing the exact location of contact points. The initial grasp equilibrium condition is then used as a constraint to solve the redundancy of fingers in in-hand manipulation tasks, using a closed-form positioning formula herein introduced, and by computing the domain of proximal joints that guarantees grasp equilibrium. This domain is calculated by considering that contact forces can be moved to the edges of friction cones.

The rest of the paper is organised as follows. Section II reviews soft fingertip modelling for spatial in-hand manipulation and presents a new model for soft fingertips which is used in section III for solving the soft fingertip positioning problem. Numerical and experimental validation of the proposed method using soft fingertips with different shore hardnesses are presented in section IV with a two-fingered hand composed of four-degree-of-freedom fingers with out-of-plane motion. Finally, we conclude in section VI.

II. Soft Fingertip Modelling for Spatial In-hand Manipulation

A simple approach to simulate soft fingertips for in-hand manipulation in planar cases is presented in [3]. In this approach, the contact condition for a soft fingertip is no longer a point contact with friction with twist, as in the traditional soft finger model, but a segment line with friction. Normally, both point contact with friction and soft finger can be modelled as a revolute joint in the planar case [20]. Thus, in order to deal with the uncertainties due to deformation, it is proposed to model soft fingertip contacts as revolute joints with clearance. In this paper, this notion is extended to 3D objects, modelling the interaction between soft fingertips and objects as spherical joints with clearance (see Fig. 2 (left)), and then approximating clearances via affine arithmetic [21] to facilitate computation.

For the spatial case, the unknown contact point between a soft fingertip and an object is bounded by an area. This grasping area is shown in light blue in Fig. 2(left). This area comes from modelling the contact as a spherical joint with clearance to maintain the fingertip contacts on the object

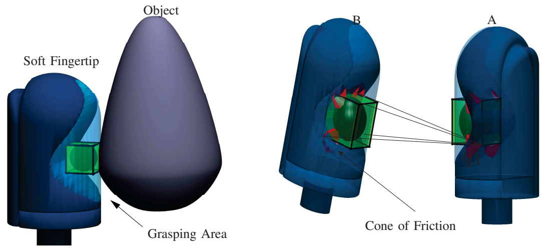

Fig. 2. **Left to right:** Soft fingertip deformation model based on approximating interactions between fingertips and object as spherical joints with clearances. The clearance sphere defines an area where the contact between fingertip and object can occur. The green square indicates the affine arithmetic method to cover the clearance sphere which simulate the approximate contact range. For each interval value of fingertip A, say q_1, there are 4 lines between it and fignertip B. Thus, a total of 16 lines quantify the grasp equilibrium.

surface during the manipulation. The sphere size is based on the hardness of the fingertip. To achieve an efficient mathematical model, affine arithmetic is applied to provide guaranteed bounds for this spherical contact area (green cube). Therefore, each contact point can be defined by its interval range. This contact model can be now used to obtain a grasp equilibrium model. To this end, consider two soft fingertips that grasp a 3D object (see Fig. 2 (right)). Each contact point can be represented by an interval which is obtained via affine arithmetic. Interval values are shown as the last edges of the green cube Fig. 2(right). According to Fig. 2 (right), for each interval value of fingertip A (say q_1), there are 4 lines between these two soft fingertips, therefore in total, there are 16 lines for a two-fingered hand. The friction coefficient and normal at interval value create a friction cone about the axis of the normal by using $\mu = tan\lambda$, where μ is the coefficient of friction and λ is the angle of the friction cone. If there is at least one line between these two soft fingertips which lies in a certain double-side friction cone, the grasp is equilibrium, otherwise, it is not an equilibrium grasp.

The proposed grasp equilibrium model is used in the next section to solve the in-hand manipulation problem with soft fingertip in such a way to keep the initial grasping condition. The determination of the initial grasp is outside the scope of this work, it can be obtained using different approaches such as optimal on-line contact adjustments (see [22] for reviews on the different proposed methods). In our experimentation, we used a two-fingered hand and the initial grasp is obtained by moving fingertips towards the desired object to be grasped.

III. Method for Solving In-Hand Manipulation with Soft Fingertips

The in-hand manipulation problem assume finding the joint angles in relation to the known position of a fingertip from an initial to a goal configuration that places the soft fingertips precisely in the desired position. The computational complexity will increase dramatically with the increase of a fingers' degrees of freedom when each finger has one-degree freedom more than necessary (finger with four joints),

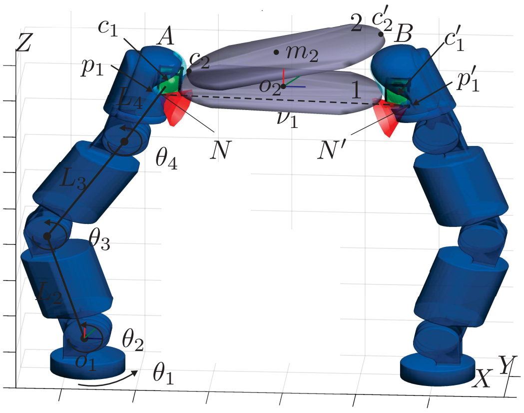

Fig. 3. The in-hand manipulation problem is to determine joint values to displace object from position 1 to position 2

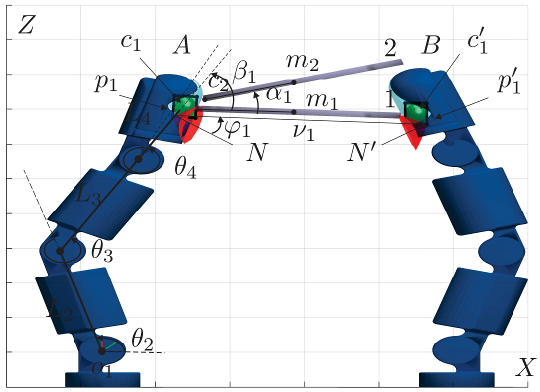

Fig. 4. Illustration of soft fingertip positioning problem in ZX plane

therefore there are many joint configurations for a unique Cartesian fingertip position. The main contribution of the paper is providing a solution for the in-hand manipulation problem of soft fingertips by using the additional degree of freedom to satisfy some constraints on the initial grasping condition.

Let us also denote $\mathbf{T}$ as a small homogeneous transformation that represents the displacement of the object from the first to the second configuration, the problem is to determine joint values which respect the grasp stability. To solve this problem, the following assumptions have been considered: the initial grasp is stable, the object is rigid, the object's center of mass is known. These assumptions may seem strong but, in contrast to a learning-based strategy, the proposed method does not require training sessions and data extraction, which may be time-consuming particularly given the presence of compliant fingertips.

According to Fig. 3, for a small transformation $\mathbf{T}$ to displace the object from position 1 to position 2, and the definition of the contact points as a spherical joint and the mentioned assumptions, the center of spheres for position 1 in the reference frame of the fingertip, o_1, are known and it is tried to find them in the second configuration of this frame. To do this, a reference frame on the object's center of mass in position 1 is defined as o_2 with the same direction of o_1, and the center of the spheres in that frame are redefined. Then by applying the transformation, the points can be found in the reference frame o_2 in position 2. Finally, by using the transformations between two reference frames, the positions of these points can be obtained in reference frame o_1 mentioned as c_2 and c_2' in Fig. 3. Then the problem of soft fingertip positioning for each finger such as A is as follows;

- **Problem 1**: **In-hand manipulation keeping initial grasp condition** - solving the In-hand manipulation problem by determining θ_2, θ_3, and θ_4 to move contact point from position c_1 to c_2;
- **Problem 2**: **Maximum out of plane motion without losing grasp equilibrium** - determine θ_1, and the domain of θ_1 with respect to the initial grasp condition, that guaranties the grasp equilibrium.

Problem 1 for finger A can be solved by keeping the initial grasp condition in as a constraint for the redundant fingers. According to the grasp equilibrium model for initial grasping, there are some lines between these two soft fingertips which lay in a certain double-side friction cone, for instance, ν_1. As can be seen in Fig. 4, there is an angle between each line and force unit vector N in the ZX plane called φ_1. To keep the initial grasp condition which guarantees that the normal forces remain inside the cone friction, φ_i's should be fixed in both configurations. To do this, angle β_i between the last link L_4 and the vector which connects the contact point c_i to the center of mass m_i is defined. By equaling β_i to initial β_1, φ_i's do not change. Also, another variable ω is defined which is the angle between the last link L_4 and X-axis. The value of ω's for the second configuration is defined as:

$$\omega = \beta_1 + \alpha_1 \tag{1}$$

where α is the angle between the vectors that connect the contact point to the center of mass for positions 1 and 2. Therefore, by knowing ω, a closed-form formula for determining the θ_2, θ_3, and θ_4 is obtained as follows:

$$\begin{aligned} a_x =& \text{sign}(c_{2_x}).\sqrt{c_{2_x}^2 + c_{2_y}^2} - L_4\cos(\omega) \\ =& L_2\cos(\theta_2) + L_3\cos(\theta_2+\theta_3) \end{aligned} \tag{2}$$

$$a_z = c_{2_z} - L_4\sin(\omega) = L_2\sin(\theta_2) + L_3\sin(\theta_2+\theta_3) \tag{3}$$

From equation (2) and (3) we have:

$$\theta_3^a = \text{acos}(\frac{a_x^2 + a_z^2 - L_2^2 - L3^2}{2L_2L3}) \tag{4}$$

$$\theta_3^b = -\text{acos}(\frac{a_x^2 + a_z^2 - L_2^2 - L3^2}{2L_2L3}) \tag{5}$$

By expanding equations (2) and (3) and rearranging them, we have two solutions for θ_2:

$$\theta_2^a = \text{atan}(\frac{a_z}{a_x}) - \text{atan}(\frac{L_3\sin(\theta_3^a)}{L_2 + L_3\cos(\theta_3^a)}) \tag{6}$$

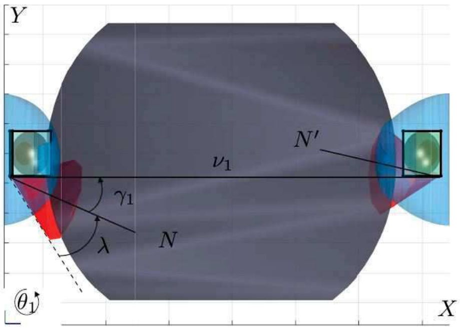

Fig. 5. Illustration of soft fingertip positioning problem in XY plane. Where **N** and **N**' are force unit vectors in the XY plane corresponding to fingers A and B, respectively. γ_i is the angle between line i which connect two soft fingertips and satisfy friction cone constraint and force unit vector N. λ is the angle of friction cone which is determined by the softness of fingertip.

$$\theta_2^b = \text{atan}(\frac{a_z}{a_x}) + \text{atan}(\frac{L_3 \sin(\theta_3^b)}{L_2 + L_3 \cos(\theta_3^b)}) \quad (7)$$

If the signs of a_x is negative then $\theta_2^{a,b} = \theta_2^{a,b} + \pi$. Finally, θ_4 is obtained as follows:

$$\theta_4^a = -\omega - \theta_2^a - \theta_3^a \quad (8)$$

$$\theta_4^b = -\omega - \theta_2^b - \theta_3^b \quad (9)$$

Therefore, we have two solutions for each finger to displace the object from position 1 to position 2 by keeping the initial grasp condition. The one which is near to position 1 is the desired solution. According to our definition for the contact model as a spherical joint, θ_1 can be obtained as follows, but it should be in the domain that guarantees the grasp equilibrium.

$$\theta_1 = \text{atan}(\frac{c_{2_y}}{c_{2_x}}) \quad (10)$$

The lines which connect two soft fingertips and satisfy friction cone constraint can be used to solve problem 2 to find the domain for θ_1. There is an angle between each line and force unit vector N in the XY plane such as γ_1 shown in Fig. 5. According to the definition of the equilibrium grasping which states that the line can be moved to the edges of friction cones, the bound of θ_1 for each line is obtained using γ_1 and λ, where λ is the angle of friction cone which is determined by the softness of fingertip. Therefore the sub domain of all bounds gives the range for θ_1 that keep the initial grasp equilibrium and main domain of all bounds gives the range for θ_1 that guaranties the grasp equilibrium.

IV. Numerical and Experimental Results

A. Numerical results

In order to evaluate the proposed soft fingertip model, we consider two numerical analyses for a two-finger four-DOF-finger hand with 3 different softness of fingertips (Fig. 6). The soft fingertips used in this analysis were Dragon Skin 30, Ecoflex 50 , Ecoflex 30 with shore hardness 30A, 50OO, and 30OO respectively. All soft fingertips are from Smooth-on, USA. Both tasks are examining the maximum out of plane motion without losing grasp equilibrium, but in two different ways. The first analysis is to find out the relationship between the proposed grasp equilibrium model and the soft fingertip positioning. The simulation considers the two-finger hand grasped a 70 mm sphere with a parallel distal phalanx starting position, and the center of mass is between two soft fingertips. Then both finger start bending its middle phalanx inwards shown like Fig. 6. Fig. 7 illustrates the grasp equilibrium of three different hardness fingertips for various intersection angles between two distal phalanges (ϕ), range from 0 to 140.The grasp condition is obtained as a grasping success where there is at least one line that lies in a certain double-side friction cone or failure. This method has been explicated in Section II. The figure shows that the grasp equilibrium increases when the softness of the fingertip increases.

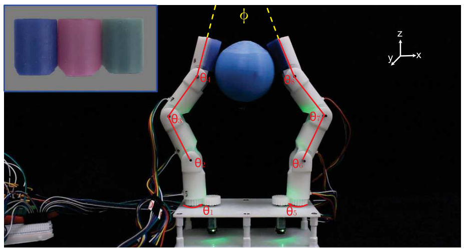

Fig. 6. Two-finger multi-DOF hand with changeable fingertip design for experiment purpose. Top left sub-figure demonstrates the three tested fingertips which are moulded with different material: blue is Dragon skin 30, purple is Ecoflex 50, and green is Ecoflex 30.

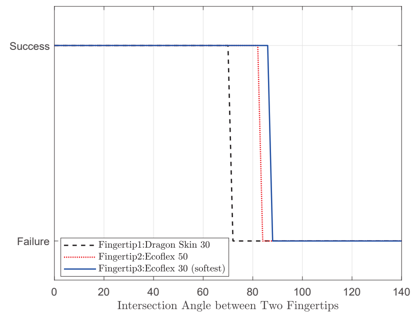

Fig. 7. Grasp condition for different soft fingertips with the intersection angle ϕ between two fingertips.

The second analysis is to find out the range of values of θ_1 for different fingertip softness when in the initial configuration the center of mass is between two soft fingertips and two soft fingertips are parallel (Fig. 8). This domain shows the maximum rotation capability of the hand in z direction. The domain for θ_1 is obtained by considering that the contact forces can be moved to the edges of friction cones in the YX plane (Fig. 5). Table I shows the domain of θ_1, which guaranties the grasp equilibrium for three different hardness fingertips. It shows that the workspace improves

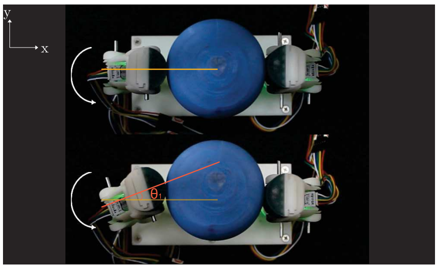

Fig. 8. Experimental illustration of grasping domain for θ_1 in XY plane with a 70mm sphere.

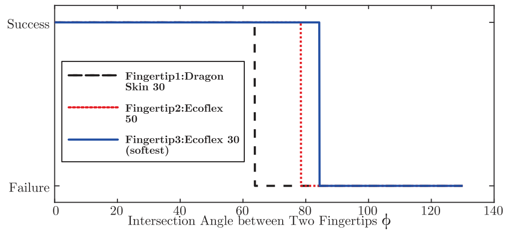

Fig. 9. Grasping condition varies with the intersection angle ϕ between two fingertips.

TABLE I

DOMAIN FOR θ_1 BY CONSIDERING THAT THE CONTACT FORCES CAN BE MOVED TO THE EDGES OF FRICTION CONES IN FIG. 8

Soft Fingertip Material	Domain for θ_1
Dragon Skin 30	[-32 32]
Ecoflex 50	[-38 38]
Ecoflex 30	[-42 42]

by increasing the softness of fingertips. Therefore for each manipulation task, the values of θ_1 which is calculated from equation (10) and lies in the range, is the desired solution of soft fingertip position.

B. Experimental results

Both numerical analyses have been verified through experiments, as well as the in-hand manipulation tasks. The detailed experimental process can be found in the paper video attached in the multimedia material.

1) Prototype: A 3D printed two-finger multi-DOF hand was designed to verify the proposed soft fingertips positioning strategy, which includes the soft fingertips modeling and the soft fingertips positioning using initial grasp condition. Fig. 6 illustrates the prototype appearance, the schematic, and the tested soft fingertips. Each finger consists of four revolute joints with one rotation along the z-axis and the rest along the y-axis. The selected actuation method for this fast prototyping hand was direct driven via 8 DC geared motors.

The distal phalanx of the hand was designed for fast-changing fingertips. By slotting in the fingertips into the distal phalanx, the hand is capable to perform the test with various fingertips rapidly. Three different softness fingertips in section IV-A were molded for the soft fingertip positioning tests (shown in Fig. 6).

2) Soft Fingertip Model Verification: Based on the numerical analyses, we evaluate the proposed grasp equilibrium model for soft fingertip practically by using the two-fingered hand we built. The grasp is defined as grasping success or failure. The hand grasped a 70 mm sphere with a parallel distal phalanx starting position. Then, continue actuating the distal phalanx DC motors to increase the intersection angle between two distal phalanx shown as ϕ in Fig. 6. Figure 9 shows the result of the grasping condition for various softness fingertips. During the test, when the object dropping from the hand we count that as a failure. The intersection angle ϕ when the failure occurs was defined by the image capture of the experimental videos. The results are similar to the simulation prediction (Fig. 7), where the grasping equilibrium increases when the softness of the fingertip increases.

In the proposed soft fingertip model, Fig. 5 demonstrates the domain for θ_1 is defined by the angle between each line and force unit vector N in the XY plane such as γ_1 and the angle of friction cone λ. Therefore, for the second verification test, we found out the range of values of θ_1 for various fingertip softness, which guaranties the grasp equilibrium. We actuate the base DC motor to change the θ_1, once the object drops, we count that position is the limit value of θ_1 as shown in Fig. 8. The fingertip surface was designed as a cylindrical curve, it can easily move along the object surface during the rotation. Table II shows the mean values of 5 test trials. Similarly, the results are close to the simulation results with a little deviation due to mechanical errors.

3) Soft Fingertip In-hand Manipulation tests: Here, we used the two-finger multi-DOF hand to evaluate the closed-form formula for the soft fingertip in-hand manipualtion. The control process is straightforward: firstly, let the hand grasp the object. Secondly, input the joint angle for each motor into the closed-form formula. Then, based on the manipulation tasks, input the object target position into the closed-form formula. Finally, use the outputs to control the DC motors. Fig. 10 illustrates the performed tasks which consist translate a 70 mm sphere in x and z-direction, and rotate along y-axis as well. The same tasks have also been tested with a 70 mm cubic. For more detailed performance, please check the attached video.

The proposed soft fingertip positioning method is solved by keeping the initial grasp condition in solving the inverse kinematic. From the simulation results shown in Fig. 10, the target fingertip gestures(red and green) are parallel to the initial gestures (blue) which indicates the method has capability to manipulate objects with the same grasping condition. With the proposed closed-form formula, the solution is not unique, by applying the mechanical constraints of the prototype and the motion rationality, we used the second solution (red) to control the prototype. The schematic structure of the hand has been highlighted in the figure with blue for the initial structure and red for the final structure. The frame ’O’ represents the initial object pose and the ’G’ frame is the final object pose.

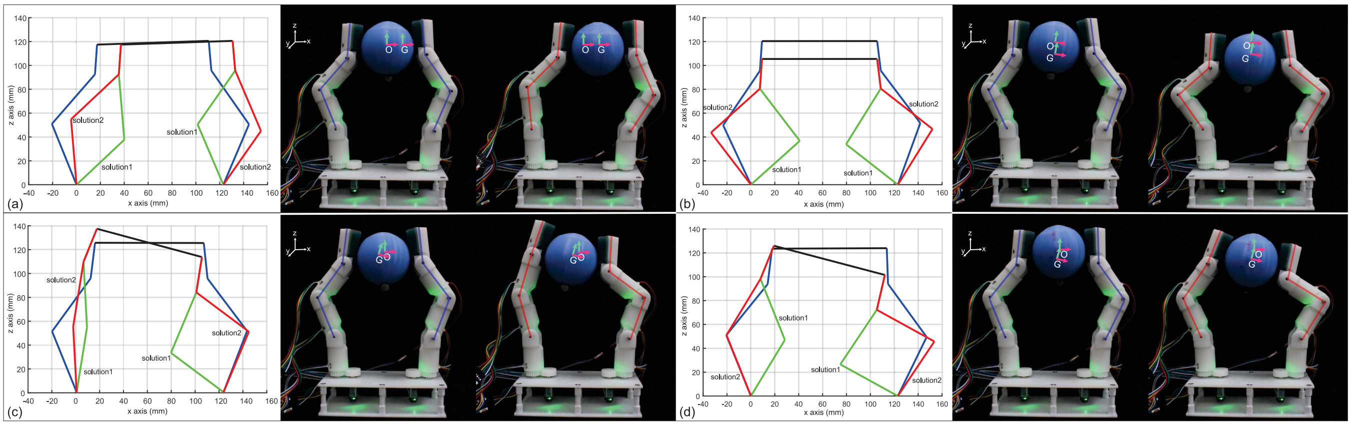

Fig. 10. In-hand manipulation keeping the initial grasping condition demonstration with both simulation and practical results. (a) object translated 20 mm along x-axis, (b) object translated 15 mm along z-axis, (c) object rotated clockwise 15 degrees along y-axis, and (d) object rotated clockwise 15 degrees along y axis and translated 10 mm along z-axis. Blue indicates the finger initial configuration, green and red indicate the two results of the finger target configuration. The frame 'O' represents the initial object pose and 'G' frame is the final object pose.

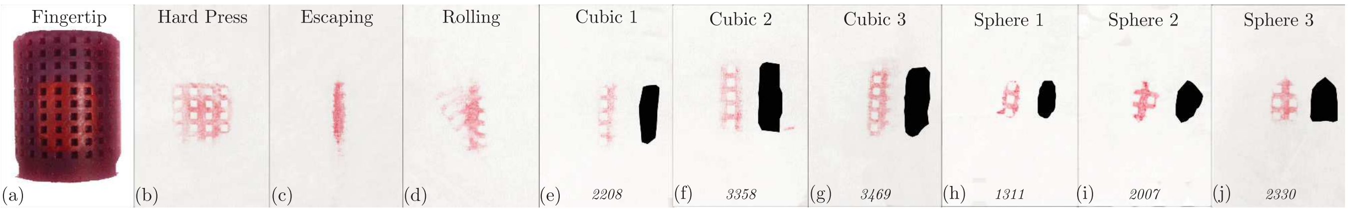

Fig. 11. Fingertip with checked pattern for determination of the grasp capability during the in-hand manipulation. (b) to (d) show the ink marker as a sample reference with hard press, escaping and rolling conditions. (e) to (j) are the marker results of three softness of fingertips grasping a 70 mm cubic and 70 mm sphere. Black shaded area are the image processing results of the marks. The average area size of each condition for 3 trails is shown at the bottom.

TABLE II

EXPERIMENTAL DOMAIN FOR θ_1 FOR VARIOUS FINGERTIP SOFTNESS

Soft Fingertip Material	Domain for θ_1
Dragon Skin 30	[-28.5 28]
Ecoflex 50	[-31 32.3]
Ecoflex 30	[-35.6 35]

TABLE III

A COMPARISON OF THE TARGET POSE WITH THE ACTUAL POSE FOR ALL 4 MANIPULATION TASKS. UNIT: MM & °

	Task1	Task2	Task3	Task4	
	T ∼ x	T ∼ z	R ∼ y	T ∼ z	R ∼ y
Simulation	20	15	15	10	15
Experiment	16.32	12.01	15.6	8.86	15.8

We examined the proposed grasp equilibrium model by using a "stamping method" as shown in Fig. 11. Here we molded the fingertip with a checked pattern in all three mentioned material, before grasping the object, the center of the fingertip was marked with red ink (Fig. 11(a)). The grasped object is covered with masking tape, once the object being grasped, the checked marker would leave on the masking tape. Fig. 11(b)-(d) demonstrate the marker conditions when hard press, escaping and rolling occurs. Those are being used as references to evaluate the gripper performance later. After the specified manipulation, we hold the object manually and open the two-finger hand to check the masking tape. If the marker is clear and not blurred, we determine the hand manipulated the object with the same grasping condition and with no rolling occurs. Fig. 11(e)-(j) illustrate the ink marks on the masking tape of all three softness of fingertips grasping a 70 mm cubic and 70 mm sphere. Here '1' indicates the Dragon skin 30, '2' indicates the Ecoflex 50, and '3' indicates the Ecoflex 30. Those marks are evaluated through the image processing to calculate the area through pixels shown as the black shaded area. The average area size of each condition for 3 trails is shown at the bottom. Larger area size refers to larger contact area.

Additionally, the object positions were tracked by a motion tracking camera (OptiTrack Prime^x 41). Table III shows the comparison of the tracking results with the desire positions of 5 trials of sphere, where 'T' indicates translation in unit mm, 'R' indicates rotation in unit degree °, and '∼ x' indicates along x axis. The caption of Fig. 10 explains each task in details.

V. DISCUSSION

According to the results of both verification tests, the experimental intersection angles and the domain θ_1 are slightly smaller than the simulation prediction, this may because of the prototype error, friction, or softness prediction error. Nevertheless, the proposed soft fingertip model method and the initial grasp condition have been used to solve the soft fingertip positioning problems. Therefore, several soft fingertip manipulation tasks have been conducted to test the proposed closed-form formula for soft fingertip positioning.

For the grasp capability inspection, the 'stamp method' gives reliable results by examining the properties of the marks. As the fingertip is a semi-cylinder shape, when the contact force is not large, the contact area with a flat surface is close to a line and with a curved surface is closed to a circle which can both observed from the results. Additionally, for the same object, image processing results shown that softer fingertip has larger contact area, also experiments with softer fingertip have higher successful rate on manipulating an object without changing the grasp capability.

For the in-hand manipulation accuracy, the results show that the hand can achieve rotation with around 96% and translation with mean value of 83.4%. These errors are because of the uncertainty of the mini DC motors used in the robot hand, and the large number of actuators. Additionally, the successful rate for the manipulation tasks increases when the softness of fingertip increases. With the same position control of the hand, softer fingertip grasped objects with larger contact area which increases the grasping stability during the manipulation and also absorbs some dynamic effects. Overall, the results show that the proposed formula for soft fingertip in-hand manipulation is properly working for a two-fingered multi-DOF hand. Also using single-precision arithmetic on a PC with a 1,8 GHz Intel Core i5 processor the average execution time of the proposed method is 0.15 μs.

VI. Conclusion

The in-hand manipulation problem of high-DOF robot fingers with soft fingertips has been analyzed in this study. A new soft fingertip modeling for in-hand manipulation as spherical joints with clearance has been proposed. 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. Different manipulation tasks show the suitability and robustness of the proposed method. Given the efficiency and low computational cost of the introduced technique, it is more suitable for compact, low-cost, and low-power industrial electronics. In the solution of the in-hand manipulation problem with soft fingertips proposed in this paper, no dynamic constraints have been taken into account which is a possible extension of the proposed approach.

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